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Cover illustration (Clockwise from upper left): The cover includes a collage of various experimental components that drive the research of the Physics Division of Oak Ridge National Laboratory. The pictures show clockwise from the top left: a scanning electron microscope image of the carbon matrix used for ISOL targets; remote handling robot on the RIB Injector Platform; CLARION and HyBall arrays at the target chamber of the Recoil Mass Spectrometer; central magnet and one spectrometer arm of PHENIX; central column structure of the 25-MV tandem accelerator; Daresbury Recoil Separator.
The Future Please, Not the Past

I should have known better. A casual comment to the editor during a conference dinner at Trento about the *Nuclear Physics News* editorials, and here I am landed with producing the next one. Worse still, I have to make public my comment, at the risk of offending my older colleagues.

The concern I voiced was that over the last few years, too many of the editorials seemed to involve backward looks to a time of better funding of nuclear physics and to times when there were no pressures on “pure” research activities. The point is that for the many younger members of our community, the present state of affairs is perfectly natural and the only one they know. We (if I may put myself in that group) have grown up in a period of static or declining budgets, and in a climate where society wishes to see applications from research. Moreover, we don’t see nuclear physics as being treated any different from other fields of research in this regard, for if we talk to our colleagues in other areas of physics research such as plasma, atomic, solid state, etc., we hear of the same pressures on funding and the favoring of applications work. For the younger community, the habit of looking backward is all very dated and of little interest. Nuclear physics operates in the same environment and with the same pressures as other areas of the physical sciences, just as it should.

To avoid too much emphasis on past reflection, perhaps more of the editorials should be from our younger colleagues; as a challenge I have forwarded a few names to the editor.

There was, if I recall, another topic in the conversation that evening. That is the growth of facilities at the larger laboratories at the expense of facilities in smaller institutions and universities. Although I will comment on this in the context of developments in Europe, I believe that the same comments probably apply to our colleagues elsewhere. In the light of what I said at the beginning of this article, it is worth noting that here again, we are really little different from other areas of physics research, as evidenced by the ESF for the synchrotron community and now the proposed ESS for the neutron community. The same pressures which drive us to aspire to larger and more expensive facilities are also felt by other research communities. However, we must always be aware of one important difference. While the ESF, or ILL, or the proposed ESS can at any time support 20 or more groups simultaneously, the nature of nuclear physics facilities is such that they generally support only one group at a time. The needs of the European community require far, far more than just a few large facilities. Moreover, the scientists of the future emerge from the Ph.D. students in universities, where the opportunity for hands-on training can be given.

Our community must take positive action to evolve a future strategy which supports a balance of large, medium, and small facilities, based both in national laboratories and in universities. In the European context, I look to NuPECC to provide a lead in these discussions.

*BRIAN FULTON*

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The views expressed here do not represent the views and policies of NuPECC except where explicitly identified.
Nuclear Physics at Oak Ridge National Laboratory

Introduction

Oak Ridge National Laboratory (ORNL) is the largest U.S. Department of Energy (DOE) science and engineering research laboratory. The research portfolio of ORNL spans a broad range of sciences including materials research, biology, computational sciences, energy technology, environmental science, and nuclear physics.

Nuclear science within the Physics Division includes several major thrust areas ranging from experimental studies of nuclear structure, astrophysical processes involving nuclei, plasma formation using relativistic heavy ions, and a new research program in neutron science.

Nuclei offer an extremely rich playground in which to perform research. Increasing interest is being placed on understanding nuclei under extreme conditions of isospin and excitation energy. The scientific motivation here is to understand emergent phenomena that occur when we move away from stable nuclei into regions where nuclei are weakly bound or are indeed unbound with respect to particle decay. Nuclei also play quite important roles in astrophysical processes such as nova and supernova energy generation and element production in the universe. At very high energy scales, nuclear collisions shed light on the deconfined phase of QCD and on the zero-baryon phase of the early universe. Finally, the nucleus is a fine laboratory where we can test the fundamental symmetries of nature and the standard model.

The Holifield Radioactive Ion Beam Facility

The low energy nuclear physics program at ORNL is centered on the Holifield Radioactive Ion Beam Facility (HRIBF), which is operated as a national facility supporting the nuclear science research program of the U.S. DOE. The HRIBF is the only U.S. facility devoted to the production of radioactive ion beams (RIBs) using the isotope separator on-line (ISOL) technique and is a bridge to the realization of the planned Rare Isotope Accelerator (RIA). The ISOL technique, as implemented at HRIBF, is illustrated in Figure 1. An intense ion beam from the production accelerator is used to bombard a thick target and create radioactive nuclei. These newly produced nuclei diffuse out of the heated target and are ionized and formed into a beam, which is then mass analyzed, injected into the post-accelerator, and finally delivered to an experimental end station. The HRIBF supports active research programs with beams of both neutron-deficient and neutron-rich radioactive species. In fact, at the present time, the HRIBF is the only facility in the world that is able to provide beams of medium-mass neutron-rich species, such as doubly magic $^{132}$Sn, post-accelerated to energies above the Coulomb barrier. Altogether, the facility accelerates about 80 stable beams and more than 100 p- and n-rich beams (with intensities in excess of $10^3$ pps) above the Coulomb barrier (see Figure 2).

Operation of the HRIBF involves four major components: the light ion production accelerator ORIC (Oak Ridge Isochronous Cyclotron), the RIB Injector, the 25-MV tandem post-accelerator, and several state-of-the-art experimental end stations that are well equipped with flexible detector arrays and spectrometers. The layout of the facility is shown in Figure 3.

Figure 1. ISOL technique at HRIBF.
The production accelerator, ORIC, is a variable energy cyclotron which provides light ion beams with intensities in the tens of microampere range. The maximum beam energies for protons, deuterons, $^3$He, and $^4$He are about 50 MeV, 50 MeV, 120 MeV, and 100 MeV, respectively. The ORIC beam bombards a thick target mounted on the RIB Injector. The RIB Injector is the heart of the HRIBF, where the severest challenges of ISOL RIB production must be met. It is here that the radioactive nuclei are created and extracted from the production target, a process that must be accomplished in a time commensurate with the lifetime of the species of interest. The RIB injector is comprised of a high voltage (300 kV) platform on which a target and ion source system, electrostatic beam transport system, a first stage mass analysis system ($M/\Delta M \approx 1,000$), and a charge exchange cell are mounted, followed by a high resolution mass separator (isobar separator) ($M/\Delta M \approx 20,000$). The RIB is formed in the RIB Injector ion source and subjected to an initial stage of mass analysis. The tandem post-accelerator requires a negative-ion beam. Consequently, if the ion source produces positively charged ions, a charge exchange cell is required. After being accelerated off the high voltage platform, the negative ions pass through the high-resolution mass analyzer and are injected into the 25 MV tandem (which holds the world record for tandem operating voltage). It is routinely used with terminal potentials ranging from near 1 MV for astrophysics experiments to above 24 MV for nuclear structure and reaction studies. The tandem is folded so that the beam is bent 180 degrees inside the terminal, stripped of bound electrons by a gas or foil stripper, and perhaps stripped a second time partway down the high energy column. The beam may be delivered to one of six experimental end stations that contain very versatile detector systems.

The development of radioactive beams at HRIBF is driven by the needs of our users. Each new beam species presents challenges, often requiring development of specialized production targets or ion sources. The HRIBF now routinely uses two types of ion sources and has several others in various stages of development. The Kinetic Ejection Negative Ion Source (KENIS) is a novel device conceived and developed at HRIBF.
to produce beams of halogen species (especially fluorine isotopes). The Electron Beam Plasma Ion Source (EBPIS), based on an ISOLDE design, is a general-purpose positive ion source. The EBPIS is also used with other target systems, e.g., a liquid germanium target to produce beams of As and Ga. Both positive and negative surface ionization sources designed for RIB's have been developed, but not yet used on line.

Production targets are a critical part of beam development. Even though the total production-beam power at HRIBF is rather low (~1kW), the power density in the production target can be very high. The target material must have a low vapor pressure at the operating temperature (up to 2,000°C), be robust enough to withstand the power deposited by the beam, and have a format conducive to fast release of the species of interest. Two critical geometrical features are short diffusion paths for the beam-species atoms and a highly-permeable, open structure that allows atoms or molecules to effuse out of the target quickly. We have developed a number of target systems for RIB production at HRIBF which meet these requirements. An oxygen-bearing target was needed to produce 17,18F. Our solution was a highly-refractory HfO$_2$ matrix, made up of thin (10 µm) fibers. Neutron-rich RIBs are produced at HRIBF by proton-induced fission of $^{238}$U. The target consists of thin layers (<10 µm) of uranium carbide deposited on an open-structured carbon fiber matrix (see the cover).

The nuclear reactions employed to produce RIBs generally result in comparable quantities of several isotopes of the same mass (isobars). Some experiments can use a beam containing such a mixture of species, but others require higher beam purity. The ability to produce beams which are nearly free from isobaric contamination is a critical capability for a RIB facility. The high-resolution magnetic isobar separator is intended to fill this function; however, in many cases the quality of the negative ion beam entering the separator, or the small mass difference between adjacent isobars results in insufficient beam purification. In some cases, the ionization process itself can be made species selective, such as the enhancement of alkalis by positive surface ionization, or suppression of species that do not form negative ions in negative sources. Another technique applicable to light nuclei is elimination of isobars with smaller atomic number than the species of interest by fully stripping the beam after acceleration but prior to final energy analysis. Recently a new technique to purify Sn and Ge beams was discovered at HRIBF, which is a variant of a chemical technique long employed at ISOL facilities. The importance of this discovery follows from the critical importance of pure beams of the double closed shell nucleus $^{132}$Sn, and the closed shell nucleus $^{92}$Ge to many fields of RIB science. $^{132}$Sn is produced along with a dominant background of $^{132}$Te and $^{132}$Se. If small quantities of sulfur are introduced to the production target (e.g., as H$_2$S), it is empirically found that the EBPIS produces a strong molecular beam of $^{132}$SnS$_2$, with no detectable $^{132}$TeS$_2$ or $^{132}$SeS$_2$ contamination. The same effect is seen with Ge isotopes.

Particularly interesting radioactive beams have an intensity that is orders of magnitude lower than a typical stable beam, even after production and purification techniques are carefully optimized. The HRIBF has a remarkable suite of end stations that are well suited for RIB research. The Recoil Mass Spectrometer (RMS) is the centerpiece of the nuclear structure end station. This state-of-the-art spectrometer separates reaction products from primary beam and spatially separates the products by their mass-to-charge ratio. Many detector systems can be employed with the RMS: CLARION, an array of 11-segmented Clover Ge gamma-ray detectors; HYBALL, a 95-element CsI charged particle detectors which can be augmented by the forward array; Forward Array, an annular array of double-sided silicon strip detectors in a AE-E arrangement; Microchannel Plate Detectors (MCP) for low-intensity beam diagnostics and counting as well as large area position sensitive focal plane detectors; Double-sided silicon strip detectors for implantation and decay experiments such as ground state proton- and alpha radioactivity; CARDS, CLARION Ge detectors coupled to the LSU Moving Tape Collector.

The Daresbury Recoil Separator (DRS) is the centerpiece of the astrophysics end station. The DRS filters low-energy capture reaction products from primary beam through velocity selection and momentum analysis. The annular silicon detector array SIDAR is used for charged particle detection. MCPs and an ionization chamber are used to uniquely identify reaction products. A windowless gas cell will soon be coupled to the DRS and can produce a hydrogen target equivalent to ~15 µg/cm$^2$ (10$^{19}$ atoms).

The Enge Spectrograph, which may be operated in either vacuum or gas-filled mode, is used for reaction studies.

The RIB On-line Test Facility (OLTF) is used to test and evaluate...
the performance of RIB targets and ion sources using relatively low-intensity beams from the tandem. Along with our two off-line ion source test facilities, the OLFT provides us with excellent tools for the development of new or more intense RIB beams.

The HRIBF is able to bring together many different experimental techniques because it has a large number of flexible, highly efficient detector systems that are designed to work together. This detector compatibility gives us the selectivity and efficiency to make full use of radioactive and stable ion beams.

**Nuclear Structure**

Our nuclear structure program is centered on studies of nuclei far from stability. Below we shall describe some highlights of our recent experimental results, as well as possible directions for future studies.

*Spectroscopy of Neutron-Rich Nuclei*

Modifications of shell structure and novel excitation modes are examples of fascinating new phenomena that are predicted to occur in neutron-rich nuclei away from the stability line. These phenomena may be explored using a number of reactions with n-rich RIBs available at HRIBF. To take advantage of these beams, we have developed new experimental techniques and a powerful suite of specialized detectors to cope with the weak intensities and isobaric contaminations of the beams, as well as the high background resulting from their decay. In a series of pioneering γ spectroscopy experiments, we have used these beams to perform Coulomb excitation, fusion, and transfer reaction studies in the A ~ 80 and A ~ 130 regions. The results for Coulomb excitation of the first 2+ states in 126,128Sn and 132,134,136Te nuclei with a 12C target are shown in Figure 4. The experimental B(E2) value for 136Te is significantly smaller than the value expected from either the systematics (right panel), or shell model calculations. These measurements, which may be performed with beam intensities of 10^5 pps, will soon be extended to 130Sn and doubly-magic 132Sn, as well as to A ~ 80 nuclei close to the N ~ 50 line.

Transfer reactions with RIBs provide a powerful tool to probe the evolution of single-particle states and pairing strengths as one moves from the stability line. We have demonstrated the feasibility of such studies with RIBs, using complementary heavy-ion reactions of 9Be(134Te,8Be) and 13C(134Te,12C) to populate several previously unobserved states in 135Te, including a new J = 5/2 state that is an excellent candidate for the f_{5/2} orbital. We plan to extend such studies to other nuclei in the vicinity of 132Sn, using transfer reactions induced by n-rich RIBs incident on both light and heavy targets.

Our first fusion-evaporation reaction with an n-rich RIB was performed using beams of 118Ag (10^6 pps) bombarding 9Be and 12C targets. Data collected consisted of gamma-HYBALL and gamma-gamma-recoil coincidences. Fusion-evaporation reactions leading to the known nuclides (e.g., the 31/2 state in 125I) were observed, together with
previously unobserved states in $^{123}$Sb. It should be possible to study more neutron-rich nuclei such as $^{139}$Ba, $^{141}$La and $^{143}$Ce in the future.

Spectroscopy of Proton-Rich Nuclei

Because of the reinforcement of the proton and neutron shell effects, self-conjugate nuclei and their neighbors play a distinctly important role in nuclear structure. We have recently explored many fascinating phenomena along the N ~ Z line, including: (a) the possible existence of a proton-neutron superconductive phase in heavy self-conjugate nuclei, (b) deformed and superdeformed structures that arise from multiparticle-multihole excitations across the doubly magic $^{40}$Ca and $^{56}$Ni nuclei, which help elucidate the microscopic origin of collective rotation, and (c) discovery of proton and alpha radioactivity from deformed excited states. Spectroscopic studies of nuclei close to $^{100}$Sn remain one of the most important and challenging areas of nuclear structure physics. We have been able to obtain, for the first time, information about high-spin single-particle states in $^{99}$Cd and $^{101,102}$In, which involve particle-hole excitation across the $^{100}$Sn core. This information was used to test and improve results of large-scale shell model calculations. The above experiments were performed at the GAMMASPHERE in close collaboration with the experimental groups at Washington University, Lund, McMaster, ANL, LBL, and University of Tennessee.

At the HRIBF, our studies of nuclei beyond the particle-stability limit have concentrated on proton radioactivity. Five new proton emitting states were discovered, with four of them having half-lives in the microsecond range. Fine structure in proton emission has been observed in the decays of $^{141}$Ho, $^{145}$Tm and $^{146}$Tm$^{85\text{m}}$. These studies have helped elucidate the problem of proton tunneling through a deformed potential, and compositions of wave functions of unbound resonant states in exotic nuclei. A novel technique, based on digital signal processing, has been developed, which allows detection of radioactive decays within a few hundred nanoseconds. In future, proton- and alpha-radioactive nuclei with very short half-lives, such as those along the rp-process path, will be studied with this technique. This work has been conducted in collaboration with researchers from 10 institutions comprising the UNIRIB consortium.

Experimental and theoretical nuclear structure researchers at ORNL enjoy a strong synergy, and have worked closely together to address several issues related to the structure of far-from-stability nuclei including calculations to interpret excitations across the $^{100}$Sn core, and detailed theoretical interpretations for the structures of proton-emitting states.

Nuclear Reaction Spectroscopy

In recent years the emphasis of the nuclear reaction group has shifted to lower energy reactions induced by RIBs, and the development of the experimental techniques that would take advantage of these beams efficiently.

Studies of subbarrier fusion of heavy ions provide opportunities to explore tunnelling through multiple barriers. We have reconfigured the Enge split-pole spectrograph as a gas-filled separator, and we are preparing instruments for studying fusion-evaporation and fusion-fission reactions induced by neutron-rich RIBs. Systematic studies of fusion with neutron-rich nuclei can provide important information on the production of super-heavy elements.

Breakup is an important reaction channel in the scattering of weakly bound nuclei. How breakup affects fusion near the Coulomb barrier remains an open question. To better understand this problem, we have measured the breakup of $^{17}$F produced at HRIBF from 10 MeV/nucleon to energies slightly above the barrier. A large yield of stripping breakup, which arises from the absorption of the valence proton by the Pb target, was observed near the grazing angle.

We have begun a program to study resonant states in light nuclei with RIBs bombarding thick targets. With this technique, we can map a complete excitation function in one measurement. Our first experiment with a $^{17}$F beam has led to the discovery of the simultaneous emission of two-protons from excited states in $^{18}$Ne. In addition, these measurements provide important information regarding the quantum numbers of resonance states in light unstable nuclei that are of astrophysical interest.

Nuclear Astrophysics

Unstable nuclei play an influential, and in some cases dominant, role in many phenomena in the cosmos such as novae, supernovae, X-ray bursts, and other stellar explosions. In the extremely high temperatures ($>10^8$ K) of these astrophysical environments, the interaction times between nuclei can be so short (~ seconds) that unstable nuclei formed in a nuclear reaction can undergo subsequent reactions before they decay. Sequences of nuclear reactions occurring in exploding stars are therefore quite different than sequences occurring at lower
temperatures characteristic of our sun. Measurements of the structure and reactions of unstable nuclei are therefore required to improve our understanding of the astrophysical origin of atomic nuclei and the evolution of stars and their sometimes explosive deaths.

At the HRIBF, we are making some of the first precision measurements of reactions needed to probe the details of exploding stars. We have used RIBs of $^{17}$F and $^{18}$F to study important reactions including $^{14}$O($\alpha$,p)$^{17}$F, $^{17}$F(p,$\gamma$)$^{18}$Ne, and $^{18}$F(p,$\alpha$)$^{15}$O. Our approach of measuring multiple reaction channels, such as $^{18}$F(p,p)$^{18}$F and $^{18}$F(p,$\alpha$)$^{15}$O, has resulted in excellent reaction rate determinations. The RIBENS Collaboration (Radioactive Ion Beams for Explosive Nucleosynthesis Studies), consisting of 20 members at 12 institutions, is carrying out these experiments.

Our measurement of a thin-target $^{17}$F(p,p)$^{17}$F excitation function to better determine the $^{17}$F(p,$\gamma$)$^{18}$Ne reaction rate exemplifies our indirect studies. With a low-energy, high-quality $^{17}$F beam we found the crucial s-wave resonance in the $^{17}$F + p system which had not been found in 30 years of studies with stable beams. Our precision measurement of the excitation energy and total width of this level resolved an orders-of-magnitude uncertainty in the $^{17}$F(p,$\gamma$)$^{18}$Ne rate at high temperatures.\(^8\)

While most astrophysical reactions occur at center of mass energies less than 2 MeV/u, higher energy RIBs allow us to employ indirect techniques. For example, we measured a proton transfer reaction, $^{14}$N($^{17}$F, $^{19}$Ne)$^{13}$C, with a higher-energy $^{17}$F beam to help determine the direct capture rate for the $^{17}$F(p,$\gamma$)$^{18}$Ne reaction. Other indirect measurements requiring higher energy beams include the inverse of the reaction occurring in an astrophysical environment. For example, we made a complete measurement of the excitation function of the $^{17}$F(p,$\alpha$)$^{14}$O reaction, spanning the energy range needed for X-ray bursts. This allows a better calculation of the $^{16}$O($\alpha$,p)$^{17}$F reaction rate. Measurements of elastic and inelastic scattering of $^{17}$F and hydrogen were also needed to constrain the $^{14}$O($\alpha$,p)$^{17}$F reaction proceeding to both the ground and excited states of $^{17}$F.

We also put considerable effort into improving the rates of the $^{18}$F(p,$\alpha$)$^{15}$O and $^{18}$F(p,$\gamma$)$^{18}$Ne reactions\(^9\) that determine the production of the long-lived radioactive isotope $^{18}$F in novae and may serve to constrain nova models via observations of the decay 511-keV gamma rays. We measured $^{18}$F(p,p)$^{18}$F and $^{18}$F(p,$\alpha$)$^{15}$O, at energies corresponding to two important $^{19}$Ne resonances. We resolved a serious discrepancy in the literature concerning one level (Figure 5), and made the first statistically significant measurement of the strength of another. Further investigations to search for missing $^{19}$Ne resonances are planned.

Future experimental work will involve direct measurements of capture reactions with the DRS, a mass spectrometer optimized for astrophysics. For example, we will measure the $^7$Be(p,$\gamma$)$^{18}$B reaction to help understand measurements of the solar neutrino flux. We also plan to directly measure $^{17}$F(p,$\gamma$)$^{18}$Ne to determine the gamma partial width of the dominant s-wave resonance.

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Figure 5. Excitation functions of the $^{18}$F(p,p)$^{18}$F (top) and $^{18}$F(p,$\alpha$)$^{15}$O (bottom) for the 665-keV $^{19}$Ne resonance.
The experimental nuclear astrophysics effort at HRIBF is closely coupled with nuclear data evaluations which determine the best rates of reactions based on all available information. The new rates are available, and new visualization tools are being developed to access reaction rate information. These rates are then incorporated into ORNL astrophysical simulations to determine the impact of our measurements and to guide future experiments. For example, our new $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$ rate changed the predicted amount of $^{17}\text{O}$ synthesized by up to a factor of 3 when averaged over the entire exploding star in comparisons to some previous predictions, and by up to a factor of 15,000 in the hottest portions of the explosion. Our new $^{19}\text{F} + p$ rates were also found to change the amount of $^{19}\text{F}$ produced in the hot zones of novae by a factor of 3 compared to other estimates; this has an impact on future observational constraints on nova models.

The Theory Program

The theory program covers a broad range of science including studies of the quantum many-body problem, astrophysics, and nuclear phenomenology related to RHIC and hadronic physics. We are also very fortunate to enjoy significant support from the Joint Institute for Heavy Ion Research which funds a significant theory visitors program.

Understanding nuclei requires one to solve the Schrödinger equation for many interacting particles. While this statement is obvious, its implementation has been quite difficult due to the computational difficulties involved in the solution of the problem.

The quantum many-body problem may be solved in several ways and with various levels of approximation. One successful approach has been to use quasiparticle mean-field theory that includes Skyrme interactions and a self-consistent pairing field. Our group has recently implemented deformed Hartree-Fock-Bogoliubov calculations using the parallel computational facilities at ORNL. These facilities allow us to calculate in one day a mass and deformation table for 3,000 nuclei, as shown in Figure 6.

We also investigate methods to solve the quantum many-body problem using quantum Monte Carlo algorithms (such as Auxiliary Field Monte Carlo), parallel shell model diagonalization, and Coupled Cluster theory. Recently we began investigations of the continuum shell-model using the Berggren complex-energy basis and Density Functional Renormalization Group methods. All of these efforts require significant computational resources.

Our astrophysics effort primarily focuses on the evolution of core collapse supernovae. The search for the explosion mechanism of core collapse supernovae is one of the important and challenging problems in computational astrophysics. Core collapse supernovae are among the most energetic explosions in the Cosmos, releasing tremendous amounts of energy in the form of neutrinos of all flavors, disrupting stars more massive than ten suns and disseminating and producing many of the elements in the periodic table, without which life as we know it would not exist. Understanding these events requires input from numerous areas of science including nuclear and particle physics, general relativity, radiation transport, and fluid dynamics. Our major contribution here has been to fully incorporate Boltzmann neutrino transport and general relativity into the simulations of the core collapse. We also incorporate nuclear structure information on weak processes in nuclei into our core collapse simulations.

Our theory effort also focuses on the phenomenology of RHIC collisions, and in particular on open-charm production and $J/\Psi$ suppression.
sion that are used as probes of these collisions. Calculations of in-medium hadronic cross sections that will be important to disentangle the signals obtained from the experimental program constitute a major portion of our RHIC theory effort.

**ORNL at PHENIX**

The Physics Division has participated since the beginning in the PHENIX Experiment at the Brookhaven Relativistic Heavy-Ion Collider (RHIC). Major goals of RHIC are to produce collisions in which the entrance-channel nucleons undergo a phase transition to a deconfined state of quarks and gluons, the so-called quark-gluon plasma, to study this novel state of matter, to learn about the detailed phase diagram of QCD, and to determine if more than one “partonic” phase exists. PHENIX is one of the two large experiments located at RHIC and is designed particularly to detect penetrating probes of the system produced. Such penetrating probes, including direct photons and lepton pairs, are not perturbed by the final-state hadronic evolution of the created system and thus carry out information from the early time of the collision. The collision energies at RHIC are high enough that initial-state scattering of the entrance-channel partons can be detected by looking for the resulting partons to manifest themselves as jets having high-pT particles. The energetic scattered partons are most likely to be created at the start of a collision and would find themselves propagating through deconfined matter prior to hadronization.

PHENIX was conceived as a pair of central-rapidity spectrometers that could observe photons, electrons, and identified hadrons in the central unit of rapidity, coupled with two endcap spectrometers that could identify muons; a photograph of the central magnet and one central spectrometer arm is shown on the cover illustration of this issue.

The final spectrometer arm will be completed in the summer of 2002. Physics also designed the muon identifier section of the PHENIX muon arms and has collaborated on its construction, installation, and operation. The Physics and Instrumentation & Controls Divisions at ORNL have collaborated throughout PHENIX in designing and building electronics for six of the PHENIX subsystems; this included manufacture of some 60,000 custom analog integrated circuits of 6 different types and design and construction and installation of over 2,200 circuit boards for front-end electronics.

During 2001 PHENIX measured Au-Au collisions at 200 GeV/nucleon pair as well as polarized proton collisions at 200 GeV. Some dozen papers have been submitted from this first run period. One interesting result, new to RHIC, is presented in Figure 7. One examines the rate of high-pT particle production and compares it to the expected rate determined either by scaling up p-p collisions at the same center-of-mass energy by the number of binary nucleon-nucleon collisions, or by scaling from the rates seen in peripheral Au-Au collisions. Surprisingly, the production rate of such high-pT events in central Au-Au collisions is less than expected from scaling the simpler colliding systems. This is not seen in Pb-Pb collisions at 6.5 times lower bombarding energy at the CERN SPS, which is shown in the upper curves in Figure 7. Instead, in that case one sees a moderate increase in production with ever larger pT, the so-called “Cronin effect” noted in p-A collisions, which seems to herald only multiple-scattering of the partons. Instead, at RHIC, a depletion in rate is observed. This has led to the speculation that one is observing a consequence of increased energy loss of fast partons in a colored medium, perhaps the so-called “jet-quenching” which is predicted for partons propagating in a QGP.

![Figure 7. High pT events at RHIC.](image-url)

Significant further work studying this effect, especially via jet-jet or photon-jet correlations, is needed to establish any proposed interpretation.

Neutron Science

Oak Ridge is poised to become a world-class center for neutron research with the addition of a cold source to the High Flux Isotope Reactor (HFIR) and with the construction of the Spallation Neutron Source (SNS). When completed next year the new HFIR (85 MW) cold source will have a brightness (~10^{16} n/s/cm^2/sr/eV) comparable to that at the ILL—the brightest in the world. When the SNS (target power 1.4 MW) comes on line in 2005/2006 it will provide pulsed neutron beams over an order of magnitude more intense than available at the best existing spallation sources (LANSCE and ISIS). Although the focus of both projects is on traditional neutron scattering experiments, they present significant opportunities to make major improvements to the measurement of fundamental properties of the neutrons themselves. The Physics Division is in the process of securing funding to establish dedicated fundamental neutron measurement facilities at both HFIR and at the SNS. These facilities will enable a rich variety of experiments, a significant part of the emerging national program in fundamental neutron physics.

As the simplest of all radioactive decays the beta-decay of the free neutron provides an excellent laboratory for the study of the weak nuclear interaction. Precision measurements of neutron decay parameters can be directly related to the fundamental parameters of the underlying quark-lepton weak interaction and can be used to provide powerful tests of the Standard Model (SM). A significantly improved measurement of the neutron electric dipole moment could perhaps find a clear sign of time-reversal invariance violation at a level significantly greater than SM predictions. Measurements of parity violating quantities such as the asymmetry in the process n + p → d + γ and neutron spin rotation in light nuclear targets would provide values for hadronic weak coupling constants and would shed light on current inconsistencies.

Experiments to measure some of these quantities are best sited at a reactor. Others are best sited at a spallation source. Both benefits are ultimately due to the a priori knowledge of the neutron energy at a spallation source (through time-of-flight information). Backgrounds are also typically lower at a spallation source. In addition, some are best performed with Ultra-Cold neutrons (defined as having low enough energy that they are totally externally reflected, ~100 neV). Such neutrons can be produced by illuminating superfluid 4He, which serves both as superthermal source and as detector, with 8.9 A neutrons.

Summary

During the last 10 years the Physics Division at ORNL has strengthened its position as a world leader in nuclear physics: the HRIBF facility came on line and now produces excellent, high-quality radioactive beams for both nuclear structure and astrophysics research. Research activities at HRIBF are enhanced by a strong external-users community and our unique asset, the Joint Institute for Heavy-Ion Research.\textsuperscript{11} We have established a strong effort in theoretical research in both nuclear structure and astrophysics phenomena. The Phenix collaboration began last year to produce exciting data that will shed light on the formation and properties of the quark-gluon plasma.

We also look forward to a bright future. We anticipate significant science coming from HRIBF during the next ten years, and new scientific discoveries emanating from our fledgling program in neutron science to our theoretical programs in nuclear science and astrophysics.

Acknowledgment

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Critical Point Symmetries in Nuclei

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Introduction

Recently, a new concept, called “critical point symmetry,” has been introduced to elucidate the nature of quantum phase transitions in many-body systems [1], [2]. In a series of experiments at several Laboratories both in the United States and in Europe (the A. W. Wright Nuclear Structure Laboratory of Yale University, the University of Köln in Germany, the Laboratori Nazionali di Legnaro in Italy, the Institut Laue-Langevin in Grenoble, France), strong evidence for the occurrence of these symmetries in nuclei has been found [3], [4].

Shape Phase Transitions

Several many-body systems (nuclei, molecules, atomic clusters, macromolecules, polymers, etc.) display phase transitions whenever the geometric configuration of the system changes. For example, in molecules, phase transitions occur whenever the structure changes from linear to non-linear or from planar to a-planar or from a geometry with point group \( C_{1} \) to one with point group \( C_{2h} \). These phase transitions are called “shape” phase transitions. One of the best studied cases of shape phase transitions is that occurring in nuclei, where the geometric configuration changes from spherical to quadrupole deformed either with or without axial symmetry. Phase transitions are described in terms of sharp changes in some quantity, called the order parameter, describing the structure of the system, as a function of another quantity, called the control parameter. The order parameter for shape phase transitions in nuclei is the quadrupole deformation \( \beta \). (There is another order parameter associated with distortions from axial symmetry, \( \sin \gamma \), but this will not be discussed here.) For quantum phase transitions the control parameter is the value of the dimensionless coupling constant that appears in front of the interaction driving the transitions (in nuclei the quadrupole-quadrupole interaction). Figure 1 shows the experimental values of \( B\left(E2; 2^+ \rightarrow 0^+\right) \sim \beta^2 \) as a function of the valence neutron number for some rare-earth nuclei. The sudden jump at valence neutron number \( \sim 6 \) is indicative of a phase transition. (The control parameter is related to the number of valence particles.)

Although nuclei are finite systems and thus cannot exhibit phase transitions in the true sense of the word, nonetheless phase transitions can be defined in the classical limit in which the number of particles, \( N \), goes to infinity. Numerical simulations of quantum phase transitions within the framework of algebraic models (the Interacting Boson Model in Nuclear Physics [5], [6] and the Vibron Model in Molecular Physics [7], [8]) show that, even for small systems, the order parameter increases sufficiently fast as a function of the control parameter to be able to detect experimentally “shape” phase transitions (Figure 2). The only difference between finite and infinite systems is that in infinite systems there is a discontinuity in some quantity while in finite systems the discontinuity is smoothed out. (This statement applies also to other phase transitions in nuclei, such as the liquid-gas transition, and to other finite quantum systems. It has been verified experimentally in molecules by measuring the specific heat of small water droplets with \( N \sim 10 \).)

Quantum phase transitions are best studied by means of algebraic models. In condensed matter physics, the Ising model, for example, has provided a deep understanding of phase transitions in spin systems. The

Figure 1. Experimental \( B\left(E2; 2^+ \rightarrow 0^+\right) \) values as a function of neutron number for some rare-earth nuclei, showing a sudden jump at neutron number 90, indicative of a shape phase transition.
shape phase structure of nuclei was indeed studied in the early 80’s within the framework of the classical limit [9], [10], [11] of the Interacting Boson Model [5], [6]. (The phase structure of nuclei when the proton-neutron degree of freedom is included was also studied, but will not be presented here.)

The situation is best discussed in terms of a phase diagram [12], as shown on the left in Figure 3. Here the three dynamic symmetries of the Interacting Boson Model, \( U(5) \), \( SU(3) \), and \( O(6) \), are schematically shown at the vertices of a triangle, called Casten’s triangle. The classical limit of these symmetries shows that they correspond to spherical shape, \( U(5) \), deformed shape with axial symmetry, \( SU(3) \), and deformed shape without axial symmetry (the so-called \( \gamma \)-unstable shape), \( O(6) \).

The studies performed in the 80’s demonstrated that there is a line of first-order transitions ending in a point of second-order spherical to \( \gamma \)-unstable transition \( (U(5) \rightarrow O(6)) \). From numerical diagonalization of the Interacting Boson Model Hamiltonian. Courtesy of N. V. Zamfir.

Several experimental studies performed in the 80’s showed that indeed the situation described by Figure 3 is what actually happens in nuclei [6]. For example, the occurrence of a first-order shape transition in nuclei can be detected by plotting the derivative of the ground state energy, i.e., the separation energy, here the two-neutron separation energy, \( S_{2\pi} \), as a function of the control parameter (or a function of it, here the valence neutron number). This quantity is discontinuous in a first-order transition. Figure 4 shows the experimental values for the Sm isotopes. The occurrence of a first-order transition is clearly visible.

**Critical Point Symmetries**

In understanding the nature of phase transitions an important question is what is the structure of the spectrum of a system at the critical point of a second-order phase transition or in the coexistence region of a first-order transition. This question has been extensively investigated within the framework of algebraic models. As already shown in 1978 [13], the Interacting Boson Model provides an accurate description of shape phase transitions in nuclei. Recent calculations [14], [15] have confirmed that the entire transition region can be well described by simple algebraic Hamiltonians. However, the description of the critical region is obtained by numerical diagonalization of the Hamiltonian. One may wonder whether the nature of the spectrum at the critical point can be understood from general arguments based on some “symmetry” of the problem. This question has not been investigated, except from some general statements within the framework of quantum field theories, where the structure at the critical point is associated with conformal invariance. Without going into details of what conformal invariance in quantum field theory is, the net results of these arguments is that the “symmetry” of the problem reduces the number of parameters by one and the properties of the system at the critical point are given only in terms of a scale.

Recently, I have suggested that, within the framework of quantum mechanics (i.e., a Schrödinger-like equation), the structure of the spectrum at the critical point can be associated with Euclidean invariance within a certain domain [1]. The physical argument for this suggestion is that at the critical point of a second-order transition the potential as a function of some coordinate...
(here $\beta$) is flat and it can be approximated by a constant (in one dimension a square-well potential). The Hamiltonian for a flat potential is just the kinetic energy, which is invariant under Euclidean transformations. Two major consequences of this suggestion (referred hereafter as “critical point symmetry”) are that the spectrum of the system at the critical point of a second-order transition is given in terms only of a scale parameter, and, most importantly, the energy eigenvalues and other observables both for first- and second-order transitions can be given in explicit analytic form.

The suggestion of a possible occurrence of critical point symmetries in nuclei has stimulated considerable work both theoretical and experimental. On the theoretical side, a detailed investigation of the structure of nuclei in the critical region of second- and first-order shape transitions has been initiated. As mentioned above, critical point symmetries are analyzed best within the framework of a differential (Schrödinger-like) equation. In the case of collective quadrupole shapes in nuclei, a convenient differential equation is the Bohr equation \[16\]. Two situations have been so far investigated:

(i) The structure of the spectrum at the critical point of the second-order transition between $U(5)$ and $O(6)$ (spherical to $\gamma$-unstable transition), called $E(5)$ \[1\]. It has been found that the spectrum is given by the simple formula

\[ E(s, \tau) = A_1(x_{s\tau})^2, \]

where $x_{s\tau}$ is the $s$th zero ($s = 1, 2, 3, \ldots$) of the Bessel function $J_{\tau+3/2}(z)$ of half-integer order $\tau + 3/2$. The quantum number $\tau (\tau = 0, 1, 2, \ldots)$ labels the irreducible representations of $O(5)$, which is an exact symmetry for spherical and $\gamma$-unstable nuclei. This formula explicitly

Figure 3. *Left-hand side: Schematic representation of the phase structure of the Interacting Boson Model-1. The three dynamic symmetries of this model are placed at the vertices of the triangle. Adapted from Feng, Gilmore and Deans \[12\]. Right-hand side: Schematic representation of the results obtained recently \[1\], \[2\]. The two new “symmetries” are placed on the side of the triangle and in the coexistence region. The dynamic symmetry $U(5)$ that can be also obtained as a solution of the Bohr Hamiltonian is placed at one of the vertices of the triangle.*

Figure 4. *Experimental values of the two-neutron separation energies, $S_{2n}$, as a function of neutron number, indicative of a first-order shape phase transition.*
shows that the spectrum is given in terms only of a scale parameter, $A_1$.

(ii) The structure of a portion of the spectrum in the coexistence region of the first-order phase transition between $U(5)$ and $SU(3)$ (spherical to deformed with axial symmetry), called $X(5)$ [2]. This phase transition is much more complex than the transition from spherical to $\gamma$-unstable shape for two reasons: (a) the transition is first order; (b) the transition involves simultaneously two variables, $\gamma$ and $\beta$. In nuclei, however, the potential hump separating the two coexisting minima is very small (see, for example, Figure 4 of [17]) and the transition can be treated effectively as a second order. Also, the two variables can be (approximately) decoupled. The portion of the spectrum involving the variable $\beta$ is given by the formula

$$E(s,L) = A_2(x_{sL})^2$$

where $x_{sL}$ is the $s$th zero ($s = 1, 2, 3, \ldots$) of the Bessel function $J_s(z)$ with

$$v = \left( \frac{L(L + 1)}{3} + \frac{9}{4} \right)^{1/2}.$$

Note that the order here is an irrational number. $L$ is the angular momentum quantum number ($L = 0, 2, 4, \ldots$) of each state and again energy levels are given in terms of a single scale, $A_2$.

Both predictions have recently been tested by a series of experiments performed at various laboratories.

(i) Casten and Zamfir [3] have shown that the spectrum of $^{138}$Ba (as well as its $E2$ transition rates) can well be described by the $E(5)$ formula. A search for other nuclei lying at the critical point of the second-order spherical to $\gamma$-unstable transition is currently under way. Candidates are some isotopes of Xe, Pd [18], and Ru [19].

(ii) The region of coexistence of the first-order spherical to axially deformed transition has received most of the attention, in view of its intricate nature and the fact that it is easily accessible in rare-earth nuclei, Nd-Sm-Gd-Dy. Casten and Zamfir [4] have shown that the $\beta$ part of the spectrum in $^{152}$Sm (as well as its $E2$ transition rates) can be described very well by the $X(5)$ formula. The agreement between the formula and data is not limited to the behavior of the energies of the ground state band ($s = 1$) with $L$, shown in Figure 5, but it extends also to the location of the $\beta$-vibrational excitation. In this case, the $X(5)$ spectrum contains a parameter-independent prediction that has been verified experimentally: the energy of the first excited $0^+$ level is predicted to be at 5.67 times the energy of the first $2^+$ state. Experimentally in $^{152}$Sm it lies at 5.62 times; see Figure 6. The verification of parameter-independent (universal) properties is evidence for the occurrence of “critical point symmetries” in nuclei. There is no a priori reason (in both microscopic and macroscopic models) why the ratio of vibrational to rotational excitation energies should be 5.67. It is a consequence of a “critical point symmetry,” wherein the energies of states are given by zeros of Bessel functions of a particular order. The evidence presented in [4] has been reinforced by an even more recent experiment in $^{150}$Nd by Krücken et al [20] and it appears to extend to the set of nuclei $^{150}$Nd-$^{152}$Sm-$^{154}$Gd-$^{156}$Dy, lying on the line of first-order transitions in the phase diagram of Figure 3. Experiments are being planned to elucidate the nature of this phase transition even further, both in the rare-earth region and in other regions of the periodic table.

**Implications for Other Fields**

The concept of “critical point symmetry” is being applied to other fields, most notably molecular physics. Here the transition from linear to non-linear shapes has been studied and the corresponding formulas applied to the analysis of spectra of several molecules. It has been found [21] that fulminic acid, HCNO, lies very close to the critical point of a second-order shape phase transi-
tion between linear and non-linear (bent) configurations. This molecule thus plays the role in molecular physics that 134Ba plays in nuclear physics. The same concept can, in principle, be used for a variety of systems including atomic clusters, macromolecules, and polymers. For second-order transitions, in \( n \geq 2 \) dimensions, spectra are given by the universal formula \[ E(s, \tau) = A(x_s, \tau)^2, \]
where \( x_s, \tau \) is the \( s \)th zero of \( J_v(\nu) \) with \( \nu = \tau + (n - 2)/2 \) (integer or half-integer). From this point of view, symmetries at the critical point are another example of symmetries theoretically introduced and experimentally found in nuclear physics and later used in other fields.

Open Problems

The introduction of the new concept of “critical point symmetries” opens up a wealth of problems. (i) The derivation of the equations given above has been done in the limit \( N \to \infty \). In nuclei, the number of particles is finite. This problem has been investigated by Caprio, who has found that finite \( N \) effects are not important for the low-lying states [23] for the case of \( E(5) \). (ii) Also, in nuclei, the transition operator cannot be simply taken as linear in the variable \( \beta \), but \( \beta^2 \) terms are important. This problem has been solved by Arias [24], who has calculated the \( \beta^2 \) contribution to \( E2 \) transition rates and found in 134Ba better agreement with experiment. (iii) The description given above for the \( U(5) - SU(3) \) transition is only in terms of one variable \( \beta \). The inclusion of the \( \gamma \) degree of freedom in a consistent fashion has been investigated and the corresponding formulas will be published soon [25]. (iv) The coupling between \( \beta \) and \( \gamma \) degrees of freedom needs to be studied and introduced in this context (it was studied years ago within the context of the Interacting Boson Model). (v) The effect on the spectra of the small hump in the potential description of the first-order, \( U(5) - SU(3) \) transition needs to be investigated (again, this effect has been studied within the context of IBM [17]). (vi) Finally, the connection between the differential realization of critical point symmetries and their algebraic counterparts needs to be investigated. This connection will allow one to describe both types of symmetries, the usual dynamical symmetries, \( U(5), SU(3), SO(6) \), and

Figure 6. Comparison between the energy and transition rates of the \( \beta \) part of the spectrum of \( ^{152}\text{Sm} \) and \( X(5) \). From Casten and Zamfir [4]. The two experimental ratios \( E(0^+)/E(2^+) = 5.62 \) and \( E(4^+)/E(2^+) = 3.01 \) should be compared with the parameter free predictions of \( X(5) \), 5.67 and 2.91, respectively, and are a measure of how well the “critical symmetry” is realized in these nuclei.
the “critical point symmetries,” $E(5)$ and $X(5)$, within the same framework. At the moment, they lie on different parameter spaces, as shown schematically on the right-hand side of Figure 3.

Conclusions

In conclusion, a new concept, “critical point symmetries,” has been introduced. This concept produces new benchmarks (explicit solutions in terms of quantum numbers) for studies of nuclear spectra, in which the solutions for energy levels and transition rates are parameter free, except for an overall scale. The occurrence of critical point symmetries has been experimentally established in nuclei. This finding has been made possible by the development of very sensitive $\gamma$-ray detector systems, such as the YRAST-Ball at Yale, and of techniques for measuring nuclear level lifetimes with Döppler-based methods. These have allowed a much more accurate analysis of the spectra of nuclei. It is yet another example of how the improvement of experimental techniques that has been occurring in nuclear physics is providing a deeper understanding of physics and of how theoretical ideas developed in nuclear physics have a wide range of application to other quantum systems.

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References


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Density Functional Theory

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Introduction

Density functional theory (DFT) in quantum chemistry is a method for calculating ground state properties of atoms and molecules from first principles. It was invented by Walter Kohn and his collaborators Pierre Hohenberg and Lu Sham in 1964 and 1965 and has been developed to the level where it is accurate enough to play an important role in atomic physics, in chemistry, and even in biochemistry. Kohn shared the Nobel Prize in Chemistry in 1998 in recognition for this important contribution. One of the aims of this article is to explain the basic ideas behind the Kohn-Sham density functional method. Another is to compare it with Skyrme Hartree-Fock theory in nuclear physics, which dates back to papers published by Tony Skyrme in 1957. A third is to review some recent developments.

An atom or a molecule consists of electrons and a nucleus or nuclei interacting by Coulomb forces and a wave function which satisfies the Schrödinger equation. In principle it should be possible to solve this equation and to calculate properties of the atom or molecule from first principles. As pointed out by Dirac in 1929 the difficulty lies in the fact that, except for the simplest systems, the Schrödinger equation is too complex to be solved. This is because the wave function is a multi-dimensional function depending on the positions and spins of all the electrons and nuclei.

The Born-Oppenheimer approximation gives a big simplification to the theory of molecular structure. The nuclei in a molecule move slowly compared with the electrons, and the Born-Oppenheimer approximation assumes that the electron wave functions can be calculated for fixed positions of the nuclei. The equilibrium shape of the ground state of the molecule is obtained by minimizing the energy with respect to the positions of the nuclei. The Hartree-Fock approximation is another simplification. The wave function of an atom or molecule with \( n \) electrons is approximated by an antisymmetrized product of single electron wave functions. The antisymmetrization ensures that the restrictions imposed by the Pauli principle are satisfied. It depends only on \( n \) single particle wave functions, one for each electron. The Hartree-Fock approximation includes the effects of Pauli correlations, but not other many-body correlations.

Density functional theory takes a different tack. It focuses on the electron density \( \rho(r) \), which is a function of one position variable \( r \) rather than the electron wave function \( \Psi(r_1\sigma_1, r_2\sigma_2, \ldots, r_n\sigma_n) \) which is a function of the positions and spins of each of the \( n \) electrons and argues that the ground state energy of the molecule is determined by \( \rho(r) \).

An approximation to the quantum mechanics of electrons in an atom was suggested in 1927 by Thomas and Fermi. They argued that the ground state energy of the electrons in an atom could be approximated by a function of the electron density

\[
E[\rho(r)] = E_{TF}^{TF}[\rho(r)] + E_C[\rho(r)].
\]  

The first term in (1) is the Thomas-Fermi approximation to the kinetic energy of the electrons; the second term is the electron-electron Coulomb interaction and the second represents the Coulomb interaction of the electrons with the nucleus of the atom. The equilibrium ground state energy and density are obtained by minimizing \( E[\rho] \) in (1) with respect to \( \rho(r) \). Thomas-Fermi theory

\[
E_{TF}[\rho(r)] = \frac{3}{5}(3\pi^2)^{2/3} \int d^3r \rho(r) \frac{\rho(r)}{r}
\]

with the constraint that the atom contains \( n \) electrons

\[
\int d^3r \rho(r) = n.
\]  

The Thomas-Fermi approximation for the Coulomb energy is

\[
E_C[\rho(r)] = \int d^3r \int d^3r' \frac{e^2\rho(r)\rho(r')}{|r-r'|}
\]

\[
+ \int d^3r \frac{Ze^2\rho(r)}{r}.
\]

The first term is the electron-electron Coulomb interaction and the second represents the Coulomb interaction of the electrons with the nucleus of the atom. The equilibrium ground state energy and density are obtained by minimizing \( E[\rho] \) in (1) with respect to \( \rho(r) \) subject to the constraint in (2). Thomas-Fermi theory
predicts a scaling behaviour for bulk properties of atoms. For example, the radius of an atom is proportional to $Z^{1/3}$. Heavy atoms are smaller than light ones.

The Kohn-Sham density functional theory for an atom can be thought of as an extension of the Thomas-Fermi model. In practical terms the energy functional in Kohn-Sham theory is similar to (1) but makes a better approximation to the kinetic energy and includes an exchange-correlation energy.

Kohn-Sham Density Functional Theory

The starting point of the Kohn-Sham density functional method is the theorem of Hohenberg and Kohn [1] published in 1964, which gave the theoretical foundation of their approach. The Hamiltonian for an atom or molecule contains the kinetic energy of the electrons, the Coulomb interaction between the electrons and a one-body potential $v(r)$ which includes the Coulomb interaction energy of the electrons with the nuclei, and possibly an external field. Hohenberg and Kohn proved that the exact ground state electron density uniquely specifies the Hamiltonian and therefore all the properties of the ground state. Stated another way, they proved the existence of a functional $E[\rho]$, which gives the exact ground state energy for a given ground state density. The minimizing $E[\rho]$ is a variational principle which gives the exact ground state energy and density and, indirectly, the many electron ground state wave function.

Of course, all this is too good to be true. The difficulty is that specifying the functional $E[\rho]$ would require a complete solution of the quantum mechanical many-body problem for the atom or molecule. Kohn and Sham [2] bypassed this problem by using physical arguments to fix an approximate energy functional which is remarkably good. Their energy functional consists of three parts:

$$E[\rho] = E_K[\rho] + E_C[\rho] + E_{XC}[\rho]. \quad (5)$$

The single particle density matrix is written in diagonal form

$$\rho(r, r') = \sum_i n_i \phi_i(r)\phi_i^*(r'). \quad (6)$$

The eigenstates $\phi_i(r)$ of the single particle density matrix form an orthonormal set of single particle states and the Pauli principle requires that the occupation numbers $n_i \leq 2$. The total number of electrons is $\sum n_i = Z$. The kinetic energy of the electrons is

$$E_K[\rho] = \frac{\hbar^2}{2m} \sum_i \int d^3r |\nabla \phi_i(r)|^2. \quad (7)$$

This expression for the kinetic energy is exact but the occupation numbers are unknown. In their 1965 paper Kohn and Sham [2] assumed that the eigenstates are either fully occupied ($n_i = 2$) or unoccupied ($n_i = 0$). Other choices are possible. The remaining term in (5) is the exchange-correlation energy. It can be calculated exactly for a uniform electron gas for any density $\rho$. Kohn and Sham made the local density approximation and wrote

$$E_{XC}[\rho] = \int d^3r \rho(r) e_{XC}(\rho(r)), \quad (8)$$

where $e_{XC}(\rho(r))$ is the exchange correlation energy density for an electron density $\rho(r)$. Now that the energy functional is specified, the ground state energy and electron density can be computed by minimizing the energy functional with respect to the eigenstates $\phi_i$ of the single particle density matrix with the constraint (3) on the total number of electrons. This yields a set of equations for the single particle wave functions which are similar to Hartree-Fock equations.

The Kohn-Sham density functional theory resembles Hartree-Fock theory but there are important differences. Hartree-Fock theory is based on a Slater determinant wave function which is an approximation to the many-electron wave function. There is no Slater determinant wave function in Kohn-Sham theory. With Hartree-Fock theory one imagines that there should be corrections due to zero point fluctuations. In Kohn-Sham DFT these are already included. Hartree-Fock theory uses a non-local expression for the exchange energy calculated with the Slater determinant wave function and there is nothing to include the effects of many-electron correlations. Kohn-Sham density functional theory includes the correlation energy and the exchange energy in a local density approximation.

Big advances in density functional methods have been made during the past 15–20 years. In a recent review on the application of DFT to transition metal problems Koch and Hertwig [3] wrote:

It is beyond doubt that approximate DFT has advanced in only a few years from an exotic method hardly known to the average quantum chemist to one of the most attractive tools in computational quantum
chemistry and, in particular, to transition metal chemistry. The reason for this is that DFT methods are not only highly efficient, they are capable of giving results which are in most cases superior to those obtained with much more demanding conventional \textit{ab initio} methods.

In their article they discuss the exotic molecules Cr(CO)$_6$, Mo(CO)$_6$, W(CO)$_6$, and give results for bond lengths, bond dissociation energies, and molecular vibrational frequencies. The theoretical results agree with experiment to within a few percentage points. There are two main reasons for recent advances. One is the development of powerful numerical methods for representing the wave functions and solving the Kohn-Sham equations so that quite large molecules can be studied. Another is the development of accurate semi-empirical expressions for the exchange-correlation energy.

There is a multitude of applications in physics and chemistry. Some chemical applications have been reviewed by Ching-Han Hu and D. P. Chong [4]. On the more physical side Yabana and Bertsch [5] have applied the time-dependent local-density approximation (TDLDA), a time-dependent version of density functional theory, to calculate the optical response for molecules like carbon chains, polyenes, benzene, and C$_{60}$. Natatsukasa, Yabana, and Bertsch have used TDLDA to calculate the shift and broadening of absorption lines of Cs atoms embedded in superfluid helium.

**Skyrme’s Energy Functional for Nuclear Structure**

The interaction between nucleons has been studied intensively and is now quite well known. Potentials which have been fitted to nucleon-nucleon scattering data, and when supplemented by appropriate three-body forces, can describe the properties of nuclear matter and light nuclei. For example, Pieper et al. [6] have added a pion exchange three-nucleon interaction to the Argonne $v_{18}$ realistic two-nucleon interaction and have calculated the energies of 17 bound or narrow resonance states of nuclei with $3 \leq A \leq 8$. The calculations use the Green’s function Monte Carlo method which gives an almost exact solution of the A-nucleon problem. The calculations reproduce the observed energies with an rms error $<1\%$. It is also possible with realistic forces to calculate properties of heavier nuclei. Even though realistic nuclear forces are very complicated, effective forces have been derived from them which can be used for shell model calculations in certain regions of the periodic table. For example, Elgaroy et al. [7] have calculated the excitation energies of $2^+$ states in even Sn isotopes with $102 \leq A \leq 130$ with a realistic force. Martinez-Pinedo et al. [8] have made full fp-shell model studies of $A = 47$, 48, and 49 nuclei.

In view of the success of density functional theory for atoms and molecules one can ask if an analogous theory exists for nuclei. A derivation of a density functional directly from the realistic nucleon-nucleon force is a project for the future but there is a phenomenological approach, nuclear Hartree-Fock theory with an effective interaction, which resembles Kohn-Sham theory and which has been very successful in calculating properties of nuclear ground states. About 45 years ago Skyrme [9] introduced an effective nucleon-nucleon interaction and was able to calculate some of the properties of nuclear matter and light nuclei in a very simple way. His interaction was written as a potential:

$$V = \sum_{i<j<k} v_{ijk}(3) \quad (9)$$

containing two-body and three-body parts. Skyrme justified his three-body force by the following physical argument: "The potential used in our analysis must contain 3-body, and generally many-body, terms which describe the way in which the interaction between two particles is influenced by the presence of others; the two body terms alone should be related closely to the scattering between free nucleons." In 1970 Vautherin and Brink [10] noticed that Skyrme’s interaction was very convenient for making Hartree-Fock calculations of ground state properties of closed shell nuclei. This Skyrme Hartree-Fock theory leads to a density functional and a set of self-constant equations. They can be solved to give the binding energy of a nucleus, the matter and charge density of the ground state, and various other properties. Skyrme Hartree-Fock theory for nuclei has many similarities with Kohn-Sham DFT for atoms and molecules. The contribution of electron correlations in Kohn-Sham theory is included by a term added to the density functional. The three-body force plays a similar role in Skyrme Hartree-Fock theory.

To simplify calculations Skyrme used a short-range approximation for the two-body interaction

$$v_{ij} = t_0(1 + x_0 P_{ij}) \delta(r_1 - r_2) + \cdots + v_{ij}^{(3)}. \quad (10)$$

The leading term is a $\delta$-function potential with strength $t_0$ and a spin exchange term with strength $x_0$. The dots indicate terms which give the leading finite range corrections with strengths and spin-dependence fixed by pa-
rameters $t_1, t_2, t_3$. There is also a short-range spin-orbit interaction between nucleons $v^{(1)}_{\text{SO}}$ with a strength $W_0$. Skyrme’s three-body force is also a zero range interaction

$$v^{(3)}_{\text{SO}} = t_3 \delta(r_1 - r_2, r_3 - r_1).$$

The energy functional of a nucleus in Skyrme Hartree-Fock theory is the expectation value of the effective interaction with a wave function represented by a single Slater determinant $\Phi$. The explicit form of the energy functional is

$$E[\rho, \tau, f] = \langle \Phi | T + V | \Phi \rangle = -\int H(r) d^3r,$$

where the energy density $H(r)$ is a sum of kinetic and potential energy contributions each depending on densities which are expressed in terms of the single particle states $\phi_i(r)$ defining $\Phi$

$$\rho(r) = \sum |\phi_i(r)|^2, \quad \tau(r) = \sum |\nabla\phi_i(r)|^2,$$

$$f(r) = \frac{1}{r} \sum \phi_i^*(r) \sigma \phi_i(r). \quad (12)$$

Here $\rho(r)$ is the nucleon density and is analogous to the electron density in Kohn-Sham theory. The density $\tau(r)$ determines the contribution of the kinetic energy to the total energy and $f(r)$ is a spin-orbit density associated with the spin-orbit term in Skyrme’s effective interaction.

We write the total energy density $H(r)$ as a sum of three parts: $H^*(r)$ depending on the total nucleon densities, $H^t(r)$ depending on the differences between neutron and proton densities, and $H_{\text{coul}}(r)$ containing the Coulomb repulsion between the protons. The first part is

$$H^*(r) = \frac{\hbar^2}{2m} \tau + a_0 \rho^2 + a_1 (\nabla \rho)^2 + a_2 \rho \tau + a_3 \rho^3 + a_4 \rho \nabla^2 \rho. \quad (13)$$

The term proportional to $\tau$ in $H^*(r)$ represents the kinetic energy of the nucleons. It has the same form in the Kohn-Sham theory. The coefficients $a_i$ can be expressed in terms of the parameters of Skyrme’s effective interaction; $a_0 = 3t_3/8S$, $a_1 = (9t_1 - 5t_2)/64$, $a_2 = (3t_1 + 5t_2)/16$, $a_3 = t_1/16$, $a_4 = 3W_0/4$. The term proportional to $\rho^2$ comes from the zero range part of the two-body potential and the two terms depending on $(\nabla \rho)^2$ and $\rho \tau$ are finite range corrections. The $\rho^2$ term is the contribution of the three-body force. In modern versions of the Skyrme interaction the three-body force is replaced by a density-dependent two-body force and the $\rho^3$ term is replaced by a $\rho^{2+\alpha}$ term where $0 < \alpha \leq 1$. The second part $H^t(r)$ of $H(r)$ depends on differences of the proton and neutron densities are

$$H^t(r) = b_0 (\rho_p - \rho_n)^2 + b_1 (\nabla \rho_p - \nabla \rho_n)^2 + \cdots . \quad (14)$$

There are five terms in $H^t$ analogous to the terms in $H^*$. Only two are written explicitly in (14). The coefficients $b_0, b_1, \ldots$ depend on parameters in Skyrme’s effective interaction.

Combinations of terms in (13) and (14) have a simple physical significance. The strengths of the $\rho^2$, the $\rho \tau$, and the $\rho^3$ terms in (13) fix the binding energy, the density and compressibility of symmetric nuclear matter. The term proportional to $\rho \tau$ fixes the spin-orbit coupling. The $(\nabla \rho)^2$ term is large at the nuclear surface and is important for fixing the surface energy of a nucleus. The $\rho \tau$ term is an exchange term and gives the nucleons an effective mass. The term $b_0 (\rho_p - \rho_n)^2$ in (14) influences the symmetry energy of nuclear matter and $b_1 (\nabla \rho_p - \nabla \rho_n)^2$ contributes to the surface symmetry energy.

Many improvements in the choice of the parameters in the Skyrme interaction have been made since 1970. One was the replacement of the three-body interaction by a density-dependent two-body interaction. Two others relate to the symmetry energy and isospin properties and to the spin-orbit interaction. The first is important for applications to neutron-rich nuclei. In 1981 Friedman and Pandharipande [11] made a variational calculation of the equation of state for neutron matter with the $\times_{\text{iso}}$ interaction and a semi-realistic three-body force. Modern Skyrme parametrizations aim to fit this equation of state as well as properties of stable nuclei with the expectation that these interactions should be good for neutron-rich nuclei. A second improvement concerns the spin-orbit contribution. With the spin-orbit force used by Vautherin and Brink [10] the strengths of the spin-orbit contribution $a_{\text{iso}}$ to the density $H^t$ and $b_{\text{iso}} (J_n - J_p) (\rho_n - \rho_p)$ to $H$ were related and depended only on the parameter $W_{\text{iso}}$. Nuclear radii for sequences of isotopes obtained by measuring by isotope shifts in atoms showed characteristic feature at neutron closed shells $N = 82$ and $N = 126$ which was not reproduced by Skyrme Hartree-Fock calculations with the interactions then in use. Sharma et al. [12], with experience from relativistic mean field theory, pointed out that the situation could be improved by fitting $a_{\text{iso}}$ and $b_{\text{iso}}$ independently.

A Skyrme energy functional SkX developed by Brown [13] depends on just 12 parameters, the $10 a_i$ and $b_i$ in (13), (14), the parameter $\alpha$ giving the exponent of...
the density-dependent term, and a parameter $\chi$, which fixes the strength of an approximation to the exchange part of the Coulomb interaction. It fits the Friedman and Pandharipande [11] equation of state for nuclear matter and the experimental binding energies of 11 double-closed shell nuclei ($^{16}$O, $^{20}$O, $^{34}$Si, $^{40}$Ca, $^{48}$Ca, $^{48}$Ni, $^{68}$Ni, $^{88}$Sr, $^{100}$Sn, $^{132}$Sn, and $^{208}$Pb). This list includes several which are far from the line of $\beta$-stability. Brown's parameter set also gives a good fit to about 40 single particle energy levels in these nuclei, the rms radii of the five closed shell nuclei which have been measured, and the measured charge distributions of $^{40}$Ca, $^{90}$Zr, and $^{208}$Pb. Another interaction with improved isospin properties, intended for applications to nuclei far from $\beta$-stability, was developed recently by Chabanat et al. [14].

Skyrme Hartree-Fock theory has also been used to calculate other nuclear properties. Extensions involving random phase approximation or time-dependent Hartree-Fock have been very successful in describing giant resonances: dipole, monopole, quadrupole, and Gamow-Teller. Well-deformed nuclei can be treated by the deformed Hartree-Fock method. The first paper using the Skyrme interaction for deformed nuclei was published by Vautherin [15] in 1973. A recent reference [16] uses the Chabanat et al. [14] interaction and contains an application to nuclei far from $\beta$-stability, which was developed recently by Chabanat et al. [14].

Summary and Outlook

Hartree-Fock and density functional theory are very similar in their practical applications, but the underlying philosophy is different. The focus in Hartree-Fock is the Slater determinant wave function which is an approximation to the many particle wave function. The anti-symmetry of the wave function ensures that the Pauli exclusion principle is satisfied. According to the Hohenberg-Kohn theorem the fundamental entity in density functional theory is the single particle density. In the Kohn-Sham applications it is rather the single particle density matrix which, in principle, is associated with the exact many particle wave function. The Pauli exclusion principle is imposed by requiring that the eigenvalues of the single particle density matrix (single particle occupation numbers) do not exceed unity. The single particle wave functions in HF theory specify the Slater determinant wave function, while in density functional theory they are the eigenfunctions of the one-particle density matrix. In HF the occupation numbers are either zero or one, while in density functional theory fractional occupation is the norm. In Kohn-Sham theory occupation numbers are chosen to be zero or unity to simplify the calculations.

Skyrme Hartree-Fock theory occupies the middle ground. Sometimes it may be better to stress the Hartree-Fock aspects. Then the Slater determinant wave function is an approximation to a more exact many particle wave function and is open to improvement by calculating higher order effects which are not included in the effective interaction. If, on the other hand, one thinks of it as a density functional theory, then improvements of the theory would result from choosing a better density functional. Vautherin’s application [15] of Skyrme’s interaction to deformed nuclei is an interesting example. He modified Skyrme’s density functional to include pairing in a constant gap BCS approximation. From the Hartree-Fock point of view he should have improved the theory by making a Hartree-Fock-Bogoliubov extension and then do particle number projection, etc. From the density functional point of view he made an improvement to the density functional. A better single particle density matrix comes out of the theory and there is no necessity to project particle number. It gives fractional occupation numbers to single particle states and yields a theory which can be used to describe deformed nuclei.

Looking at Skyrme’s Hartree-Fock theory, or other mean field theories with effective interactions, from a density functional point of view might give a new perspective and could lead to new and interesting ways of thinking about nuclear structure.

References


Free Muons and Muonium: Some Achievements and Possibilities in Low Energy Muon Physics

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Introduction
The Standard Model (SM) is a theory framework, which allows an accurate description of all confirmed measurements in particle physics up to the turn of the century. However, many observations are left without deeper explanations. Among those are the fundamental fermion mass spectrum, the origins of parity and CP violation, the fact of exactly three particle generations, and many more. A variety of speculative models has been invented, in order to suggest physical interpretations of such not yet understood features contained in the SM.

Muons (µ-) and their antiparticles (µ +), the charged leptons in the second generation of fundamental fermions, have no internal structure down to dimensions of 10^{-18} m as shown in high energy lepton scattering experiments. They may therefore be regarded as point-like objects. The behaviour of muons can be described within standard theory with sufficient accuracy for all high precision experiments that have been carried out on them. Muons are therefore important and central tools in a variety of research programs: The dominant µ + decay into a positron (e +), muon anti-neutrino, and electron neutrino (µ + → e + ν + ν − µν e) yields the best value for the weak interaction Fermi coupling constant GF. The insensitivity of muons to strong interactions makes muons important probes of nucleon properties in deep inelastic high-energy scattering. Muonic atom spectroscopy has given very reliable values for nuclear parameters, in particular nuclear charge radii. Searches for as yet unobserved lepton number violating decays have yielded numerous bounds on crucial parameters in speculative models. High precision measurements of the electromagnetic interactions of free muons and such bound in the muonium atom (M = µ +e -)—the hydrogen-like bound state of a positive muon and an electron (e -)—have established stringent tests of standard theory, which includes in particular Quantum Electrodynamics (QED). The excellent agreements between measurements and this underlying theory has contributed significantly to today’s view upon QED as the best available field theory. This solid confidence allows us in return to extract most accurate values of fundamental constants such as the muon mass mµ, muon magnetic moment µµ, and magnetic anomaly aµ, and the electromagnetic fine structure constant α.

In many muon experiments a limitation has been reached by now which is determined by the available particle fluxes at today's sources. For new accelerator facilities, such as the recently approved Japanese Hadron Project (JHP), a next generation of experiments has already been proposed. In addition to the exploitation of higher fluxes with established approaches, novel techniques will be introduced to the field. This promises an expansion into new regions and can be expected to result in significant progress in exploring fundamental interactions and symmetries in physics (Table 1) [1].

In this article we will focus mainly on measurements of electromagnetic properties of the free muon and on spectroscopy of the muonium atom.

Muonium
The close confinement of the bound state in the muonium atom offers excellent opportunities to explore precisely fundamental electron-muon interactions. Since the effect of all known fundamental forces in this system are very well calculable within bound state QED, it renders both the possibility to extract precise constants as well as the possibility to search very sensitively for yet unknown interactions between these leptons. In contrast to natural atoms and ions as well as to artificial atomic systems, which contain hadrons, muonium has the advantage of being free of complications arising from the finite size and the internal structure of any of its constituents. Therefore, the system is particularly suited for searching new and yet unknown forces in nature.

In the muonium atom (Figure 1) the most precise spectroscopy measurements can be performed on the ground state hyperfine structure splitting [2] and the 1s-2s energy interval [3]. Such experiments have been completed very recently after reaching limitations given by the quantities of available muons at the late Los Alamos Meson Physics Facility (LAMPF) in Los Alamos, USA, and at the Rutherford Appleton Laboratory (RAL) in Chilton, United Kingdom. These two transitions are experimentally favoured because they involve the 1s ground state in which the atoms can be produced with feature article
the highest yields. For accurate measurements the atoms need to be at low, ideally thermal velocities in the laboratory. The efficient conversion of an energetic $\mu^+$ beam into $M$ is a key element in all experiments.

### Muonium Production

The best-known mechanism to produce muonium is $e^-$ capture after stopping $\mu^+$ in a suitable noble gas, where yields of 80 (10)% can be achieved for krypton. Muons at accelerator facilities are born in weak pion decays and parity violation in this process causes the muon beams to be polarized. The moderation processes involve dominantly the electric interaction and there is no muon depolarization. In strong axial magnetic fields ($B \gg 0.16 \, T$) $M$ is formed with a well-defined ensemble average of the muon spin direction.

Muonium atoms at thermal velocities in vacuum can be obtained by stopping $\mu^+$ close to the surface of a target consisting of fine $\text{SiO}_2$ powder. The atoms are formed through $e^-$ capture and a fraction of a few percent of them diffuses through the target surface into the surrounding vacuum. Additional cooling with, e.g., laser techniques would not provide any significant advantages. Due to the $\tau_{\mu} = 2.2 \, \mu$s muon lifetime the natural line width of all transitions has a lower limit at $\Delta \nu_{\text{nat}} = (\pi \cdot \tau_{\mu})^{-1} = 145 \, \text{kHz}$ and cooling could not provide a much more advantageous line width. This thermal $M$ production technique has become an essential prerequisite for Doppler-free two-photon laser spectroscopy of the $^{1}\Sigma_{1/2} - ^{2}\Pi_{1/2}$ interval $\Delta \nu_{1s2s}$, at KEK in Tsukuba, Japan, and with significantly higher precision at RAL. It was also the key to a sensitive search for a conversion of $M$ into its anti-atom $\bar{M}$ at the Paul Scherrer Institut (PSI) in Villigen, Switzerland.
Ground State Hyperfine Structure

The most recent experiment at LAMPF had a Kr gas target inside of a microwave cavity at typically atmospheric density and in a homogeneous magnetic field of 1.7 T. Microwave transitions between the two energetically highest, respectively two lowest, Zeeman sublevels of the n = 1 state at the frequencies $\nu_{12}$ and $\nu_{34}$ (Figure 2) involve a muon spin flip. Due to parity violation in the weak interaction muon decay process the $e^+$ from $\mu^+$ decays are preferentially emitted in the $\mu^+$ spin direction. This allows a detection of the spin flips through a change in the spatial distribution of the decay $e^+$. As a consequence of the Breit-Rabi equation, which describes the behaviour of the M ground-state Zeeman levels in a magnetic field B, the sum of $\nu_{12}$ and $\nu_{34}$ equals at any strength of B the zero field splitting $\Delta\nu_{\text{HFS}}$. For sufficiently well known B the difference of these two frequencies yields the magnetic moment $\mu_{\mu}$.

The latest LAMPF experiment [2] has utilized the technique of “Old Muonium,” which allowed us to reduce the line width of the signals below half of the “natural” line width $\Delta\nu_{\text{nat}}$ (Figure 3). For this purpose an essentially continuous muon beam was chopped by an electrostatic kicking device into 4 $\mu$s long pulses with 14 $\mu$s separation. Only decays of atoms which had been interacting coherently with the microwave field for periods longer than several muon lifetimes were detected.

The magnetic moment was measured to be $\mu_{\mu} = 3.183\ 345\ 24(37)$ (120 ppb), which translates into a muon-electron mass ratio $m_{\mu}/m_e = 206.768\ 277(24)$ (120 ppb). The zero-field hyperfine splitting is determined to be $\Delta\nu_{\text{HFS}}(\text{exp}) = 4.463\ 302\ 765(53)$ Hz (12 ppb), which agrees well with the theoretical prediction of $\Delta\nu_{\text{HFS}}(\text{theo}) = 4.463\ 302\ 563(520)(34)(<100)$ Hz (120 ppb). Here, the first quoted uncertainty is due to the accuracy to which $m_{\mu}/m_e$ is known, the second error is from the knowledge of $\alpha$ as extracted from Penning trap measurements of the electron magnetic anomaly, and the third uncertainty corresponds to estimates of uncalculated higher order terms. Among the non QED contributions is the strong interaction through vacuum polarization loops with hadrons, which adds 250 Hz and a parity conserving axial vector–axial vector weak interaction which is $-65$ Hz.

For the muonium hyperfine structure the comparison between theory and experiment is possible with almost two orders of magnitude higher precision than for natural hydrogen because of the not sufficiently known proton charge and magnetism distributions. For hydrogen the achieved some six orders of magnitude higher experimental precision (in hydrogen maser experiments) can therefore unfortunately not be exploited for a better understanding of fundamental interactions.

Among the possible exotic interactions, which could contribute to $\Delta\nu_{\text{HFS}}$, is muonium-antimuonium conversion [4] (see below). Here, an upper limit of 9 Hz could be set from an independent experiment described below.
Recently, generic extensions of the SM, in which both Lorentz invariance and CPT invariance are not assumed, have attracted widespread attention in physics. Diurnal variations of the ratio \( (v_{12} - v_{34})/(v_{12} + v_{34}) \) are predicted. An upper limit could be set from a reanalysis of the LAMPF data at \( 2 \times 10^{-3} \) GeV for the Lorentz and CPT violating parameter. In a specific model by Kostelcky and co-workers a dimensionless figure of merit for CPT tests is sought by normalizing this parameter to the particle mass. In this framework \( \Delta \nu_{\text{HFS}} \) provides a significantly better test of CPT invariance than electron g-2 and the neutral Kaon oscillations [5].

The hyperfine splitting is proportional to \( \alpha^2 \cdot R_\alpha \) with the very precisely known Rydberg constant \( R_\alpha \). Comparing experiment and theory yields \( \alpha^2 = 137.035 \ 996 \ 3(80) \ (58 \text{ppb}) \). If \( R_\alpha \) is decomposed into even more fundamental constants, one finds \( \Delta \nu_{\text{HFS}} \propto \alpha \cdot m_e/h \). With \( h/m_e \) as determined in measurements of the neutron de Broglie wavelength we have \( \alpha^2 = 137.036 \ 004 \ 7(48) \ (35 \text{ ppb}) \). In the near future a small improvement in this figure can be expected from ongoing determinations of \( h/m_e \) in measurements of the photon recoil in Cs. A better determination of the muon mass, e.g., will result in a further improvement and may contribute to resolving the situation of various poorly agreeing determinations of the fine structure constant, which is important in many different fields of physics.

It should be mentioned that the present agreement between \( \alpha \) as determined from M hyperfine structure and from the electron magnetic anomaly is generally considered the best test of internal consistency of QED, as one case involves bound state QED and the other one QED of free particles.

The results from the LAMPF experiment are mainly statistics-limited and improve the knowledge of both \( \Delta \nu_{\text{HFS}} \) and \( \mu_\mu/m_e \) by a factor of three over previous measurements. This gain could be significantly surpassed at a future high flux muon source.

The 1s-2s Interval in Muonium

In muonium the 1s-2s energy difference is essentially given by the relevant quantum numbers, \( R_\alpha \) and a reduced mass correction. Therefore, this transition may be regarded ideal for a determination of the muon-electron mass ratio. QED corrections are well known for the needs of presently possible precision experiments and do not play an important role here.

Doppler-free excitation of the 1s-2s transition has been achieved in pioneering experiments at KEK and at RAL. In all these experiments two counter-propagating pulsed laser beams at 244 nm wavelength were employed to excite the \( n = 2 \) state. The successful transitions were then detected by photo-ionization with a third photon from the same laser field. The released \( \mu^+ \) was then registered on a microchannel plate detector.

The accuracy of the early measurements was limited by the ac-Stark effect and rapid phase fluctuations (frequency chirps), which were inherent properties of the necessary pulsed high power laser systems. The key feature for the latest high accuracy measurement at RAL was a shot by shot measurement of the spatial laser intensity profile as well as the time dependences of the laser light intensity and phase. This together with a newly developed theory of resonant photo-ionization [6] allowed a shot-by-shot prediction of the transition probability as a basis for the theoretical line shape (Figure 4).

The latest RAL experiment [3] yields \( \Delta \nu_{1s2s}(\text{exp}) = 2 \ 455 \ 528 \ 941.0(9.8) \ \text{MHz} \) in good agreement with a theoretical value \( \Delta \nu_{1s2s}(\text{theo}) = 2 \ 455 \ 528 \ 935.4(1.4) \ \text{MHz} \). The muon-electron mass ratio is found to be \( m_\mu/m_e = 206.768 \ 38(17) \). Alternatively, with \( m_\mu/m_e \) as extracted from the M hyperfine structure, a comparison of experimental and theoretical values can be interpreted in terms of a \( \mu^+ - e^- \) charge ratio, which results as \( q_\mu/q_e + 1 = -1.1(2.1) \times 10^{-9} \). This is the best verification of charge equality in the first two generations of particles. The existence of one single universal quantized unit of charge is solely an experimental fact and no underlying symmetry could yet be revealed. The interest in such a viewpoint arises because gauge invariance assures charge quantization only within one generation of particles.

Major progress in the laser spectroscopy of M can be expected from a continous wave laser experiment, where

![Figure 4. Muonium 1s-2s signal. The frequency scale corresponds to the offset of the laser system base frequency from a molecular iodine reference line. The open circles are the observed signal, the solid squares represent the theoretical expectation based on pulse-by-pulse measured laser beam parameters (phase and intensity) and a line-shape model [3, 6].](image-url)
frequency measurement accuracy does not present any problem because light phase fluctuations are absent. For this an intense source of muons will be indispensable.

Muon Magnetic Anomaly

The spectroscopy experiments on muonium and a measurement of the muon magnetic anomaly $a_\mu = (g_\mu - 2)/2$ are closely related through $\mu = g_\mu e\hbar/(2m_\mu c)$. This arises from the precise values of fundamental constants and the high accuracy tests of the validity and reliability of QED for leptons, which both form an indispensable basic input for the analysis of the measured data and the calculations of a theoretical value. The measurements in muonium spectroscopy and of $a_\mu$ together put a stringent test on the internal consistency of theory and the values of the involved constants $a_\mu$, $m_\mu$, $\mu_\mu$, and $\alpha$.

The muon magnetic anomaly has been measured in three past experiments at CERN to 7 ppm. The anomaly arises from interactions with virtual particles created by the muons own radiation field. It is dominated, like in case of the electron, mostly by virtual electron, positron and photon fields. However, the effects of heavier particles are enhanced in comparison to the electron case by the square of the mass ratio $m_\mu/m_e \approx 4 \times 10^4$. Whereas for the electron such contributions altogether amount to about the present experimental uncertainty at 4 ppb, they have been experimentally demonstrated for muons already clearly in the last CERN experiment. The influence of the strong interaction can be determined in its dominating first order vacuum polarization part from a dispersion relation with the input from experimental data on $e^+ - e^-$ annihilation into hadrons and hadronic $\tau$-decays. It amounts to 58 ppm. Part of the hadronic contributions is hadronic light-by-light scattering. This can only be determined from calculations and is the subject of ongoing highly actual research [7]. Even the sign of the effect has frequently changed in calculations within the past decade. The weak interaction adds 1.3 ppm. Accounting for all known effects, present standard theory yields $a_\mu$ to 0.57 ppm. Possible influence from physics beyond the SM may be as large as a few ppm. Such could arise, for example, from supersymmetry, compositeness of fundamental fermions and bosons, CPT violation, and from many others.

There is a twofold high value for a precision measurement of $a_\mu$. Firstly, a discrepancy with finally agreed and confirmed standard theory calculations would give hints to yet undiscovered interactions and particles and it would stimulate more direct searches. Secondly, a good agreement at a high level of accuracy would set stringent limits on parameters in a large number of speculative models.

A new determination of $a_\mu$ is presently carried out in a superferric magnetic storage Ring at the Brookhaven National Laboratory (BNL) in Upton, USA (Figure 5) [8]. The difference between the spin precession and the cyclotron frequencies of the stored muons is determined. The detailed analysis of data obtained in 1999 with 2 billion $\mu^+$ has given an experimental value of $a_\mu(\text{exp}) = 11\,659\,202(14)(6) \times 10^{-10}$. The accuracy of 1.3 ppm is expected to be significantly improved with the analysis of the already recorded data sets with four times as much positive particles and twice as much negative muons. The plans foresee to obtain statistically equivalent datasets for both signs of charge.

The most recent and most accurate theory value in the framework of the SM $a_\mu(\text{SM}) = 11\,659\,276.8(6.5) \times 10^{-11}$ (0.56 ppm) [7] appears to differ from the experimental value by some 1.6 times the combined experimental and theoretical uncertainties. An earlier larger difference had led to a careful review of all standard theory contributions. In this process a calculational error was found in hadronic light-by-light scattering, showing the sensitivity to the precision of calculations and uncertainty assignments for theoretical values. This is work in progress and the future will show whether the final result will be a hint to new physics beyond the SM.

It should be noted that there is a severe limitation to the interpretation of a perhaps future muon $g_\mu - 2$ measurement, in connection with extracting or limiting parameters of speculative models, which arises from the hadronic vacuum polarization and owes to the fact that measurements of $e^+ - e^-$ annihilation into hadrons and hadronic $\tau$ decays have reached a statistical limitation. Hadronic light-by-light scattering, which can only be taken from calculations, sets a principal limit as long as the associated conceptual problems remain unsolved.
In order to find new physics in precision measurements it may therefore be advantageous to use systems, where the standard theory predictions are simpler. Searches for a permanent electric dipole moment (edm) of any fundamental particle are here good examples. Electric dipole moments are forbidden by P, T, and CP invariance, and the SM predictions are several orders of magnitude below present search limits. Furthermore, such research gains additional motivation, because the identification of new sources of CP violation could be a crucial ingredient for explaining the dominance of matter over antimatter in the universe. Driven by these arguments a novel idea has been brought forward [9]. It is to search for a muon edm by exploiting the motional electric field a highly relativistic muon experiences in a magnetic field. This motional field can be orders of magnitude stronger than technically achievable fields. A six orders of magnitude improvement over the present limit is aimed for by a collaboration at BNL. At this level a muon edm experiment will be competitive with electron or neutron edm experiments and has the further benefit of probing a new particle generation.

**Muonium to Antimuonium Conversion**

In addition to the indirect searches for signatures of new physics in the muon magnetic anomaly and in electromagnetic interactions within the muonium atom the bound state also offers the possibility to search more directly for predictions of speculative models. The process of muonium to antimuonium-conversion violates additive lepton family number conservation. It would be an analogy in the lepton sector to $K^0\bar{K}^0$ oscillations. MM-conversion appears naturally in many theories beyond the SM. The interaction could be mediated, e.g., by a doubly charged Higgs boson $\Delta^{++}$, Majorana neutrinos, a neutral scalar, a supersymmetric $\tau$-neutrino $\bar{\nu}_\tau$, or a doubly charged bileptonic gauge boson $X^{\pm\pm}$.

At PSI an experiment was designed to exploit a powerful new signature, which requires the coincident identification of both particles forming the anti-atom in its decay [4]. Thermal muonium atoms in vacuum from a SiO$_2$ powder target, are observed for $M$ decays. Energetic electrons from the decay of the $\mu^-$ in the $M$ atom can be identified in a magnetic spectrometer (Figure 6). The positron in the atomic shell of $M$ is left behind after the decay with 13.5 eV average kinetic energy. It has been post-accelerated and guided in a magnetic transport system onto a position sensitive microchannel plate detector (MCP). Annihilation radiation can be observed in a segmented pure CsI calorimeter around it. The decay vertex can be reconstructed.

The measurements were performed during a period of 6 months in total over 4 years during which $5.7 \times 10^{10}$ M atoms were in the interaction region. One event fell within a 99% confidence interval of all relevant distributions. The expected background due to accidental coincidences is 1.7(2) events. Depending on the interaction details one has to account for a suppression of the conversion in the 0.1 T magnetic field. This amounts maximally to a factor of about 3 for $V^{\pm}A$ type interactions. Thus, the upper limit on the conversion probability is $8.2 \times 10^{-11}$ (90% C.L.). The coupling constant is bound to below $3.0 \times 10^{-3}$ GF.

This new result, which exceeds limits from previous experiments by a factor of 2500 and one from an early stage of the experiment by 35, has some impact on speculative models. For example, a certain $Z_3$ model is ruled out which has more than 4 generations of particles and where masses could be generated radiatively with heavy lepton seeding. A new lower limit of $m_X \leq 2.6$ TeV/c$^2 g_{3l}$ (95% C.L.) on the masses of flavour diagonal bileptonic gauge bosons in GUT models is extracted, which lies well beyond the value derived from direct searches, measurements of the muon magnetic anomaly or high energy Bhabha scattering. Here, $g_{3l}$ is of order unity and depends on the details of the underlying symmetry. For 331 models the experimental result can be translated into $m_X \leq 850$ GeV/c$^2$ (95% C.L.) which excludes some of their minimal Higgs versions, where an upper bound of 600 GeV/c$^2$ has been extracted from an analysis of electro-weak parameters. The 331 models need now to refer to a less attractive and more complicated extensions. In the framework of R-parity violating su-
persymmetry the bound on the relevant coupling parameters could be lowered by a factor of 15 to $\lambda_{132} \cdot \lambda_{231}^* \times 3 \times 10^{-4}$ for assumed superpartner masses of 100 GeV/c².

A future MM-experiment could particularly take advantage of high intensity pulsed beams. In contrast to other lepton number violating muon decays, the conversion through its nature as particle-antiparticle oscillation has a time evolution in which the probability for finding a system formed as M decaying as $\bar{M}$ increases quadratically in time. This gives the signal an advantage, which grows in time over exponentially decaying background. For example, with a twofold coincidence as part of a signature after $\Delta T = 2\tau$, beam related accidental background has dropped by almost two orders of magnitude, whereas a $\bar{M}$-signal would not have suffered significantly at all.

Future Possibilities

All precision muonium experiments are now limited by statistics. For this reason significant improvements can be expected from more efficient M atom formation. There are some encouraging developments at RIKEN-RAL where hot metal targets are used [10]. However, by far the most promising approaches are muon sources with higher intensities. Such may become available, in principle, at any high power proton facility with particle energies above the pion production threshold. The dominating figure of merit is the beam power on the production target.

At JAERI in Japan the construction of the Japanese Hadron Project (JHF) has been started which has a 1 MW proton beam. Further, novel muon beam line concepts used compare to present facilities much larger particle collection solid angles at the production target and aim for significant phase space cooling of the beam. Examples are the DIOMEGER and PRISM projects [10].

In Europe a spallation source and a neutrino factory are being discussed. Also, the planned new GSI machine could provide such beams, if rapid cycling would be foreseen. In a similar way, the Brookhaven AGS could be upgraded. The success of such high power facilities will crucially depend on the capability of the possible targets to withstand high beam powers. Therefore, strong research activities should be focussed on this aspect soon.

In addition to more precise measurements in muonium a rich variety of experiments could be served at such expanded facilities. In Table 1 some possibilities are given, which include spectroscopy of artificial atoms and ions like muonic hydrogen and muonic helium where important parameters describing the hadronic particles within these systems can be determined. At such new facilities in particular several novel experimental techniques will become feasible and can be expected to provide most sensitive tests of fundamental interactions in an area with a high potential to discover new physics.

Conclusions

Professor I. I. Rabi’s question after he learned about the muon being a heavy lepton, “Who ordered that?”, has not been answered yet. The nature of the muon—the reason for its existence—still remains an intriguing mystery to be solved. On the way to finding an answer, theorists and experimentalists have contributed through their complementary work in fundamental muon physics to an improved understanding of basic particle interactions and fundamental symmetries in physics. In particular, muonium spectroscopy has verified the nature of the muon as a point-like heavy lepton, which differs only in mass, related parameters from the electron (and the tau). In addition, these measurements have provided accurate values of fundamental constants. With new high flux machines a fruitful future must be expected.

References

From Nuclear Physics to NMR Tomography

New technologies for producing sizable quantities of helium-3 with its nuclear spins aligned have transformed this substance from a laboratory curiosity into a promising practical commodity.

Helium-3 ($^3$He) is extremely rare in nature; its abundance is only 1.4 × 10^-4 percent of helium-4, the only other stable isotope of the noble gas helium. Since $^3$He is produced by the $\beta$-decay of tritium, it became available in considerable quantities in the mid-1950s as a by-product of the large-scale production of tritium for nuclear fusion weapons. With sufficient $^3$He available one of the most fascinating discoveries of condensed matter physics was made in the early 1970s: $^3$He becomes superfluid when condensed and further cooled down to temperatures close to absolute zero. Superfluidity is a quantum mechanical phenomenon which turned out to be an ideal testing ground for fundamental concepts of modern theoretical physics.

In recent years, the interest in and the use of $^3$He has undergone a second blooming, based on another quantum mechanical property, its nuclear spin of $\text{I}_2$. As often pictured, atoms and their nuclei behave like rotating tops. Normally, the “tops” are statistically directed in space, their rotation axes pointing in all directions. If, however, the individual tops can be made to point collectively in the same direction, the spin distribution is said to be polarized, and such polarization opens the way to the new phenomena.

We report here on a technique to polarize $^3$He nuclei on a large scale. Originally developed for studies of the neutron’s structure, polarized $^3$He soon found applications in the production of polarized neutron beams for condensed-matter research and in lung diagnostics in medicine—another story of basic research having spin-offs benefitting other fields.

A key problem is the production of spin-polarized $^3$He in large volumes and with high yield. An elegant method to polarize $^3$He is optical pumping, a method which traces back to the early 1960s [1, 2]. In order to force $^3$He nuclei to undergo a synchronized rotation, the gas is exposed to a laser beam directed along the axis of an external magnetic field. The laser light is circularly polarized, its plane of polarization rotating around the direction of propagation. Energy and uniform spin of the light quanta can be transferred to the atomic electrons of $^3$He, which in turn transmit their spin direction to the nucleus via magnetic coupling between electrons and nucleus.

For $^3$He, optical pumping from the atomic ground state is not possible because no excited states of sufficiently low energy exist. Pumping, however, can occur from the metastable $2\,^3S_1$ state ($^3$He*). This metastable state can be produced in concentrations of about 1 ppm in a low-pressure (=1 mbar) discharge cell that works like a fluorescence tube. The metastable state can be optically pumped using a transition [from $2\,^3S_1 (F = 1/2)$ to $2\,^3P_0 (F = 1/2)$] that can be induced by laser light with a wavelength of 1083 nm. The orientation of the metastable atoms builds up in microseconds. Within the same time scale the orientation of the metastable state is transferred to the nuclear spin of the ground state atom by so-called metastability exchange collisions. During such a collision, metastable and ground state atoms form a short-lived molecule that allows the exchange of energy and polarization and thus leads to the nuclear polarization of the $^3$He ground state atom.

The main obstacles which, until recently, made it impossible to polarize large quantities of $^3$He were the lack of efficient light sources at the required wavelengths and the difficulty of compressing the polarized gas. The optical pumping of metastable $^3$He provides a spin transfer rate of one per second per ground state atom; with commercial lasers of several watts, production rates of >10^19 nuclear spin-polarized $^3$He atoms per second can be achieved. Expressed in more convenient units, about 3 to 4 liters per hour at one bar pressure can be produced with 50 percent of the $^3$He in the polarized form. This is roughly what is required for recent applications.

For many applications, dense samples of polarized $^3$He gas are mandatory. Compression of the gas to several bar pressure proved to be extremely difficult because frequent interactions with the compressor walls, in particular with magnetic material, destroy the spin orientation [3]. Using an innovative compression technique, our group of the University of Mainz has been able to compress polarized $^3$He gas and to store it in glass cells whose inner surfaces are coated with a few monoatomic layers of cesium. This thin coating prevents the interfering magnetic interaction between para-
magnetic centers of the cell walls and ³He nuclei [4]. We are able to compress polarized ³He gas up to 10 bar pressure without loss of polarization and to store it in detachable and transportable containers for more than 200 hours. The whole procedure can be carried out at room temperature, and only a weak homogeneous magnetic field across the sample is sufficient to guide the spins. The practical advantages are evident.

Polarized Neutron Target

Scattering experiments have played a crucial role in the exploration of nuclei and their constituents, protons and neutrons, as well as of the forces acting between them. It was found that such interactions are spin dependent. To understand the fundamental question of whether the spins of neutrons and protons are entirely due to the spins of the three quarks constituting each nucleon or whether there are other contributions, one uses scattering experiments with spin degrees of freedom.

Experiments involving the neutron's spin are hampered by the fact that a target of free, polarized neutrons is not available. Neutrons would quickly disappear by radioactive decay (with half-life of 10 minutes) and by capture in surrounding material. But polarized ³He is a good approximation to a target of polarized neutrons, because the spins of the two protons are paired off and it’s the neutron which carries the spin of the nucleus. Plans for such an experiment were indeed the driving force for the development of the new ³He polarization technique.

Since quarks, the constituents of neutrons and protons, are believed to carry fractional electric charges, a touchstone for specific quark models is the charge distribution within proton and neutron, often expressed as so-called form factor. Precise measurements were available for protons, but not for neutrons, while carrying no net charge, are nevertheless believed to have internal structure characterized by some charge distribution. Also, there exists a magnetic form factor of the neutrons which entirely dominates the unpolarized cross-section measurements. Using, however, the scattering of polarized electrons on the neutron of polarized ³He an interference term between electric and magnetic form factor occurs in contrast to the unpolarized case which allows to separate off and even enhance the looked-for effect.

At the Mainz Microtron (MAMI) the electric form factor G_en was measured using the quasielastic reaction ³He (e,e'n) in the four momentum transfer range Q² = 0.2–0.7 (GeV/c)². In Figure 1 an overview of recent G_en measurements using different reaction channels is given [5]. The dashed line is a fit to these data using the so-called Gaster-parametrization. Due to medium effects the measured data points on G_en had to be corrected afterwards, which is indicated by the arrows shown in Figure 1. It is obvious that a thorough theoretical understanding of the underlying reaction mechanism is essential both for deuterium and Helium-3 in order to make a safe extrapolation of G_en to the free neutron case.

Neutron Spin Filter

Neutron scattering is one of the most powerful techniques used to investigate the microscopic properties of condensed matter, especially magnetic phenomena. The main limitations which, up to now, have prevented broad application of neutron polarization analysis studies are the low counting rates involved and the severe restrictions regarding the range of energy transfer and scattering angle available, in other words the phase space which can be covered by existing polarizer and/or

![Figure 1. Recent G_en neutron electric form factor measurements using the quasielastic reactions ³He (e,e'n) and D (e,e'n). The slope of G_en at Q² = 0 was extracted from thermal neutron scattering on heavy atoms.](image-url)
analyzer devices. It has therefore long been recognized that a spin-dependent broad-band neutron filter would have enormous potential, in analogy to the polarizer foils in light optics, which operate efficiently for polarizing and analyzing light over the whole visible spectrum.

A very promising material for neutron-spin filters is gaseous, spin-polarized $^3$He functioning as an absorption filter. Neutrons impinging with spin opposite to that of the $^3$He nucleus are absorbed with very large probability (the cross-section is 6000 barn at a neutron de Broglie wavelength of 1 Å and decreases in proportion to the wavelength). The parallel-spin component, on the other hand, is hardly attenuated and thus passes through the filter, so that the result is a highly polarized neutron beam. The contrast (or effectiveness) of the filter rises, of course, with the $^3$He polarization. With $P_{He} \approx 70\%$ presently being achieved, $^3$He neutron spin filters meet the numbers of transmission ($T_n \approx 30\%$) and polarizing power ($P_n \approx 94\%$) of classical polarizer devices, e.g., supermirrors. Unlike supermirrors, however, they provide their performances over the full energy range of cold, thermal, and hot neutrons from reactors and spallation sources.

It did not take long for the neutron physics community to become interested. The Institut Laue-Langevin (ILL) at Grenoble, operating the powerful European high-flux research reactor, initiated a development program in this direction. A copy of the Mainz $^3$He polarizer and compressor is being installed in a dedicated laboratory at ILL. The short filling time of such a neutron-spin filter cell makes it possible to provide several cells nearly simultaneously for different experimental applications at the multipurpose ILL reactor. The cells are used in a remote type of operation. In order to keep the $^3$He polarization close to the initial polarization value, the cells are refilled with freshly polarized gas every day.

In a first round of experiments, several possible applications were explored, including polarization analysis in fundamental physics experiments. In solid state physics a search for magnetic correlations in high temperature superconducting materials like the famous yttrium-barium-copper oxides was undertaken, since a possible explanation for the still mysterious phenomenon of high temperature superconductivity could be magnetic fluctuations surviving in the superconducting phase.

Also, first steps were undertaken towards a highly efficient polarization analysis of scattered neutrons [6]. The idea is simple: close to the sample under study a banana-shaped $^3$He neutron-spin filter cell, is positioned, surrounded by a large multidetector array. With the cell tailored to the detector arrangement of a diffuse-scattering instrument at ILL, an angle of 90 degrees in the horizontal plane and ±15 degrees in the vertical direction was covered. From the measured non-spin-flip and spin-flip differential cross-sections, the nuclear and magnetic cross-sections could be extracted over the kinematically accepted range of scattering vector $Q$ which are shown in Figure 2.

The full potential of $^3$He neutron spin filters will become available with accelerator-based neutron sources. In these sources neutrons of a wide range of energies are produced, by a process known as spallation, when heavy-metal target is

Figure 2. Extracted nuclear and magnetic cross-sections (a.u.) from uniaxial polarization analysis on amorphous ErY$_6$Ni$_3$ as a function of the scattering vector $Q$. 

impact and applications
bombarded with very energetic protons from a high power accelerator. Due to the pulsed structure of the proton beam, the neutrons also appear as pulses. This allows the simultaneous use of the whole range of neutron energies provided in the neutron pulse, the different energies being distinguished by time-of-flight techniques. Needless to say, that broad-band polarizers had to be used in order to make use of these benefits for an efficient polarization analysis measurement, too.

**Tomography of Human Lungs**

In a seminal 1994 paper, W. Happer's group at Princeton University in cooperation with the magnetic resonance imaging group at Duke University demonstrated the possibility of imaging lung tissue filled with a “hyperpolarized” noble gas. The term hyperpolarized is used to convey the fact that the noble gas is polarized by optical pumping to a degree far beyond the so-called Boltzmann-polarization achieved in the magnetic field of a magnetic resonance imaging (MRI) device as a result of the Zeeman-splitting of the magnetic sublevels.

The medical community became interested in this method because porous tissues like the lungs are difficult to image by conventional MRI techniques. Also X-rays and γ-rays do not give satisfactory results. X-ray imaging suffers from poor contrast and γ-ray scintigraphy from marginal resolution. With our technique of compressing hyperpolarized 3He into detachable and transportable cells, we found ourselves well prepared for entering this new field. In collaboration with the Radiological department of the University of Mainz and the German Research Center in Heidelberg we made a first attempt to image human lungs *in vivo* by having the subject inhale 0.5 bar liter of 3He polarized to 46%.

A series of morphological images during apnea were performed. The purpose of this study was to describe the 3He findings of normal pulmonary ventilation in healthy volunteers and to evaluate abnormalities in patients with different lung diseases. Figure 3 shows images of lungs from a healthy volunteer and a smoker. The lung parenchyma of volunteers with normal ventilatory function exhibited a rather homogeneous intermediate to high signal, whereas patients (here a smoker) presented with severe signal inhomogeneities with patchy or wedge-shaped defects, a diagnosis of high relevance. Tumors and tuberculosis have also been identified in a first survey of patients.

For transport to the MR-scanner, cells filled with hyperpolarized 3He gas are stored inside cylindrical transport boxes made out of soft-iron and µ-metal with permanent magnets, providing a homogeneous magnetic guiding field. Cell transport by car, train, and airplane were done within Europe without noticeable loss of 3He polarisation. Inside the MR-scanner, the 3He samples are connected to a gas administration unit developed in our group. This device permits administration of 3He bolus of fixed volume (20...500 ml at atmospheric pressure) into the inspiratory tidal volume at any predefined time with high reproducibility and negligible loss of hyperpolarization. Volunteers or patients can either breathe spontaneously through the application unit, or ventilation can be supported by commercial respirator units. Finally, the exhaled air-3He gas mixture is collected into a helium-tight bag and, by means of cryogenic traps, the rare helium isotope can be recycled to a high degree (≈95%) and be reused as contrast agent for a next 3He-MRI cycle.

Besides morphological MRI, studies of the dynamics of lung functioning have become an integral part of a routine examination protocol now, i.e., ultra-fast imaging, diffusion weighted imaging, and 3He-MRI based measurements of the intrapulmonary oxygen partial pressure.

Looking more closely on the latter example: the longitudinal relaxation time $T_1$ of 3He administered to
the airspaces is limited to 10–20 s. The key factor is paramagnetic oxygen, which, via dipolar coupling to the $^3$He nuclei, causes rapid depolarization and hence irreversible signal loss. Making use of this relaxation effect the local oxygen partial pressure and its evolution during apnea can be measured which is shown in Figure 4. Since intrapulmonary distribution of ($p_{O_2}$) is governed by both regional ventilation, regional perfusion, and oxygen uptake into the blood, the method constitutes a new approach to lung function analysis [7].

Judging by these encouraging results, $^3$He tomography appears to have a bright future for visualizing and assessing pulmonary ventilation. It will help provide further insights into the pathophysiology of breathing, and it may challenge ventilation scintigraphy in the preoperative treatment of patients with pulmonary diseases. Since only a few accessory tools are needed to perform $^3$He imaging with standard MRI equipment, the technique could become widely available within a relatively short time.

References
Hadrontherapy Used for First Time in Italy

In April 2002 a beam of protons, accelerated up to 62 MeV by the CS Superconducting Cyclotron, was used at Laboratori Nazionali del Sud, Catania, to irradiate uveal melanoma of the eye of three patients. Five more patients were treated in May. This is the first time that hadrontherapy was used in Italy. The irradiation of patients affected by tumours with hadrons, and in particular protons, is nowadays an established technique [1], which is, however, used in only a few centres in the world, located in seven European nations and in four non-European nations.

The dose released in tissues by charged particles is mostly concentrated at the end of their path (Bragg peak). The path itself is essentially straight. Taking advantage of these geometrical properties, and of the higher RBE with respect to gammaray, X-ray, and electron irradiation, hadrontherapy is especially suited for the treatment of well-localized tumours, particularly when the irradiation can damage nearby vital organs.

The maximum energy of the protons accelerated by the Superconducting Cyclotron operational at LNS, 62 MeV, is such that a depth of about 3 cm at most can be reached in tissues. The use of heavier projectiles would imply a shorter range. So it was decided to apply protontherapy to pathologies of the eye, in particular the uveal melanoma of the choroids and the macular degeneracy.

The project has involved the efforts of physicists of LNS, of the University of Catania and of other local and national institutions, together with the competences of ophthalmologists, radiotherapists, and radiologists. It was necessary to learn how to characterize the proton beam (shape, current, and energy modulation), define the treatment plans, and accurately control the dose released during the treatment.

It is worth noting that, due to Sicily’s geographical centrality with respect to the Mediterranean, where Catania stands, the activity of the therapeutical facility installed at LNS is of interest not only for Italy but also for other European and African countries.

Reference

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The Workshop on Future Instruments for Nuclear and Particle Physics and Methods at the FRM-II took place on April 12th, 2002 in Garching. The scope of the workshop was to bring together different groups of interest in the field of nuclear and particle physics as well as nuclear methods in view of the future experimental facilities at the new German neutron source FRM-II. Actually, two large projects in these areas are under development at the FRM-II, namely the Munich Fission Fragment Accelerator MAFF and the Ultra Cold Neutron Source. The motivation to organise the workshop was to discuss new instruments beyond these large projects and possible applications of these sources, respectively.

Besides the conventional neutron sources, the FRM-II will provide new sources for neutron-rich fission fragments, positrons, and ultra cold neutrons. They will extend intensities from existing sources by orders of magnitude. Throughout the workshop the speakers pointed out the urgent need to start the operation of the FRM-II immediately in order not to lose this unique advantage.

J. Neuhaus introduced the workshop by a short overview of the planned installations and instruments at the FRM-II. The workshop was divided into three sessions, namely Nuclear Physics, Particle Physics, and Nuclear Methods. D. Habs gave an overview of the possibilities and the status of the MAFF project. Actually a large number of components developed for MAFF are tested at other facilities like REX-ISOLDE. Concerning reactor installations, the through-going beam tube has been completed, while further installations are desperately waiting for the nuclear startup of the FRM-II. Only then can the MAFF project move further in the commissioning phase. Possible applications for the MAFF beam were pointed out by G. Seewald (nuclear orientation studies NMR-ON).

R. Casten and J. Jolie presented applications for a multipurpose beam instrument (neutron capture) for nuclear spectroscopy. With modern Ge-array detectors or high resolution crystal spectrometers together with a neutron lens a versatile instrument could be installed in the neutron guide hall, which also might serve for prompt g-ray neutron activation analysis, as pointed out by A. Türler.

The session on Particle Physics was introduced by H. Abele. He showed the large variety of applications of neutron physics ranging from astro physics to particle physics. O. Zimmer presented applications of polarised nuclei for neutron scattering. They can be used as spin filters (polarisers and analysers) and for stroboscopic spin contrast variation in the sample. Finally F. Hartmann presented the ultra cold neutron source and first applications for the ongoing research for the EDM and lifetime of the neutron. The expected large increase in neutron density by a factor of 100 to 1,000 from the UCN source, when compared to existing sources, will allow a significant decrease in statistical errors for neutron particle experiments.

In the last session on Nuclear Methods, C. Hugenschmidt presented the high intense positron source at the FRM-II. Here again a substantial increase in intensity up to 1010 positrons/s will allow new and exciting experiments ranging from fundamental physics to surface science and solid state physics. D. Schwalm showed experiments on positronium which will substantially profit from the increase in positron flux compared to conventional sources.

The workshop concluded that, with the tremendous increase in intensity for fission fragments, ultra cold neutrons, as well as positrons, new and exciting experiments will be possible. This underlines the urgent need for the startup of the FRM-II. The organiser welcomed the interest of user groups from nuclear and particle physics to build up new experiments at the FRM-II, which demonstrates the possibilities of the FRM-II as a multipurpose source.
XXV Symposium on Nuclear Physics

The 25th edition of the “Symposium on Nuclear Physics” was held in the town of Taxco, Mexico, from January 7th to 10th, 2002. This conference has been taking place every year for the last 25 and has become an important international venue for the nuclear physics community. This meeting was held for the second time in the beautiful mountain town of Taxco, renowned for its silver art and crafts. Previous symposia were traditionally held in the town of Oaxtepec, Mexico, for which reason the conference became known as “The Oaxtepec Meeting.”

The Symposium on Nuclear Physics was conceived from the beginning as a small meeting designed to bring together some of the leading scientists in the field. During these 25 years, the conference has become one of the best known international conferences on Nuclear Physics. Its most distinctive feature is its ability to gather a wide range of specialists in different nuclear physics subjects, both theoretical and experimental, in a relaxed and informal environment, providing them with a unique opportunity to exchange ideas.

This year, 40 colleagues attended our symposium, of which about half came from abroad. In addition, a dozen graduate students participated in the meeting, where 23 invited talks and 10 posters were presented. The subjects discussed covered different aspects of nuclear and subnuclear structure, radioactive beams, nuclear astrophysics, relativistic heavy-ion collisions, and several other related subjects. There were three main themes of the conference, namely nuclear structure, exotic nuclei, and relativistic heavy ion collisions, plus a small number of talks on special topics.

Nuclear structure talks ranged over a large gamut of topics including random interactions, critical point symmetries, the effects of repulsive interactions between composite bosons, level crossings, the description of spurious states, resonances, and quasimolecular states.

The field of exotic nuclei is a major growth area in nuclear physics these days, and several talks at the conference dealt with aspects of this such as symmetries in N = Z nuclei, exotic decay modes, production of superheavy and radioactive nuclei, and coupling to the continuum.

Collisions of relativistic heavy ions and the formation and possible detection of the quark-gluon plasma, as well as the structure of QCD at high densities and temperatures, formed another important theme that is very current these days now that RHIC has come on line.

The posters complemented the topics discussed and represented an opportunity for graduate students to show the progress of their research work.

During the welcoming dinner, the distinguished Mexican nuclear physicist, Prof. Marcos Moshinsky, addressed the attendants to recall the history of the Oaxtepec Symposia and to emphasize the importance of these meetings to strengthen the ties between the Mexican and international nuclear physics communities. After his words, we enjoyed the music of a mariachi band.

As is customary, many of the foreign participants stayed for a while longer in Mexico after the end of the conference to initiate or continue collaborations with their Mexican colleagues.

The level of maturity reached by the small but very active Mexican nuclear physics community leads us to believe that this 25th jubilee of the Nuclear Physics Symposium constitutes only a first stage in a long and exciting series of meetings to come. Congratulations and thanks to all our colleagues who have enthusiastically taken part in these meetings throughout the years.

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The international symposium POSTYK01 was held at the Yukawa Institute for Theoretical Physics, Kyoto, Japan, from November 12 to 14, 2001. It was organized as a post symposium of the Yukawa International Seminar (YKIS 2001) on the Physics of Unstable Nuclei held in Kyoto from November 5 to 10, 2001. There were about 86 participants from 13 countries. Most of them had also attended the YKIS 2001 conference, which prominently covered clustering in unstable nuclei. At the post-YKIS symposium unstable nuclei were further discussed in depth, but the scope was extended to clustering aspects of other quantum many-body systems as well.

At the last international cluster conference at Rab, Croatia, it was decided that the next number of that conference series will be held at Nara, Japan, in 2003. It was also decided that we would have a symposium in England in 2001. Unfortunately, organizational difficulties arose in England. The symposium in Kyoto following the YKIS conference was meant to substitute for that meeting. Our aim was to bridge the time gap between Rab and Nara and to encourage studies in this field as a preparation for the Nara conference.

The first topic discussed was “Clustering in Unstable Nuclei.” A whole morning was devoted to this main subject. Four talks were about cluster structure in He and Li isotopes and four other talks about molecular structure, especially in Be isotopes. The $^4$He + $^4$He structure in $^{12}$Be may be as fundamental for cluster studies on unstable nuclei as $\alpha + \alpha$ has been for stable nuclei.

The cluster studies which began with $\alpha$-clusters, later embraced various other clusters, e.g., d, t, $^3$He and heavier clusters, such as $^{12}$C and $^{16}$O. Further recent developments were focussed on cluster problems of unstable nuclei and on the study of hypernuclei. The cluster models for hypernuclei have been used widely and successfully in the last two decades. The subject “Cluster Structure in Hypernuclei” was discussed in the second session.

In the next session “Cluster Structure in Light to Medium-Heavy Stable Nuclei” was discussed. This session covered molecular resonances and the problem of internuclear potentials related to clustering. We learned of new developments in experimental techniques and instruments and in theoretical approaches and interpretation of resonances and internuclear potentials in heavy ion collisions.

In the session on “Alpha and Dineutron Condensation,” a very intriguing study on Bose-Einstein condensation of clusters in nuclei was reported by Dr. Schuck. The calculations of Schuck, Tohsaki-Suzuki, and their collaborators for $^{12}$C and $^{16}$O result in some states, around the $3\alpha$ and $4\alpha$ thresholds, respectively, which are interpreted as showing Bose-Einstein condensation of clusters.

We had a session on “Nuclear Cluster Physics in Astrophysics.” Cluster models were used successfully in the description of energy levels and widths for many light nuclei which appear in astrophysics. Several clustered nuclear states have been shown to play important roles in nucleosynthesis.

The session on “Fragment Formation in Nuclear Reactions and Properties of Nuclear Matter” comprised two experimental and four theoretical talks. Cluster dynamics has been shown to play an important role in fragment formation.

The session on “Clustering, Large Deformation and Formation of Heavy Nuclei” has contributed to the clarification of the relation between large deformation and clusterization.

The next topic was “Clustering Features of Few-Body Systems.” Dr. Lovas reported on $ab\ initio$ calculations for light nuclei in the framework of a stochastic variational method based on correlated Gaussian bases. Furthermore, we learned of recent theoretical developments in a more sophisticated RGM (resonating group method) and algebraic approaches of the RGM based on SU(3) cluster wave functions.

Applications of the algebraic approach to many-channel s-cluster systems were discussed also in the next session, on “Theoretical Developments in Nuclear Cluster Physics.” Three talks discussed the application of the complex scaling of the Faddeev equations and the Jost function method to unstable nuclei. One talk was on the cluster effects in nuclear binding energies.

The subject of the last session was “Cluster Effects on Photon Production and Atomic Physics.” An interesting report was presented by
Dr. Löhner on bremsstrahlung phenomena in proton and α-particle collisions with nuclei. A topic related to atomic physics, atomic spectra in a bubble of liquid helium, was discussed by Nakatsukasa. Finally, a beautiful summary was given by Dr. Brink. He emphasized the coexistence of many different structures in the same nucleus. The proceedings of the symposium will be published by World Scientific.

The International Symposium on Electromagnetic Interactions in Nuclear and Hadron Physics (EMI2001) was held at Osaka University, Japan from December 4th to 7th, 2001. The symposium is organized with the aim to discuss the fundamental current problems in nuclear and hadron physics developed with “electromagnetic probes.” The international forum brought together 128 physicists from 16 countries including 48 participants from Japan. There were lively discussions on the latest advances in the following subjects;

1. Meson and hadron productions by real and virtual photon interaction with nucleons and nuclei
2. Astrophysics studies via photon reactions and hadron reactions
3. New technologies for the electromagnetic (E.M.) probes and the detector development
4. Nuclear structure studied with E.M. probes
5. Fundamental symmetries with E.M. probes and related problems

When a decision was made in 2000 to organize this symposium, several movements towards new developments of physics with electromagnetic probes were expected to be a fashion in the world. Actually, interesting and hot results from many laboratories in the world have been presented discussed in the EMI2001 symposium.

This symposium is supported by Ministry of Education, Culture, Sport, Science and Technology (Monbu-Kagaku-shou) under COE (Center of Excellence) Program, and is hosted by the Research Center for Nuclear Physics (RCNP). The symposium belongs to a series of international meetings at RCNP. It was timely to discuss the subjects mentioned above since we expect to have some interesting results from the new facilities like the LEPS (Laser-Photon Spectrometer) facility at SPring-8 using the photon beam with an energy of 1.5–2.4 GeV, and the Jefferson Laboratory using a high intensity electron beam since noble technical developments have been delivered for future experiments. The symposium is also intended for celebrating the 30-year anniversary of RCNP, Osaka University. The ceremony and reception of the 30-year RCNP anniversary is held on December 3rd, 2001, before the symposium.

In addition to invited talks, we arranged a poster session and a special session where the students working at RCNP presented their latest results for the attendant experienced scientists. This special session seems to work very well to stimulate the young students. The proceedings of the EMI2001 symposium will be published from the World Scientific.

Mamoru Fujitaya
The Nuclear Liquid-Gas Phase Transition: Studies with the ISiS Array

The study of multifragmentation and its possible link to a nuclear liquid-gas phase transition has been motivated by the desire to understand the nuclear equation of state, with its broad applications to nuclear physics and astrophysics. Nuclear fragmentation reactions first became of interest in the 1950s as a result of radiochemical and emulsion measurements conducted with hadron beams [1–3]. However, detector technology and data-acquisition capabilities permitted only inclusive investigations of these complex reactions until the late 1970s. In a set of key experiments at Fermilab and the Brookhaven AGS, the Purdue group measured complete spectra and isotope yields from bombardments of heavy nuclei with 1–300 GeV protons [4]. While these experiments lacked the multiparticle detection capability needed to confirm the existence of a phase transition, a 4π detector was required in order to provide fragment multiplicity information, event topology and calorimetry.

Because the previous studies [4, 6] had shown a broadening to low energies in the kinetic energy spectra of the clusters (IMFs: 3 ≤ Z ≤ 20) emitted in reactions above several GeV bombarding energy), the detector design also demanded very low thresholds and good energy resolution. Thus, it was decided to construct a silicon-based array augmented by low pressure gas-ionization chambers for Z-identification of the lowest energy fragments and a CsI scintillator with photodiode readout for Z and A identification of the energetic lighter fragments, shown in Figure 1 and described in [7]. Consistent with light-ion kinematics, a spherical geometry was chosen for the 162 close-packed triple telescopes in the array, arranged in nine concentric rings, each containing 18 detector modules. A schematic of the ISiS array is shown in Figure 2. The detector configuration yielded a kinetic energy acceptance of 1 MeV ≤ E/A ≤ 92 MeV for charge-identified fragments up to Z = 16; Z and A identification for 8 MeV ≤ E/A ≤ 92 MeV products, and “grey particle” detection for fast particles (primarily protons and pions) up to 350 MeV. Some development of the detector modules proceeded in parallel with our Saclay colleagues, who were also involved in the development of the silicon modules for the INDRA array for heavy-ion measurements.

Four campaigns were carried out with the ISiS array: E228 at LNS Saclay with 1.8–4.8 GeV 3He ions; E375 at IUCF with 130–260 MeV proton and 3He beams; E900 at AGS with 5.0–14.6 GeV/c proton and π beams, and E900a at AGS with 8.0 GeV/c tagged antiproton and π beams. Principal experimentalists involved in the collaboration included scientists from Simon Fraser University (R. G. Korteling), CEA Saclay (C. Volant, R. Legrain, and E. C. Pollacco), Texas A&M University facilities and methods

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facilities and methods

Figure 2. Assembly drawing of the ISiS system. Components are as follows: (1) center ring, (2) window, (3) arc bars, (4) center disks, (5) support cones, (6) target ladder assembly, (7) steel rails, and (8) vacuum chamber.

(S. J. Yennello), Jagiellonian University (J. Brzychczyk), the University of Maryland (H. Breuer), and Warsaw University (L. Pienkowski), as well as former members of the IU group, T. Lefort, L. Beaulieu, K. B. Morley, E. Foxford, and D. S. Bracken.

The clearest signatures of a phase transition are found in the AGS data, in particular the 8.0 GeV/c $\pi + ^{197}$Au reaction, where $2.5 \times 10^6$ events with multiplicity $M \geq 3$ for thermal-like charged particles were recorded. These data exhibit several experimental criteria characteristic of an equilibrium system undergoing a phase transition. First, the fragments are emitted nearly isotropically and exhibit Maxwellian-like kinetic energy spectra. This behavior is illustrated in the differential cross section plots for carbon fragments in Figure 3 as a function of the heat content, excitation energy per residue nucleon $E^*/A$, of the hot target residue [8]. One observes that as $E^*/A$ increases, the spectra are broadened toward lower and lower energies, consistent with the breakup of a system with lower than normal nuclear density.

The fragment multiplicities and size distributions are also important criteria. Figure 4 shows the evolution of the emitting source charge and the charges of the three largest fragments as $E^*/A$ increases. For $E^*/A \approx 4–5$ MeV, which comprises ~95% of the total reaction cross section, Figure 4 indicates that the events are associated with a heavy residue, consistent with evaporative emission. At higher excitation energies the tendency is for each event to produce fragments of increasingly similar sizes, so that above $E^*/A \approx 6$ MeV, multifragmentation into

Figure 3. Kinetic-energy spectra of oxygen nuclei at four angles in the laboratory system for three bins of excitation energy for 8 GeV/c $\pi + ^{197}$Au reaction; open circles are for $E^*/A = 2–4$ MeV; closed triangles for $E^*/A = 4.6$ MeV; open triangles for $E^*/A = 6–9$ MeV. The lines correspond to SMM calculations for breakup volume $V = 3V_0$ with extra expansion energy, equal to zero (solid line) and 0.5A MeV (dashed line) [10]. For each bin in excitation energy the simulated spectrum is normalized to the maximum of the experimental one.
IMFs and light-charged particles is the dominant process. The upper panel of Figure 5 shows how the probability for a given IMF multiplicity depends on E*/A (the undetected largest residue is not included). In the second frame the corresponding charge distributions have been fit with a power law: \( \sigma(Z) \propto Z^{-\tau} \). A minimum in the power-law exponent \( \tau \) is observed near E*/A \( \sim 6 \) MeV, indicating a tendency to form increasingly large clusters up to this point. This minimum signals the possible onset of a phase transition, as discussed in [9] and [10]. At higher excitation energies, the cluster sizes begin to decrease, in part due to secondary decay of the hot fragments.

The breakup time scale is central to distinguishing between the “instantaneous” breakup associated with a phase transition and a slower sequential evaporative process. In the bottom frame of Figure 5, the evolution of the relative emission time for IMFs is shown as a function of E*/A [11]. At low excitation energy, the time scales are relatively long, typical of evaporative emission. However, with increasing E*/A the time scale decreases rapidly, reaching values of \( \Delta \tau \sim 20-50 \) fm/c for E*/A \( \approx 4 \) MeV; i.e., the breakup is nearly instantaneous. In this same excitation energy range, the third panel shows evidence for a slight extra thermal expansion energy [12], much smaller than the compression-induced values found in collisions between mass-symmetric heavy-ion studies. All of the above observables—multiplicity and charge distributions, time scale, and extra thermal expansion energy—indicate a mechanism change near E*/A \( \sim 4-6 \) MeV, corresponding to the predicted threshold from multifragmentation models [13–15].

When temperatures derived from double isotope ratios are plotted versus the heat content of the system (the caloric curve), the ISiS data exhibit behavior similar to the heating of a liquid to the boiling point, as originally shown by Pochodzalla et al. [16] for the ALADIN results. Further analysis suggests evidence for a negative heat capacity at the liquid-gas transition point, consistent with the recent results of D’Agostino et al. [17]. In both cases a first-order phase transition is indicated. Beaulieu et al. [18] showed that the ISiS data exhibit binomial reducibility and thermal scal-

![Figure 4](image1.png)

**Figure 4.** Dependence of fractional source charge and IMF charges as a function of E*/A for the 8 GeV/c \( \pi^- + ^{197}\text{Au} \) reaction [16]. Top: Fractional source charge of residue. Middle: Missing charge in ISiS, assumed be the largest fragment; and SSM prediction for missing charge (solid line) and for largest fragment (dashed line), both passed through the ISiS filter. Bottom: Charge of two largest observed fragments; solid line is the SMM prediction for second largest fragment \( Z_{\text{max}2} \), and dashed line, for third largest fragment \( Z_{\text{max}3} \).

![Figure 5](image2.png)

**Figure 5.** Dependence on E*/A for the following qualities, from bottom up: relative IMF emission time \( t \), extra radial expansion energy \( E_{\text{extra}}/A_{\text{IMF}} \), charge distribution power law exponent \( \tau \) and probability for a given IMF multiplicity [16].
Fisher scaling model analysis to the data and found an equivalent result, i.e., evidence for a phase transition and critical behavior. The collapse of the IMF data for the 8.0 GeV/c $\pi^+{^{197}}\text{Au}$ reactions onto a single locus extending over six decades, when reduced to a single set of Fisher-scaling exponents, is shown in Figure 6.

Thus, given the ISiS results, combined with heavy-ion results obtained at GANIL (INDRA), GSI (ALADIN), NSCL (Miniball/Wall), Texas A&M (NIMROD), and the former LBNL Bevalac (EOS/Purdue), it appears that the question facing the nuclear dynamics community today is no longer, “Does the phase transition exist?”, but rather, “What is the nature of the phase transition and what are the critical parameters?”

References
Investigation of the Neutronic Performance of Cold Moderators with JESSICA

Introduction

JESSICA (Juelich Experimental Spallation Target Set-up In COSY Area) is an experiment at the COSY cooler synchrotron at the Forschungszentrum Jülich. The aim of the experiment is the investigation of advanced cold moderators for upcoming next generation neutron sources like ESS (European Spallation Source) [1, 2], SNS (Spallation Neutron Source, under construction in Oak Ridge, USA) [3], or JSNS (Japanese Spallation Neutron Source). In order to design and construct intensive pulsed spallation neutron sources experimental investigations of the crucial technical components are required. JESSICA is a 1:1 mock-up of the target-moderator-reflector assembly of one 5 MW target station of the planned 10 MW source ESS. The data obtained at JESSICA will be used to find the best-suited moderator for next generation neutron sources. On the one hand, the experimental investigation of the neutronic behaviour of advanced cold moderators is a main topic of the experiment. On the other hand Monte-Carlo simulation codes can be validated as well. Especially new neutron scattering kernels—which are still under development—can be validated and checked against measured data. The target containing 35 l of mercury is located in the centre of the reflector. A lead reflector with a diameter of 1.3 m and a height of 1.3 m surrounds the target. The moderators are placed in the so-called wing geometry. This means two moderators are mounted above and below the target to prevent fast neutrons from the target directly leaking out of the system. This reduces the fast neutron background considerably. Whereas three moderators are filled with water, the lower upstream moderator position is used to study various cold moderator materials, as can be seen in Figure 1(a). Figure 1(b) gives an impression of the facility installed at COSY. But why is JESSICA installed at COSY? Due to the low proton beam intensity radiolysis, energy deposition and activation are negligible. This enables easy modifications of the experiment after switching off the proton beam and omitting a cooling loop for the mercury target.

Experimental Set-Up

JESSICA is operated with a beam intensity of $4 \cdot 10^8$–$4 \cdot 10^9$ protons per pulse. The repetition rate is 1/30 Hz with a pulse length of approximately 0.5 µs. To determine the number of protons per pulse, two proton beam monitors with different working principles are installed in the proton beam line. On the one hand a wall current monitor (WCM) measuring the mirror curr

![Figure 1(a). 3D view of the target, moderator, and reflector assembly.](image1)

![Figure 1(b). The JESSICA Experiment at the COSY proton synchrotron in Jülich.](image2)
rent in the wall of the beam tube and on the other hand an integrating current transformer (ICT) measuring the current induced in a coil when the proton beam passes through are used. The number of protons per pulse is indispensable to determine the neutron to proton ratio in order to compare the experimental data with Monte Carlo simulations on an absolute scale. The characteristics of the moderators to be investigated are studied by time of flight measurements of the neutrons coming out of the moderator surface. Therefore, a 5.37 m long neutron flight path was constructed. At the end a neutron detector is placed to measure the time of flight spectra, from which the energy spectra can be deduced. To obtain detailed information of the time structure and wavelength dependency of the neutron pulses, a graphite crystal can be moved into the neutron flight path. Neutrons fulfilling the Bragg condition are reflected by the crystal and can be detected with a second neutron detector viewing the crystal.

Figure 2 illustrates the set-up of the experiment. In order to achieve a better time resolution, the surfaces of the moderator, crystal, and detector can be aligned in parallel.

Advanced Cold Moderators

To improve the performance of next generation neutron sources JESSICA is looking for the most advantageous candidate moderator materials. Most promising moderators are

- ice at 20 K,
- solid methane at 20 K,
- methane pellets in liquid hydrogen, and
- methane hydrate at 20 K.

As a reference, water at ambient temperature and liquid hydrogen at 20 K will also be measured. Based on measurements performed by Inoue et al. [4] ice and solid methane as moderator materials are expected to be superior to liquid hydrogen moderators as can be seen in Figure 3. When comparing solid methane with liquid hydrogen the advantage is dominating for kinetic energies below 0.01 eV. Ice at 20 K is expected to yield higher neutron fluxes in an energy regime between 0.001 eV and 0.1 eV. To benefit from advantages of both ice and methane the idea is to combine both materials. One possibility is using methane hydrate because here a methane molecule is encapsulated in an ice cage. JESSICA will investigate whether an increase of the neutron flux can be

Figure 2. Set-up of the JESSICA experiment with proton monitors, neutron detectors, scattering crystal, and target-moderator-reflector assembly.

Figure 3. Measured neutron energy spectra for various cold moderators carried out at an electron accelerator [4].
observed in the energy regime between 0.001 eV and 0.1 eV when using a methane hydrate moderator. The data described above were obtained with an electron accelerator driven experiment [5]. A 45 MeV electron beam hits a heavy metal target (tungsten or lead). The deceleration of the electrons causes bremsstrahlung in an energy range of the resonance for ($\gamma$, n)-reactions with the heavy target nuclei. The generated fast neutrons are moderated in the adjoining moderator. In contrast to JESSICA no reflector was installed and another moderator geometry was used. Because of the above-mentioned differences it is up to JESSICA to prove if the same gains can be found in a spallation source driven by a 1.334 GeV proton beam.

First Results from JESSICA

Up to now the neutronic performance of two moderators was investigated. During the first measuring campaign water at ambient temperature was studied. From the time of flight spectra not only the energy spectra can be deduced but also the moderator temperature can be determined. This is possible because the kinetic energy of the neutrons is Maxwellian distributed. The determined temperature of 307 K is in a good accordance with the measured temperature of the moderator of 294 K. Furthermore, the shape of the measured time-of-flight spectrum is in line with the spectrum from a Monte-Carlo simulation performed with MCNPX [6], as can be seen in Figure 4. In this case the peak values are normalised to one. This spectrum is obtained in two steps. The first measurement counts all neutrons leaving the moderator including background. To eliminate the background a further measurement is performed. In this second measurement only those neutrons are detected, which are not absorbed in an

Figure 4. Comparison of the time of flight spectrum between experimental data (solid line) and Monte Carlo simulation (open circles) for an ambient temperature water moderator.

Figure 5. Energy spectra for 20 K and 70 K ice and water at room temperature (300 K).
additionally inserted Cadmium layer in front of the neutron flight path. The high neutron absorption cross section of Cadmium for thermal neutrons prevents them from reaching the detector. The difference of both spectra results in the time of flight spectrum for the thermal neutrons. At this time a comparison between experimental data and simulated ones is only possible for an ambient temperature water moderator due to missing neutron scattering kernels for cold moderator materials. But with JESSICA also an ice moderator at 20 K and 70 K was investigated. Transforming the time-of-flight spectrum into an energy spectrum shows a similar behaviour as observed by Inoue et al. In Figure 5 the energy spectra of ambient temperature water, ice at 70 K, and ice at 20 K are plotted. The shown data are normalised relative to the incident number of protons. In contrast to the slowing down regime (>0.2 eV) where all three moderators show the same behaviour, large differences can be observed in the lower energy regime. Water is superior in the energy regime between 3 · 10⁻² eV and 0.2 eV compared to the ice moderators. But for low energetic neutrons the intensity drops down and the ice moderators seem to be more advantageous. It can be seen that the colder the moderator is, the more shifted is the peak position towards lower neutron energies. The position of the peak for 20 K is at 6 · 10⁻³ eV, for 70 K at 1 · 10⁻² eV, and for 300 K at 3 · 10⁻² eV, respectively. To obtain more information about the moderation process inside the moderator, the wavelength-dependent time structure of the neutron pulse has to be investigated. For that reason the graphite crystal is installed in the neutron flight path. Only neutrons fulfilling the Bragg condition are reflected in the crystal and can be counted in a second detector. The observed spectra for an ambient temperature water moderator and an ice moderator at 20 K are plotted in Figure 6. The spectra show the time structure of the neutron pulses for five specific wavelengths (energies): 0.95 Å, 1.19 Å, 1.57 Å, 2.37 Å, and 4.74 Å. As expected, the peak intensity for the longer wavelengths (lower energies and longer flight times) increases (2.37 Å and 4.74 Å) in case of the 20 K cold ice moderator compared to the 300 K water moderator. These experiments confirm the results presented in Figure 5 that an ice moderator will be superior compared to a water moderator due to increasing intensity for lower energetic neutrons.

Outlook

After first experiments of JESSICA are finished successfully with water and ice moderators, we will now study advanced moderators like methane hydrate or methane pellets. As a reference moderator for cold moderators, liquid hydrogen will also be measured, because it is one of the standard cold moderators used at several neutron sources around the world. With the set of data obtained from the JESSICA experiments new developed neutron scattering kernels for neutron transport codes will be checked and optimised.

If the advanced moderators, mainly methane-hydrate, will deliver the expected gain in the neutron output, the JESSICA experiment can help to improve the neutronic performance of moderator systems.

K. NUNIGHOFF FOR THE JESSICA COLLABORATION

References

1. H. Conrad, D. Filges, F. Goldenbaum, R.-D. Neef, K. Nünighoff, N. Paul, Ch. Pohl, H. Schaaf, H. Stelzer, H. Tietze-Jaensch, M. Wohlmuth (Forschungszentrum Jülich, Germany); A. Smirnov (JINR Dubna, Russia); W. Ninaus (Technische Universität Graz, Austria).
news from NuPECC

Long Range Plan of NuPECC

NuPECC is preparing a new Long Range Plan of Nuclear Physics in Europe. In this exercise Nuclear Physics is assessed as a unified and coherent science of strongly interacting many-body system enriched by impacts on astrophysics, fundamental interactions, and symmetries as well as applications derived from nuclear physics research. In order to achieve the goal, NuPECC has established six working groups, whose compositions can be found on the NuPECC web page under http://www.nupecc.org.

The draft reports of these working groups will be presented and discussed in the open Town Meeting at GSI on January 30–February 1, 2002. The meeting will also provide a possibility for other contributions and will discuss the priorities and recommendations.

The programme committee of the Town Meeting consists of the NuPECC chairperson and the NuPECC liaison members of the working groups.

J. Äystö  
NuPECC Chairman

calendar

September 12–20  
Web: http://cern.ch/euroschool2002

September 16–24  
Erice, Sicily, Italy. Quarks in Hadrons and Nuclei. Contact: erice2002@uni-tuebingen.de, or amand.faessler@uni-tuebingen.de.

September 17–21  
Warsaw and Krakow, Poland. XXXIII European Cyclotron Progress Meeting. Heavy Ion Laboratory of the Warsaw University and Institute of Nuclear Physics. Contact: conf@slcj.uw.edu.pl.  
Web: http://www.slcj.uw.edu.pl/conf

September 23–27  
Legnaro–Padova, Italy. Nuclear Structure with Large Gamma-Arrays: Status and Perspectives (NS2002). Contact: NS2002 c/o Dr. Barbara Tonello, INFN—Laboratori Nazionali di Legnaro, Via Romea 4, I-35020 Legnaro Padova, Italy. E-mail: NS2002@lnl.infn.it. Tel: +390498068521. Fax: +390498068514.  
Web: http://ns2002.lnl.infn.it

September 30–October 3  
Web: www.atomki.hu/npdc17

September 30–October 4  
Osaka, Japan. 16th International Conference on Particles and Nuclei (PaNic02). Contact: panic02@rcnp.osaka-u.ac.jp.  
Web: http://www.rcnp.osaka-u.ac.jp/~panic02/

October 23–25  
Web: http://ssf.rug.ac.be/kris60

November 12–16  
CAARI 2002: 17th International Conference on the Application of Accelerators in Research and Industry. Contact: Jerome L. Duggan, E-mail: hall@unt.edu. Tel: +940-565-3252.  
Web: http://orgs.unt.edu/CAARI

November  
Web: http://www.vaec.gov.vn/instispun02

2003

January 26–February 2  
Bormio, Italy. XLI International Winter Meeting on Nuclear Physics. Contact: Iori Ileana. E-mail: Ileana.Iori@mi.infn.it.

June 17–21  
Moscow, Russia. VIII International Conference on Nucleus-Nucleus Collisions. Contact: Yu. Ts. Organessian or R. Kalpakchieva, Flerov Laboratory of Nuclear Reactions, JINR, 141980 Dubna, Moscow region, Russia. E-mail: nn2003@lnr.jinr.ru. Tel: 7-09621-62151. Fax: 7-09621-63083.  

March 23–30  
Erice, Sicily, Italy. Symmetries in Nuclear Structure. Contact: Annarosa Spalla, Department of Physics and INFN, Padova. E-mail: spalla@pd.infn.it.