Nuclear Physics News

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Advertising Manager
Maureen M. Williams, P.O. Box 1547,
Surprise, AZ 85378-1547, USA
Tel: + 1 623 544 1698
Fax: + 1 623 544 1699

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Cover illustration: A graduate student from the Nuclear Structure Laboratory at Notre Dame preparing for his run.

Note from the Editor

Dear Reader,

The present number of *Nuclear Physics News International* is the 50th in a series of publications which began in 1990. Therefore, at this milestone it appears appropriate to recall the basic philosophy of this journal, and to summarise some of the facts.

Nuclear Physics News International started out as a European enterprise intended to support the concept of NuPECC, an Expert Committee of the European Science Foundation: to provide information about modern research in nuclear physics, to point out the laboratories or facilities where such research can be done best, and to encourage collaboration of scientists from different laboratories and countries in the use of these facilities.

Nuclear Physics News International is prepared under the guidance of an Editorial Board, with members originally named by NuPECC and the Nuclear Physics Board of the EPS. Starting at the end of 1994, the USA, and early in 1995 also Canada and Japan, joined the venture and started to contribute members to the Editorial Board and also financially.

Today *Nuclear Physics News International* is being sent out free of charge to more than 5000 individuals located in Europe (both NuPECC member countries and others), America (North and South), Asia, and Australia.

In general each volume contains a laboratory portrait as well as feature articles, information about facilities and methods, conference summaries, an editorial about important issues in the field or for our community, and reports on the impact and applications of nuclear physics techniques in neighbouring fields of science.

The goal of the articles is to provide information about modern research, future developments, and the fascination of research in nuclear physics. They address the experts as well as those who are not familiar with a special subject. Consequently, a feature article is a compact but complete version of a review article, which would normally be ten times as long. In this way the material which is being presented can be used for teaching purposes directly or indirectly by providing a list of the most recent and relevant literature.

As a result, *Nuclear Physics News International* provides a modern, up-to-date collection of reports on new physics, the most active laboratories, and about the perspectives of our field, written by some of the best scientists working in our field.

At this point, with number 50 coming out, I would like to use this opportunity to thank all those who have contributed to make *Nuclear Physics News International* a success, i.e., those who have served as members of the Editorial Board, or as Correspondents, as well as those who have contributed to the contents of the 50 issues. They have been cooperative, when preparing an article, tried hard to keep close to the deadline, and created a very high scientific level. This high standard makes laboratory directors work hard to get the opportunity to contribute with a laboratory portrait, and makes many authors proud to write an article for this journal.

We look forward to a vigorous continuation of this fruitful cooperation, and hope that *Nuclear Physics News International* will keep the level it has achieved in its more than twelve years in the future as well.

Gabriele-Elisabeth Körner

A Worry about Nuclear Science in Southeastern Europe

The European Southeast covers a vast territory with a population of more than 120 million. When mentioning the region, to most people it invokes the idea of long beaches and isolated islands, sunny weather, ancient civilizations, and steep high mountains covered with wild forests. But if you mention the Balkans, the name by which the peninsula is known in modern history, people immediately think of wars, quarrels, and balkanized nations. I have done this psychological experiment many times, and it always worked. Situated at one of the world's crossroads, this part of the continent had a turbulent history up to modern times. People here speak a bunch of languages, which belong to several different language groups. They use three alphabets: the Greek, the Latin, and the Cyrillic. Nowhere else in Europe have borders so separated the people—and they still do. Nowadays Greece is a member of the European Community, and the other Balkan countries are at different stages on their way towards joining the Community. However, one should take my experiment seriously. The dilemma of the *Balkans* vs. *Southeastern Europe* has far-reaching consequences and influences many aspects of life here.

These days NuPECC is reviewing the whole of the nuclear science field and a new long-range plan is under way, which will provide the milestones of our science for the next years. I am writing these notes just after a meeting of the Southeast European Nuclear Group in Sofia and while on my way to the nearby Thessaloniki, where the third version of the Balkan school on nuclear physics starts tomorrow. How to contribute to the common European effort was the focus of the Sofia meeting. Six Balkan countries were represented there: Croatia, Greece, Romania, Turkey, Yugoslavia, and Bulgaria. Keeping in mind the dilemma mentioned above, we shared the common concern that the region might be omitted from the coming NuPECC document. The meeting reviewed and revealed the potential of the nuclear physics communities in the different countries. We are involved in many major endeavors in European nuclear science. In recent years, in spite of the borders dividing us, we have created a number of fruitful collaborations between ourselves. In order to move ahead, we have established a network of physics laboratories and user groups (SEENet), which aims to combine the efforts of scientists from the region and to better utilize and improve the existing facilities, as well as to train the next generations of young researchers.

Nuclear science, in all its aspects, is an important issue in the region. For example, Bulgaria and Romania run nuclear power plants, and the share of nuclear energy in Bulgaria is exceeding 40%. The support and the preservation of the scientific schools and the education of nuclear physicists and engineers are clearly of vital importance for the development of the nuclear sector in the region. On the other hand, due to the economic problems of the countries in a pre-accession phase, our nuclear physics communities have serious problems: continuous brain drain and aging of academia, underpayment of the scientific personnel, and outdated research infrastructure. We are doing our best to overcome all these problems, but we need the support of the international scientific community. The existing research installations need to be supported on a European level. A good step in this direction is the Center of Excellence on Nuclear Applications within FP5, which was established by our Romanian colleagues at the National Institute of Physics and Nuclear Engineering in Bucharest. Being the optimist that I am, I believe that other steps in this direction will follow soon, and that southeastern Europe will take its place as part of the common European effort. But I cannot push away the worry that if the support is delayed, it might become too late very soon.

DIMITER BALABANSKI
St. Kliment Ohridski University
Sofia, Bulgaria

Nuclear Physics at Notre Dame

Introduction

The Nuclear Structure Laboratory (NSL) at the University of Notre Dame is one of three U.S. low energy nuclear physics laboratories supported by the National Science Foundation. The research effort of the laboratory is built around three accelerators (JN-VdG, KN-VdG, and an FN-Tandem) and a broad program in low energy nuclear physics. The three accelerators offer a wide range of beam energies providing ideal conditions for nuclear structure and nuclear astrophysics experiments. The FN tandem accelerator operates with a Pelletron charging system up to a terminal voltage of 12 MV. The JN and KN accelerators provide high beam intensities with terminal voltages of up to 1 MV and 4 MV, respectively. At the NSL, we have the capability of producing both stable and unstable beams of various types. Our physics interests span from studies in weak interactions and fundamental symmetries, to nuclear structure, studies of nuclear reactions with radioactive ion beams (RIBs), and nuclear astrophysics. In weak interactions and fundamental symmetries, our main interest has been focused on searches for nonscalar currents by measuring $e^+ - \nu$ correlations. In nuclear structure, the emphasis has been on the study of collective modes in nuclei from the compressional mode giant resonances to novel modes of quantal rotation, and the study of low-lying collective modes in nuclei.

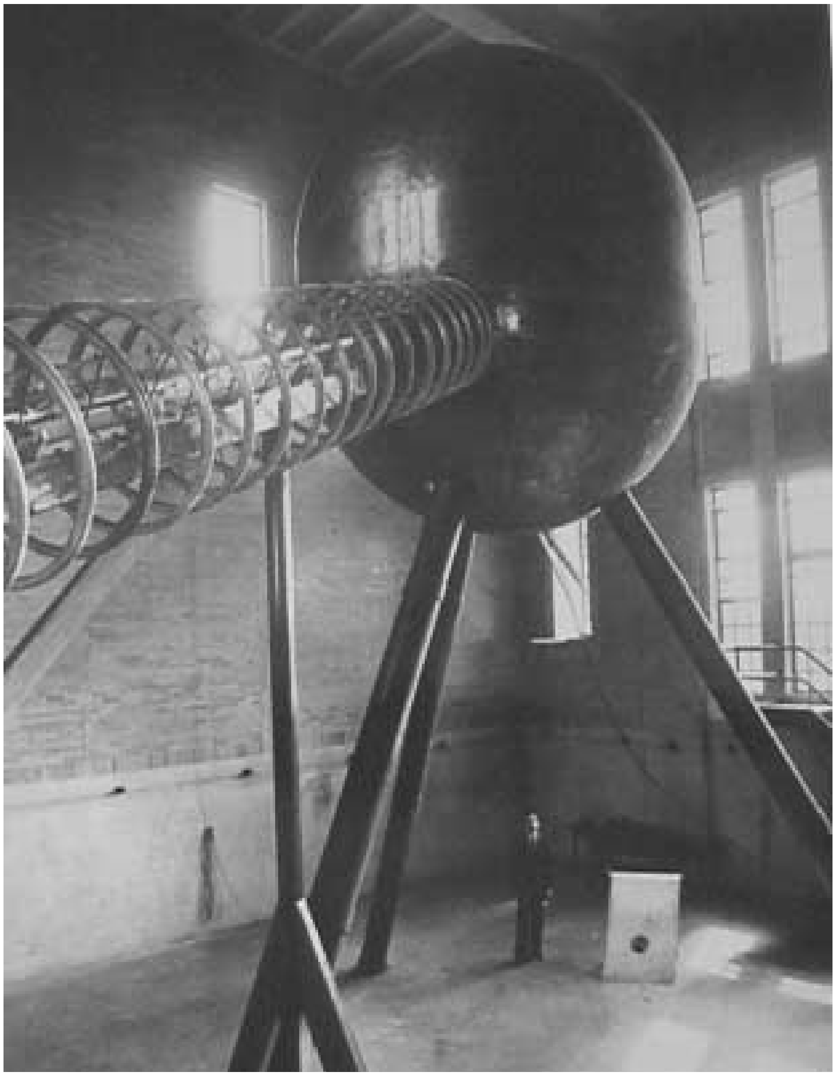
The compressional mode resonances, particularly the isoscalar giant dipole resonance, allow a direct measurement of the nuclear incompressibility coefficient. Low-lying vibrational modes give a precise analysis of the contributions of collective excitations, quasi-particles, and single-particle excited states. A significant component of the experimental nuclear structure program at the NSL is now dedicated to spectroscopy following reactions with RIBs. Complementary to the experimental program, we also have a strong nuclear theory program in structure led by Stefan Frauendorf and several visiting scientists. The focus of this research is the structure of nuclei at extreme spin, isospin, and mass with an emphasis on developing new concepts for these nuclei as they become available for measurement in our laboratory and elsewhere. In nuclear astrophysics, we are interested in issues related to slow nucleosynthesis in late stellar burning scenarios and rapid nucleosynthesis processes at explosive stellar conditions. The experimental program is complemented by a broad theoretical effort aimed at nuclear structure, stellar reaction and decay rate predictions, coupled with extensive nucleosynthesis simulations.

In addition to our basic science interests, we have an interdisciplinary program in radiation chemistry, in biomechanics, materials testing, and a newly developing program in collaboration with the university Art Museum using PIXE for element analysis in archeological samples. Our radiation chemistry program revolves around studies of the effects of ionizing radiation on the molecular decomposition of water and various organic materials, including polymers. The practical aspect of this type of work has direct implications to the management of nuclear reactors, and treatment or storage of radioactive waste media. This work is carried out in collaboration with the Dept. of Energy funded Radiation Laboratory, which is also located at Notre Dame and an outgrowth of the Manhattan project. We pursue research with two industries. This work involves testing new detectors as well as artificial human body components for durability.

Our laboratory has a large number of users from some 14 U.S. facilities inclusive of National Laboratories and Universities, 11 foreign countries, and 2 industries. In turn, members of the Nuclear Structure Laboratory are active users of various international facilities and therefore pursue a range of programs utilizing other laboratories around the world in addition to the local facility. Some of these facilities include the NSCL at MSU, ORNL, ANL, LBNL, Yale Univ., NIST, the n-TOF facility at CERN, ILL in Grenoble, France, GANIL, GSI in Germany, Legnaro in Italy, Tech. Univ. of Munich, RIKEN in Japan, Louvain la Neuve, KVI in Groningen, RCNP in Osaka, and the Tata Institute of Fundamental Research in India.

The Laboratory Then . . .

The first accelerator at Notre Dame (see the photo on next page) was built in 1935, an undertaking that was inspired by a visit to the University of Notre Dame by Edgerton (the "E") of EG&G on his way back to MIT. The Notre Dame engineering college and the physics department together managed to get a grant for $900 from the university to build the first accelerator without



The first accelerator at Notre Dame.

blueprints! The terminal had two hemispherical sections that were 12 feet (4 m) in diameter joined by a vertical cylindrical section that was only 18 inches (46 cm) tall. The legs were made of insulating tubing called Herkolite. The original belt was 70 feet (approx. 23 m) long and 3 feet (1 m) wide and it was made of paper. Construction was completed in May 1935 and testing began in August of the same year with the production of sparks, some of which were up to 19 feet (6 m) long. Rough measurements of the terminal potentials indicated 1.25 MV negative and 2.25 MV positive. First beams were available in October 1936 and the accelerator ran until 1942. The second accelerator was also funded by the university and this time it was a horizontal pressurized machine that was used to help Fermi's efforts at the University of Chicago by irradiating fissile materials to test for degradation by radiation. These two accelerators became a part of the Manhattan project and the progenitors of both the Nuclear Structure Laboratory (NSL) and the Radiation Laboratory located at the University of Notre Dame. The NSL is a part of the university and it has been continuously funded for over fifty years. Presently, funding is provided by the National Science Foundation, while the Radiation Laboratory is a national laboratory funded by the Department of Energy.

The Laboratory Now . . .

The scientific program of the NSL at Notre Dame has blossomed into studies of weak interactions and fundamental symmetries, nuclear structure, reactions with radioactive ion beams, and nuclear astrophysics. In the following sections we highlight some of our recent work.

Weak Interactions and Fundamental Symmetries

A small but intense program has developed in the study of fundamental symmetries using the nucleus as a laboratory. An example is the beta decay of ^{32}Ar where we have interesting opportunities in understanding significant issues in nuclear beta decay and about the weak interaction in general. Because ^{32}Ar is a $J^{\pi} = 0^{+}$ nucleus, its super-allowed decay is purely determined by the vector current. This allows us to use the measurement of the $\varepsilon^{+} - \nu$ correlation to search for potential scalar contributions to the weak interactions (such as produced by hypothesized charged Higgs or Leptoquarks). In addition, measuring the absolute branch, half-life, and endpoint would determine the Cabbibo angle which can be used to better understand the apparent nonunitarity of the CKM matrix. According to the standard electroweak model (SM), only vector currents contribute to the charged weak currents. Extensions to the SM, such as super-symmetric theories with more than one charged Higgs doublet or Leptoquarks, naturally predict scalar currents 1. In the absence of scalar currents the $\varepsilon^+ - \nu$ correlation coefficient, a, should equal +1. We performed an experiment to search for scalar contributions to the weak interaction via the determination of the $\varepsilon^+ - \nu$ angular correlation in the $(0^+ \rightarrow 0^+)$ β decay of ^{32}Ar. One can observe the effects of the $\varepsilon^+ - \nu$ correlation in the "energy Doppler broadening" of the proton which is emitted after the β decay. Two critical challenges for this kind of experiments are: the proton-β^+ summing, which distorts the shape of the proton peak and the optimization of the energy resolution of the proton counter. We eliminated the first obstacle by submerging our detection system in a 3.5 Tesla field. The ^{32}Ar beam from Isolde was stopped in an approximately 23 μg/cm^2 C foil. Our proton detectors were located at 90 degrees with respect to the beam and at about 1.5 cm from the beam spot. Using cooled PIN diode proton detectors we obtained an energy resolution of 4.5 keV.

Our data [1, 2] allowed us to determine the $\varepsilon^+ - \nu$ correlation coefficient with unprecedented precision. Our result was consistent with the standard model prediction.

Nuclear Structure

There is close cooperation between experiment and theory. Experimental studies in nuclear structure include a wide range of experiments addressing studies of collective excitations in nuclei, including lifetime measurements, γ-ray spectroscopy, transfer reactions, and measurements of nuclear masses.

There is close cooperation between the experiment and theory, which focuses on the structure of nuclei of extreme spin, isospin, and mass. We try to develop new concepts for these virgin regions, which are being explored by the experimental groups at our laboratory and elsewhere. The subjects studied with most emphasis at present are: new forms of nuclear rotation, the influence of spin, isospin, and magnetic field on the pair-correlations, and the shell structure of very heavy and rapidly rotating nuclei.

We have recently suggested that in contrast to molecules a nucleus may uniformly rotate about an axis, which is tilted with respect to the principal axes of its density distribution. This surprising phenomenon is described by means of the tilted axis cranking model. The development of this mean-field approach is a major concern of our theory group. As one result, *magnetic rotation* was recently discovered in a concerted effort of theory and experiment. Figure 1 illustrates this new rotational mode. The nucleus is nearly spherical, but it is well oriented and develops a rotational band, because of the cross-arrangement of the two nucleonic currents loops. According to the traditional nuclear theory, rotational bands appear only in well deformed nuclei. The current loops generate a rotating magnetic dipole, which generates strong magnetic γ-transitions. Meanwhile, magnetic rotation has been confirmed in many of the predicted mass regions. *Antimagnetic rotation* is a related phenomenon, for which the magnetic dipoles of the current loops compensate each other. Prof. Garg and his students have found a first good example (^{100}Pd). Together with other groups, they use the GAMMASPHERE and EUROBALL detector arrays in order to establish the rotational mode firmly. We have recently discovered that rotating triaxial nuclei may break the chiral symmetry as illustrated in Figure 2. First experimental evidence for *chiral rotation* has been found by means of the large γ-ray detector arrays in Europe and the U.S. Our group takes a leading role in the experimental investigation of this new structure. Thorough theoretical studies of all new rotational modes are carried out in collaboration with the Research Center of Rossendorf in Germany.

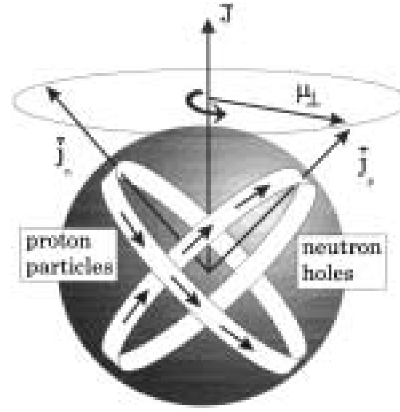


Figure 1. *Magnetic rotation of a near-spherical nucleus. Proton particles and neutron holes on the circular orbits generate a long magnetic dipole, which rotates about the angular momentum vector $\vec{J}$.*

The roles of the isospin symmetry and the proton-neutron pair correlations are an important motivation for exploring the region of the heaviest $N \approx Z$ nuclei. We study their consequences for the rotational spectra by means of a generalized version of the cranked relativistic mean field approach, which includes the isospin conservation. Applying this theory to the most recent experiments seems to indicate a dominance of the isovector proton-neu-

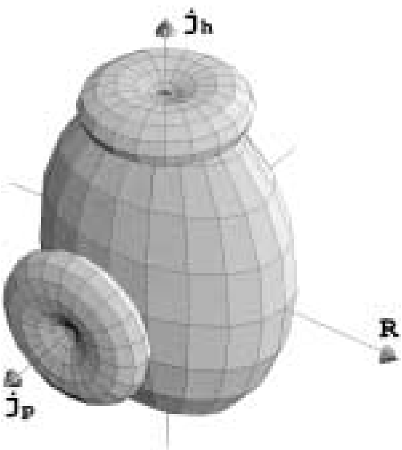


Figure 2. *Chiral composition of angular momentum in a triaxial nucleus. The orientation of the proton particles (jp) and neutron holes (jh) corresponds, respectively, to maximal attraction and repulsion of the triaxial core, which carries angular momentum (R) along the intermediate axis. The three components of angular momentum form a right-handed (shown) and a left-handed (exchange the direction of R) system, which give rise to a doublet of rotational bands.*

tron pair correlations. In collaboration with ANL, the structure of the heaviest nuclei with masses above 250 is calculated and compared with experiment. The aim is to study the reliability of the relativistic mean field theory for the heaviest nuclei, which, hopefully, will result in more reliable predictions of the stability and structure of superheavy nuclei. The transition from the paired to the unpaired state, triggered by rapid rotation, is an analog to the same transition in small superconducting metal clusters caused by an external magnetic field. In both cases, the fluctuations of the pair-field dominate the transition. We study their consequences for the transition in both the nuclear and non-nuclear systems. The study of persistent currents in the normal state reveals far-reaching analogies between rapidly rotating nuclei and metallic clusters in a strong magnetic field. Since the possible experiments are often complementary, both nuclear and solid state physics should benefit.

We study multi-phonon vibrational excitations by means of a novel theoretical approach, the projected shell model. The properties (lifetime and energies) of such excitations have been measured by our group here at Notre Dame.

From Nuclear Matter . . .

The isoscalar giant dipole resonance (ISGDR) is an exotic oscillation and can be thought of as a hydrodynamic density oscillation in which the volume of the nucleus remains constant and a compressional wave traverses back and forth through the nucleus. The mode has generally been referred to as the "squeezing mode" in analogy with the mnemonic "breathing mode" for the giant monopole resonance (GMR). The energy of this resonance is related to the nuclear incompressibilty coefficient K via a scaling relation.

We have undertaken a detailed investigation of this resonance using inelastic scattering of 400 MeV α's at forward angles, including 0°. The experiments are being carried out at the Research Center for Nuclear Physics (RCNP), Osaka University.

The extraction of a value for the nuclear incompressibility using simultaneously the excitation energies of the two compressional modes, the GMR and ISGDR, had been problematic until now. Our new results have now solved this problem and lead to a value of 220 MeV for the incompressibility coefficient, K. This is consistent with the observed properties of both compressional modes in ^{208}Pb.

. . . to Nuclear Vibrations

The nature of low-lying vibrational excitations in deformed nuclei remains enigmatic. Traditionally the first excited $K^{\pi} = 0^+$ bands along with the $K^{\pi} = 2^+$ bands were labeled as single-phonon β, γ vibrational excitations. The $K^{\pi} = 2^+$ excitations are well understood theoretically and shown to vary smoothly in collectivity across a given isotopic but the nature of $K^{\pi} = 0^+$ excitations is still not understood, thus the focus of a flurry of activity from both theoretical and experimental sides. Data on $K^{\pi} = 0^+$ bands have traditionally been relatively sparse. However, we have studied a large number of nuclei using the GRID technique, transfer reactions, and g-ray spectroscopy in order to evaluate the nature of several $K^{\pi} = 0^+$ bands that were previously inaccessible. A new high-precision (p,t) study of the ^{158}Gd nucleus was carried out with the Q3D spectrometer at the University of Munich. The result is the observation for the first time of a deformed nucleus with thirteen excited 0^+ states below an excitation energy of approximately 3.1 MeV [3]. Seven of these states are observed for the first time, and an additional three are new confirmations of previous tentative assignments. This abundance of 0^+ states was unexpected and presently not understood. We present ^{158}Gd as a unique laboratory for further investigations on the nature of $K^{\pi} = 0^+$ bands in nuclei.

A measurement of lifetimes in ^{178}Hf [4] reveals, for the first time, the existence of two excited $K^{\pi} = 0^+$ bands connected by strongly collective transitions. We show that the 2^+ and 4^+ members of the fifth excited

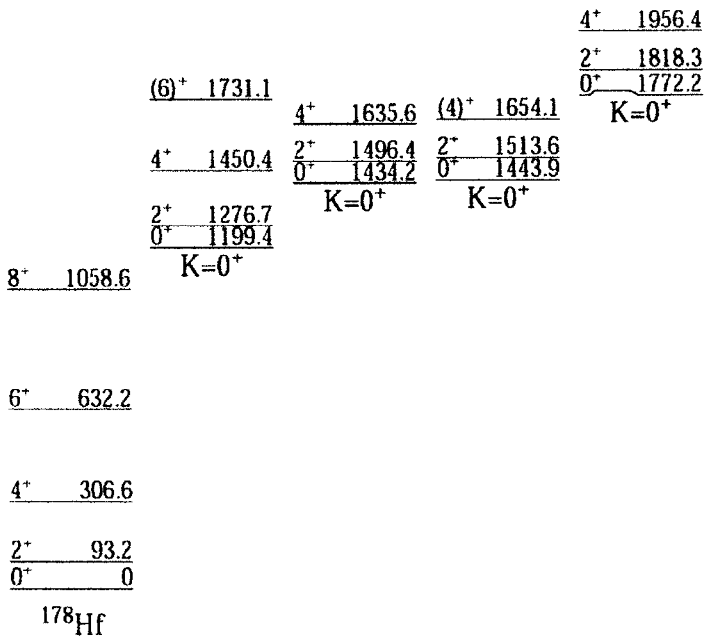


Figure 3. *A partial-level scheme of ^{178}Hf showing all the known $K^{\pi} = 0^{+}$ bands.*

$K^{\pi} = 0^{+}$ band at 1772.2 keV show a strong preference of decay to the first excited $K^{\pi} = 0^{+}$ band at 1199.4 keV. Figure 3 shows a schematic level scheme with the enhanced transitions. The collectivity of these transitions cannot be reproduced by bandmixing. All evidence points to the band at 1772.2 keV as a collective excitation built on the first $K^{\pi} = 0^{+}$ band at 1199.4 keV. If the controversy related to the nature of "b" vibrations could be resolved, the $K^{\pi} = 0^{+}$ band at 1772.2 keV would be the strongest candidate to date for the first observation of a two-phonon bb vibrational excitation.

Reactions with RIBs

One of our unique capabilities at the NSL is the ability to produce a number of exotic beams using the TwinSol spectrometer. TwinSol is an upgraded version of a radioactive ion beam facility that has been operational at the University of Notre Dame since early in 1987. A schematic diagram of TwinSol is shown in Figure 4. These dual 6-T.m superconducting magnets with low liquid He loss cryostats were a joint project between the University of Notre Dame and F. Becchetti at the University of Michigan. Some of the major successes of the facility include studies of sub-barrier fusion of the exotic and weakly bound ^{6}He nucleus [5]. New developments include an extension of the facility to enable γ-ray spectroscopy measurements following reactions with exotic beams.

From Sub-Coulomb Breakup . . .

The ^{8}B nucleus is very weakly bound against proton decay, making it an ideal candidate for a proton halo nucleus. The motivation for our study was an attempt to measure the E2 breakup of ^{8}B in a model-independent fashion using Coulomb excitation below the barrier. Our results [6] showed the important effects that the exotic proton halo structure of ^{8}B has on the breakup reaction near the Coulomb barrier and thereby provided convincing evidence that ^{8}B is indeed a proton-halo system.

. . . to Sub-Barrier Fusion

One of the earliest experiments at TwinSol resulted in the discovery of a very strong enhancement of sub-barrier fusion for an exotic, neutron-halo nucleus. The effect showed an astonishing 25% decrease in the

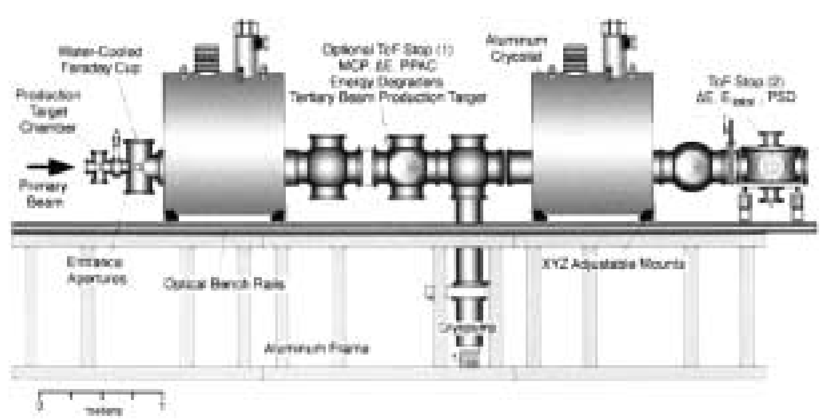


Figure 4. A schematic of TwinSol at the Nuclear Structure Laboratory.

fusion barrier for the $^{6}He+^{208}Bi$ system [5].

Neutron transfer and breakup modes were investigated for the same system at energies well below the barrier [7]. The transfer/breakup yield was shown to be 200mb at 6MeV below the barrier. This very large cross-section was later shown to be consistent with the total reaction cross-section deduced from a simultaneously measured elastic scattering angular distribution.

. . . to γ-Ray Spectroscopy with RIBs

There is a tremendous worldwide effort underway in trying to develop and use RIBs in γ-ray spectroscopy measurements. The exotic beams are several magnitudes lower in intensity than stable beams, making it imperative that radioactivity background is at a minimum and the reaction channel can be identified cleanly. We have shown [8] in one case that such a measurement can be made following a fusion evaporation reaction with a ^{6}He beam. For the reaction $^{63}Cu(^{6}He,p2n)^{66}Zn$, we showed that several side bands as well as a new non-yrast state were populated. The important consequence is the demonstration that side bands can be populated and therefore studied by RIBs, opening the door to further studies with ^{6}He.

Nuclear Astrophysics

Experimental and theoretical nuclear astrophysics represents one of the major research directions pursued by members of the nuclear structure laboratory. The theoretical work concentrates on nuclear structure and reaction aspects that are important for a reliable microscopic description of nucleosynthesis processes. The work focuses on reactions and reaction sequences which are of relevance for the understanding and interpretation of nuclear burning phases during stellar evolution and stellar explosion scenarios. The theoretical work has focused mainly on the theoretical description of far off stability nucleosynthesis processes like the r-process in supernovae or the rp-process in cataclysmic binary stars [9]. Recently, however, more attention has been given to processes closer to stability, like the s-process and s-process-related charged particle interactions during late stellar evolution and the p-processes associated with the supernova shock front. Considerable effort also goes into the theoretical calculation of nuclear reaction rates inaccessible to experiment using the nuclear shell model, nuclear cluster model, and statistical model techniques [10].

Large scale network calculations have been developed and are applied to simulate stellar burning processes and to derive reliable predictions for reaction path, timescale, energy generation, and nucleosynthesis products. This is often done in close collaboration with theory groups at the University of Basel, the University of Torino, Monash University, and the University of California at Santa Cruz. The goal of these network simulations is, however, not only to derive improved models and predictions for the nuclear astrophysics community but also to identify the key nuclear reaction processes that have a characteristic impact on the nucleosynthesis event. These key reactions determine the timescale for energy release, open new reaction branches, or trigger rapid changes in abundances. They therefore provide specific observables for the astronomy community. While the network simulations are based on up to thousands of mostly theoretically calculated reaction rates, these key processes need to be checked and tested experimentally. The laboratory study of such key reactions is one of the major goals for the experimental program of the nuclear astrophysics group at Notre Dame.

From Stellar Reactions Near Stability with Direct Capture Studies . . .

The experimental program at the laboratory itself focuses on the use of two high intensity low energy single ended Van de Graaff accelerators for the direct measurement of nuclear reaction cross-sections close to the characteristic Gamow range of stellar energy. These low energy experiments include a broad range of measurements of reactions for stellar hydrogen and stellar helium burning. Complementary reaction or nuclear structure studies are performed at the FN tandem accelerator.

Studies of processes in stellar hydrogen burning presently focus on reactions in the CNO cycle and the NeNa cycle which are important for the understanding of hydrogen shell burning during late stellar evolution and explosive hydrogen burning in novae. These measurements take advantage of newly developed detection techniques coupling an array of eight BaF_2 detectors with a high-efficiency Ge detector to uniquely identify reaction events and reject beam induced background with high efficiency. Figure 5 shows the detailed study of the excitation range between 450 and 850 keV in search of a broad resonance in $^{19}F(p,\gamma)$ around 500 keV despite the high background rate from the competing $^{19}F(p,\alpha-\gamma)$ reaction.

In recent years the experimental efforts focused more on the study of critical reactions for stellar helium

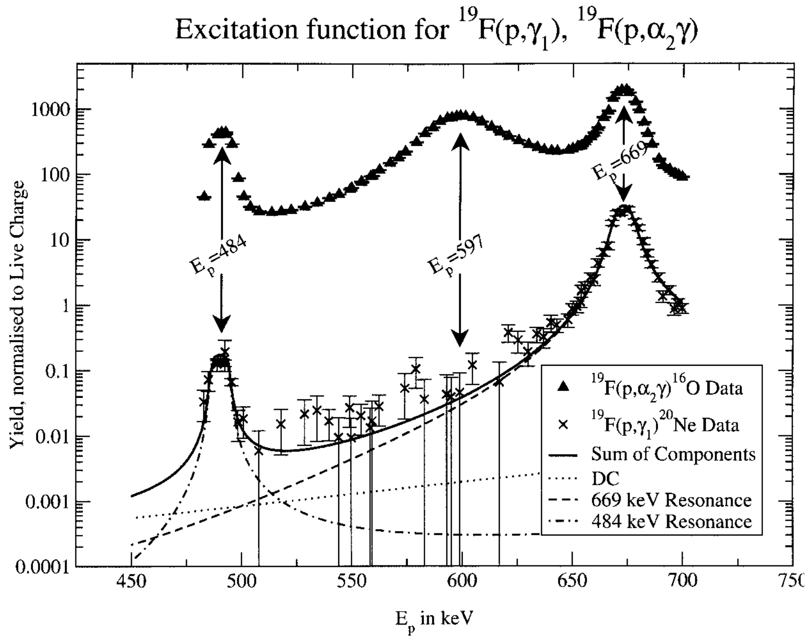


Figure 5. *Excitation curves for $^{19}F(p,\gamma)$ and $^{19}F(p,\alpha-\gamma)$ measured for the beam energy range between 0.45 and 0.7 MeV. The resonant and direct capture contribution to the $^{19}F(p,\gamma)^{20}Ne$ reaction channel have been calculated and are shown in comparison with the experimental data.*

burning. An important component of He burning is the release of neutrons which produce, by subsequent slow neutron capture processes (s-process), heavy elements up to the Pb Bi range. Particular attention has been given to the measurement of reactions related to s-process neutron sources such as $^{13}C(\alpha,n)$, $^{14}N(\alpha,\gamma)$ [11], $^{18}O(\alpha,\gamma)$, and $^{22}Ne(\alpha,n)$. These measurements have been successful in identifing a series of strong low energy resonances which dominate the reaction rates. This work is pursued in close collaboration with the Forschungszentrum Karlsruhe in Germany. The experimental program for a detailed investigation of s-process neutron sources is in close correspondence with the experimental program in s-process studies at the Forschungszentrum Karlsruhe and the n-ToF neutron spallation source at CERN, Geneva, which presently concentrates on the measurement of neutron capture on lead isotopes to identify the endpoint of the s-process and to answer the question on the origin of lead in our universe.

. . . to Indirect Probes of Reaction Rates near Stability . . .

The measurement of low energy alpha capture reactions is severely handicapped by the low reaction cross-sections. Therefore complementary experimental techniques have been developed at the FN tandem accelerator for studying the nuclear structure near the alpha threshold. This is done either by transfer reaction techniques for selectively populating unbound states near the particle threshold to determine their resonance strengths or through elastic scattering measurements over a wide energy range. The alpha transfer studies seek to identify alpha cluster structure phenomena near the particle thresholds in alpha capture compound nuclei which may dominate the reaction rates. A new detector array is presently being developed in collaboration with the University of York. The elastic scattering experiments on the other hand are designed to determine low energy phase shift and interference effects between broad resonances. Figure 2 shows the elastic scattering cross-section for $^{12}C(\alpha,\alpha)$; its R-matrix analysis led to a reliable extrapolation of the $^{12}C(\alpha,\gamma)$ cross-section towards lower energies and succeeded in further reducing the uncertainties in its reaction rate [12]. Independent sub-Coulomb $^{12}C(^{6}Li,d)$ studies at the FN tandem confirmed these results [13].

Considerable uncertainties are associated with the understanding of the p-process which is responsible for the production of neutron deficient stable nuclei above Z = 40 by photo-dissociation processes in the supernova shock front. A recent experimental goal has therefore been the measurement of proton and alpha capture processes related to the p-process gamma induced reactions. This program was initiated by an external group from Ohio State but recently has been broadened to include participants from Turkey, Germany, Hungary, and the UK. The main goal is presently the systematic study of alpha capture on even-even nuclei in the Z,N = 50 closed shell realm to identify the endpoint of the p-process and to investigate the origin of the light p-nuclei. These measurements are performed at the FN Tandem but will be extended towards lower energies using the single ended accelerators as well.

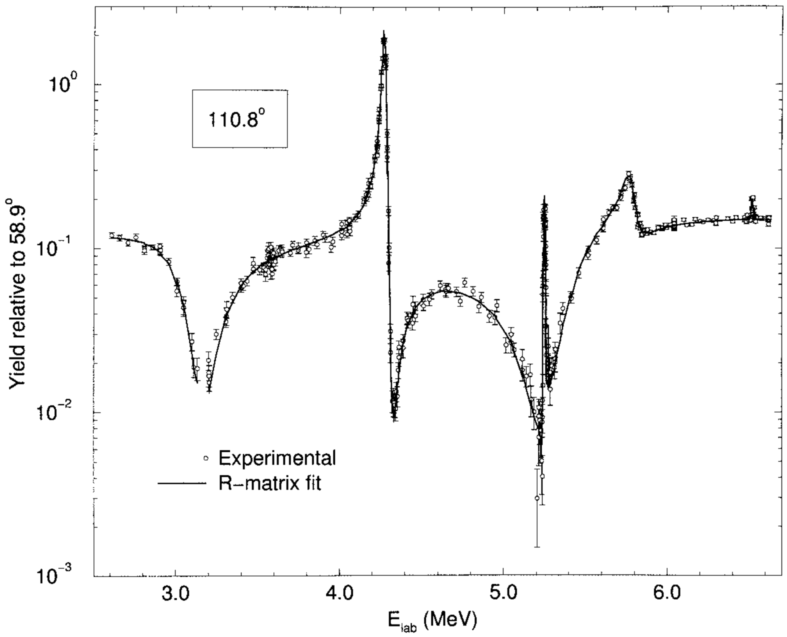


Figure 6. *Excitation curve for $^{12}C(\alpha,\alpha)$ for the energy range between 2.8 and 6.5 MeV at an angle of 110°. The data were fit with a single channel R-matrix code to determine resonant and direct capture parameters for the $^{12}C(\alpha,\gamma)$ reaction channel.*

. . . towards the Particle Drip-Lines

The understanding of nuclear processes in cataclysmic binary star explosions has been a focus of the Notre Dame astrophysics program. The two alpha-capture reactions $^{15}O(\alpha,\gamma)$ and $^{18}Ne(\alpha,p)$ have been identified as the key-processes triggering the break-out from the hot CNO cycles and the subsequent rp-process in explosive hydrogen burning scenarios [14]. The reaction rate for $^{15}O(\alpha,\gamma)$ is dominated by the contribution of a single resonance. The resonance strength is determined by the alpha particle width of the 4.033 MeV $3/2^+$ state in the compound nucleus ^{19}Ne. Utilizing the TwinSol facility as large solid angle momentum filter, the $^{19}F(^3He,t)$ is used to populate the 4.033 MeV level in ^{19}Ne and both the gamma and the alpha decay are measured in coincidence with the tritons at the TwinSol focal plane. First successful experiments lead to a direct measurement of the lifetime for the state using the Doppler shift attenuation method.

While the $^{15}O(\alpha,\gamma)$ reaction rate is determined by a single resonance, the rate for $^{18}Ne(\alpha,p)$ is characterized by the contributions of several unbound states in ^{22}Mg. The Notre Dame group participates in a series of indirect measurements at the RCNP at Osaka University where the level structure of ^{22}Mg is investigated by $^{24}Mg(^4He,^6He)$ reaction studies which selectively populates natural parity levels expected as resonances in the $^{18}Ne + \alpha$ reaction channel. Parallel to these indirect studies the group also collaborates on direct measurement of low energy $^{18}Ne(\alpha,p)$ resonances at the Louvain la Neuve radioactive beam facility. The latter is part of a long collaboration between Notre Dame, the Universities of Edinburgh and York, and Louvain la Neuve to investigate critical reactions of the hot CNO cycles.

In a joint effort between the nuclear structure and the nuclear astrophysics group we have investigated the influence of nuclear mass, decay times, and more recently the impact of long-lived isomeric states on the rp-process nucleosynthesis in the mass range A = 40 to 80. In previous years the structures of ^{80}Y, ^{80}Sr, ^{84}Nb, and ^{84}Zr have been measured at the Argonne FMA facility. Several isomeric states have been identified. A subsequent experiment at the HRIBF facility at Oak Ridge determined the lifetime of ^{80}Zr [15]. A lifetime measurement of ^{84}Mo also has been successfully completed. Of particular importance for the time-scale of rp-process nucleosynthesis is the possibility of two-proton capture reactions on ^{68}Se and ^{72}Kr [1]. The rate depends critically on the mass and also possibly on the existence of isomeric states in these even-even isotopes. Recent experimental studies at the Argonne FMA separator lead to an improved measurement of the ^{68}Se mass and to the identification of a long-lived isomer, which could change the nucleosynthesis in this mass range drastically.

The nuclear astrophysics group at Notre Dame has recently been approved as lead institution for the NSF Physics Frontier Center JINA, the Joint Institute for Nuclear Astrophysics. JINA includes nuclear and astrophysics groups at the University of Chicago, Michigan State University, and associated institutions such as Argonne National Laboratory, the SciDAC Supernova Center (SSC) at UC Santa Cruz, and the Institute for Theoretical Physics at UC Santa Barbara. The goal of JINA is to foster intense interdisciplinary collaborations between nuclear physicists, observers, and theoretical astrophysicists. The funding of JINA will not only allow considerable extension of the theoretical program but it will also lead to significant improvement of the experimental opportunities through the collaborative development of new experimental equipment and techniques. It also will open new windows of opportunity for studying nuclei on the r-process and the rp-process path using the radioactive beams at the coupled cyclotron facility of the NSCL at Michigan State University.

Conclusion

We have summarized some of our present scientific interests and future directions. Our research program, similar to many places around the world, is rapidly evolving and very dynamic, hence our evolution towards all aspects of nuclear matter, nuclear structure, and reactions that affect various nucleosynthesis scenarios in nuclear astrophysics and our growing interest in some aspects of the interdisciplinary research that takes place in our laboratory. One constant goal for us here at the NSL, however, is the education of a diverse, enthusiastic student body as the most important part of our mission. Presently, there are 14 graduate students in the laboratory enrolled in our Ph.D. program in Nuclear Physics. We also have an additional 15 undergraduate students that participate in various research, design, and development projects in the laboratory. We owe a great deal of our success to their dedication and enthusiasm. We make special efforts to recruit under-represented minorities in physics. We also work closely with our local high schools in bringing high school students and teachers to the nuclear laboratory for research every summer.

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ANI APRAHAMIAN
MICHAEL WIESCHER
University of Notre Dame

Report on EMIS-14

In order to study the properties of exotic nuclei, they generally have to be separated from the much more abundant "background" of other nuclei. The most common method of reaching this goal is electromagnetic isotope separation, which today is a mature research tool with plenty of new developments. The latter claim has been impressively confirmed at the 14th International Conference on Electromagnetic Isotope Separators and Techniques Related to Their Applications (EMIS-14), held in Victoria, British Columbia, Canada, from 6 to 10 May, 2002. The term "mature" seems appropriate as the corresponding conference series dates back to the sixties, and as the isotope separation on-line (ISOL) method just celebrated its 50-year anniversary (*Nuclear Physics News,* Vol. 11 (2002), No. 4, p. 31). Under "new developments" one may cite that experiments with radioactive ion beams, leaning heavily on various forms of electromagnetic isotope separation, are in the focus of today's nuclear physics research, and indeed form the basis of a number of major future research facilities as well as of various lines of application. The EMIS conferences mainly deal with experimental techniques rather than the corresponding scientific results. Hence, this selection criterion was also used in this report. As has become evident at EMIS-14, this field attracts a remarkably large number of young researchers. In order to underline the latter aspect, the names of speakers given in this report are restricted to those who are in, or even well below, their early forties.

In principle, radioactive ion beams have been available since the early days of heavy-ion research, and it is not really a recent development to use a magnetic spectrometer for producing a radioactive beam of reaction products. Such *recoil separators* exploit the energy and ionic-charge distribution of reaction residues as determined by the reaction dynamics. In the case of fusion-evaporation reactions, the specific energy of the primary beam of stable isotopes is of the order of several MeV/u, while that of the radioactive residues is much lower. Today, considerably improved recoil spectrometers are being actively used at many heavy-ion facilities, e.g., at Argonne National Laboratory (USA), CIAE, Beijing, (People's Republic of China), GSI, Darmstadt, (Germany), Nuclear Research Centre, New Dheli (India), JINR, Dubna (Russia), University of Jyväskylä (Finland), HRIBF, Oak Ridge (USA), and Yale University (USA) in studying, for example, proton radioactivity or nuclear properties at high excitation energy and high spin *(J. J. Ressler).*

For specific beam energies in the range from 30 MeV/u to 1 GeV/u, the domain of fragmentation reactions is reached, with the secondary beams of radioactive ions being characterized by keeping approximately the same momentum as that of the projectiles. As one cannot speak of a reaction recoil any longer, the term *in-flight separators* is more appropriate. Both recoil and in-flight separators combine electromagnetic fields with energy-loss and time-of-flight devices, yielding spatial separation between the secondary and the primary beam as well as sufficiently good isotope identification. Further advantages are that nuclear states with half-lives down to the μs range can be reached, and that, in particular for GeV/u primary beams, the energies of the (secondary) radioactive ion beams are high enough to induce nuclear reactions. Such instruments, pioneered at GANIL, Caen (France), in the eighties, now form *the* major research tool at *fragmentation facilities,* including those at GSI, Michigan State University (USA), and RIKEN, Saitama (Japan). One of the highlights of EMIS-14 was the report on first results obtained at the new Coupled Cyclotron Facility of Michigan State University (*Nuclear Physics News,* Vol. 12 (2002), No. 2, p. 5) by using the in-flight separator A1900 and/or the superconducting high-resolution magnetic spectrograph S800 *(D. Bazin).* The S800 has an energy resolution of 10^{-4}, a maximum magnetic rigidity of 4 Tm, and a momentum acceptance of 5%, and indeed offers unique experimental possibilities for research on exotic nuclei.

Contrary to recoil and in-flight separators, the method of *isotope separation on-line (ISOL)* is *not* based on the original energy and ionic-charge distribution but catches the reaction products of interest in a solid material or gas, from where they are released and extracted, after re-ionization, as singly charged ions with specific energies of the order of keV/u. Such ISOL facilities use primary beams of protons, e.g., at the ISOLDE facility at CERN, Geneva (Switzerland), or the ISAC facility at TRIUMF, Vancouver (Canada), or heavy ions, e.g., at GSI, HRIBF, Jyväskylä, and the University of Louvain-la-Neuve (Belgium). The heart of any ISOL facility is the system of target-catcher-ion source. Of particular concern is the high power (density) imposed by the primary beam on target and/or catcher. A 40 μA, 500 MeV beam of protons, corresponding to a power of 20 kW, has already been used at TRIUMF. By converting protons into neutrons, it might be possible to meet the challenge of high power deposition. The corresponding developments were reported at EMIS-14 by groups from CERN, Michigan State University, and IPN, Orsay (France). In addition to standing the power load, the system of target, catcher, and ion source of an ISOL system has to meet the quest of delivering high intensity *and* high isotopic purity for radioactive beams of *short-lived* isotopes. To this end, diffusion and surface-effusion properties of target-catcher materials are studied (U. Köster), and various ionization schemes are being investigated. The latter aspect is pursued, e.g., by laser multi-step excitation, including isomer separation using hyperfine effects (CERN, Leuven), and by methods based on molecular ions such as SnS^+. The latter technique, first introduced at the HRIBF, Oak Ridge, USA *(D. W. Stracener),* has meanwhile been carefully and systematically investigated at GSI. It is now ready to be applied for the study of short-lived isotopes of germanium and tin, offering both high yields for the wanted species and strong suppression of the unwanted isotopes of neighbouring elements.

Another field of intense ISOL development concerns the "manipulation" of keV/u beams. While ISOL studies were traditionally performed by implanting the mass-separated beams into solid catcher material or by performing collinear laser spectroscopy, the situation changed with the advent of *ion or neutral-atom traps.* For example, a Penning trap is used at ISOLDE for precise mass measurements *(K. Blaum),* and a neutral-atom trap is operated at ISAC for fundamental-physics experiments *(J. A. Behr).* While the radioactive ions used to be introduced into the Penning trap by stopping them in a foil and subsequently releasing them by heating the foil, they are now introduced in a more direct (and efficient) way, i.e., by cooling and bunching the beams of interest in additional ion traps. Such devices (non-Liouvillian like the energy-loss parts of in-flight spectrometers mentioned above) make use of ion interactions with gas atoms in a radio-frequency field. Pioneered by developments at CERN *(F. Herfurth),* Jyväskylä *(A. Nieminen)* and Leuven, they are on the way to becoming standard ion-optical parts of ISOL facilities. EMIS-14 has shown that the research involving traps expands rapidly. New projects, initiated at Argonne *(J. Clark),* GSI (G. Sikler), KVI, Groningen (Netherlands), and Michigan State University, aim at introducing ions into the trap after stopping them in gas—a challenging research topic in itself. During parts of EMIS-14, the participants got the impression of attending a meeting of specialized "trappers," which meant that there was insufficient time for discussing other exciting new techniques, such as those related to studies of high-energy radioactive beams in storage rings.

Postacceleration of ISOL beams is required in order to allow one to perform nuclear-reaction studies. The method of accelerating to specific energies of the order of 1 to 10 MeV/u., which was pioneered at Louvain-la-Neuve *(M. Gaelens),* has meanwhile been realized by several projects, namely HRIBF, SPIRAL at GANIL, REX ISOLDE at CERN, and ISAC at TRIUMF. At EMIS-14, reports on the first experiments from all four projects came on the scene, corresponding to a fourfold première:

- At SPIRAL, the neutron-deficient isotopes ^{18}Ne, produced by fragmentation reactions between a ^{20}Ne beam and a carbon target, were accelerated to 7 MeV/u in a cyclotron, the intensity of the extracted ^{18}Ne beam amounting to $2 \cdot 10^6$ ions/s (*Nuclear Physics News,* Vol. 12 (2002), No. 1, p. 29).
- REX ISOLDE involves ISOLDE beams and an entirely new postacceleration scheme, including a Penning trap for accumulating, phase-space cooling, and bunching the singly-charged ions, an electron-beam ion source for "breeding" high charge states *(F. Wenander),* and a linear accelerator including radio-frequency quadrupoles and interdigital-H structures *(O. Kester).* For the neutron-rich isotope ^{26}Na, an intensity of 10^6 ions/s was reached for a 2.3 MeV/u beam.
- The HRIBF, based on a cyclotron for production and a tandem for postacceleration, obtained a 2.6 MeV/u, 10^5 ions/s beam of the neutron-rich isotope ^{134}Te.
- At ISAC, a beam of 0.22 MeV/u, 5×10^8 ions/s of the neutron-deficient isotope ^{21}Na was produced by using TISOL and an accelerator consisting of radio-frequency quadrupoles, stripper and drift-tube linac.

These examples of radioactive beams involve isotopes with half-

EMIS-14 participants in whale-watching outfit, and the object of their desire: a "small but significant event."

lives down to 1.1 s and enable one to perform unprecedented Coulomb-excitation experiments of nuclear-structure interest or low-energy reaction studies of astrophysical interest. Additional beams have already been or are being developed at these facilities. Further projects based on postacceleration of ISOL beams are underway at Lawrence Berkeley National Laboratory, USA, where beams of light radioactive ions are accelerated at the 88″ cyclotron, with the activity being produced at a small cyclotron *(J. Powell),* at KEK, Tanashi (Japan), and at Dubna, Munich (Germany), and Orsay, the latter three facilities being based on fission reactions induced by bremsstrahlung of 50 MeV electrons or neutrons delivered by a reactor or deuteron break-up reactions *(S. Essabaa).*

Most of the experiments performed with radioactive ion beams from ISOL-plus-postacceleration facilities demand additional electromagnetic spectrometers, such as VAMOS at SPIRAL *(H. Savojals)* or DRAGON at ISAC *(S. Engel).* Another general requirement in radioactive-beam experiments are refined radiation detectors. Examples are the germanium arrays for γ-rays detection, in operation or under preparation at CERN, GANIL, GSI, and TRIUMF *(C. Svensson).* The latter array has the particularly attractive feature of including β detectors, which is instrumental when correcting for the β-γ summing effect in precision β-decay measurement. Another new and exciting technique is digital pulse processing *(R. Grzywacz).* It makes use of silicon detectors for investigating charged-particle activities in the MeV range down to half-lives of the order of μs, in spite of the order-of-magnitude higher energies deposited by the implantation of heavy ions in the same detector.

In addition to nuclear physics and astrophysics, there are other sciences and *applications* that profit from the developments described so far. This holds, on the one hand, for accelerator mass spectrometry, which has indeed become an instrument used in many fields of science but may still take cross-disciplinary profit from, among others, ion-source and detector developments. On the other hand, the EMIS-14 floor was also open for reports on the use of ISOL beams for solid-state physics or biomedical research, or on trace analysis by means of ion traps, pursued, e.g., at Argonne *(P. Müller)* and at University of Mainz, Germany.

EMIS-14 also featured presentations of the *major future projects* in radioactive beam research. New facilities based on relativistic fragmentation reactions, in-flight separators, and storage rings are under construction at RIKEN and have been proposed by GSI. The RIA Project (USA) plans to accelerate beams from an ISOL facility as well as those delivered by an in-flight separator. In this context, the above-mentioned studies of high power deposition and extraction of ions stopped in gas are particularly relevant. CERN's plans include a new high-intensity proton accelerator, the use of antiprotons and muons as novel nuclear-structure probes for studying exotic nuclei, and, as a particularly fascinating project, the production of a neutrino beam from the decay of stored radioactive ions *(M. Lindroos).*

EMIS-14 was an important scientific event, for the international community as well as for Canada and the province of British Columbia. This became evident from the fact that the B.C. Minister of Advanced Education, Shirley Bond, opened the conference. It is a must to say a final word on the excellent organization of EMIS-14 by colleagues from Simon Fraser University, Burnaby, Canada, and TRIUMF. They took care of the participants in many ways, and even handed out umbrellas to all of them. Among the social activities, there was a visit to the Royal British Columbia Museum, with the exhibits of early agriculture and settlement being "refined" by string-quartet music and local delicacies. And, last but not least, there was the chance to join a whale-watching tour, and to indeed sight a whale as a "small but significant event," as it was described in the summary talk.

Having spent a most enjoyable week at Victoria, the EMIS-14 participants have meanwhile returned to continuing their work on electromagnetic isotope separation. They are eagerly waiting for the EMIS-14 proceedings to appear as a special volume of *Nuclear Instruments and Methods in Physics Research B,* hoping that they will not suffer from a year(s)-long delay—a frequent shortcoming of today's conference proceedings. This report is just to remind the EMIS-14 participants and their many colleagues that electromagnetic isotope separation is indeed a mature and successful research tool that has plenty of new developments, most of which stem from the invaluable contributions of the about two dozen young researchers mentioned in this report—excellent perspectives for EMIS-15, which will be organized by GANIL in Normandy, France, in 5 or 6 years from now.

E. Roeckl
GSI Darmstadt

International Conference on Nuclear Structure

The International Conference on Nuclear Structure, held in honor of R. F. Casten's 60th birthday, took place from May 22–25, 2002. The conference, subtitled "Mapping the Triangle," attracted 88 participating physicists from many different countries to discuss the present frontiers of nuclear structure physics and the rich opportunities made available with Radioactive Nuclear Beam (RNB) facilities, and to celebrate Professor Casten's many contributions to this dynamic field. The conference site was located among the striking natural beauty of the Grand Teton National Park in Wyoming, USA.

The field of nuclear structure research has experienced a resurgence of growth in recent years with the increasing understanding of the evolution of nuclear structure and the growing wealth of new nuclear structure data. New microscopic and macroscopic techniques for nuclear structure theory have been introduced to the field, while major new detectors, experimental techniques, and RNB facilities have increased the range of data and nuclei available for study. In such a way, researchers are mapping the Casten Triangle and expanding the understanding of the physics responsible for nuclear collective and single-particle motion in the quantum many-body system of the atomic nucleus.

The conference was an opportune time to discuss the current understanding of nuclear structure physics and the frontiers of the field as experimental techniques, theoretical models, and new facilities lead nuclear structure research in bold and exciting new directions.

The conference was structured around the 27 plenary talks that were presented during morning and evening sessions. This allowed ample opportunity during the afternoons for informal physics discussions indoors and exciting excursions outdoors. In general, the topics covered by these speakers during the morning and evening sessions included many of the exciting areas of modern nuclear structure research. These topics included, but were not limited to, dynamic symmetries, shape transitional behavior and critical point symmetries, nuclear structure and its evolution across the nuclear landscape, multi-phonon excitations and other nuclear excitations, nuclear structure with radioactive nuclear beams, and macroscopic and microscopic approaches to nuclear structure. A poster session was included one evening during the conference, which afforded the conference participants the opportunity to investi-

gate an additional 28 presentations on modern nuclear structure research.

A buffet reception was available to the participants on Tuesday evening, May 21, before the start of the scientific program the following day. Lee Riedinger, of the Organizing Committee, greeted and made the welcoming remarks to the participants gathered at Jackson Lodge in the Grand Teton National Forest. Outside, snowfall continued to cover the mountains and National Park with a beautiful blanket of white snow. This snowfall would continue sporadically for most of the conference, slightly obscuring the view of the mountains and glaciers but not in the least inhibiting the collaborative feeling of the conference and the scientific exchange being fostered in the conference lodge.

Although it is not possible to include all of the new research presented by the plenary speakers here, a short synopsis of some of the exciting physics discussed at the conference will be given. A full synopsis of the conference will be found in the conference proceedings, to be published in the AIP Conference Proceedings.

Franco Iachello began the conference with an overview of dynamic symmetries and quantum phase transitions, including the new critical point symmetries E(5) and X(5) associated with shape phase transitions in nuclei. A related talk by Mark Caprio presented recent experimental results and the physical manifestations of critical point nuclei in the Ru, Pd and Nd, Sm, Dy nuclear regions. A presentation of mixed-symmetry states in nuclei, and the observation that high energy collective states survive in deformed nuclei, was given by Norbert Pietralla, while afterwards Alejandro Frank spoke about nuclear supersymmetry and additional dimensions of the Casten Triangle.

Witek Nazarewicz discussed modern nuclear structure theory and the continuum shell model. This is a vital model for a theoretical description of neutron-rich nuclei that are accessible at RNB facilities due to the proximity of the continuum. Till von Egidy discussed how the back-shifted Fermi gas model and the constant temperature model predict nuclear densities equally well, presenting a new view of the Casten Triangle with densities and critical point nuclei.

Peter von Brentano gave a presentation on Q-phonons and Q-invariants and the description they provide for yrast states in the parameter space of the Casten Triangle. Hans Borner discussed the future of the very precise high-resolution γ-ray spectroscopy at ILL, promising that an order of magnitude increase in sensitivity is obtainable from this already impressive facility. Shell model calculations were discussed by Taka Otsuka with a view toward a microscopic realization of IBA O(6) symmetry and the critical point symmetry E(5). A theoretical discussion was included of the recently measured ^{136}Te B(E2) as a mixing of the state with cores of ^{134}Te and ^{134}Sn. Bruce Barrett continued the discussion of shell models with ab initio large-basis no-core shell model calculations and how, for A = 3,4 this approach to calculating nuclear properties replicates other approaches. Nuclear structure research opportunities with RNBs for fragmentation and ISOL facilities and the proposed Rare Isotope Accelerator were presented by Brad Sherrill. Performed and proposed experiments, with RNBs using new and old techniques coupled with modern detector systems, were also discussed by Charles Barton. Kris Heyde gave a discussion of the theory behind nuclear mass calculations applicable to the long isotopic chains becoming accessible with RNB facilities.

Random interactions in the atomic nucleus where emerging regular spectral features are observed in calculations was the subject of the presentation by Roelof Bijker. Piet Van Isacker discussed a fascinating observation that the spectral features of quantal systems can be interpreted geometrically. It was shown that the probability of a state becoming the ground state can be related to the geometry of a hyper polyhedron dependent upon the shell size, particle number, and symmetry character of the state. John Becker discussed atomic-nuclear coupling and difficult-to-perform recent experiments exploring the possibility that an atomic trigger could release the energy of a nuclear isomeric state in a controlled way. A new interpretation of the O(6) dynamic symmetry limit of the IBA was presented by Jan Jolie. This limit is also a critical point of a prolate-oblate phase transition, resulting in a new version of the Casten Triangle.

The additional talks and physics presentations, not mentioned here, added greatly to the experience of the participants in summarizing the current status of research in the field while pointing toward the frontiers for research.

The snowfall, which continued intermittently during the conference, broke on Friday allowing the conference excursion to occur that afternoon. Many participants enjoyed a scenic float trip along the Snake River through the Grand Teton National Park. A second trip, by bus to Yellowstone National Park, was made available to others who may not have had the opportunity to venture further north during their stay. Stops on this bus tour included a viewing of the famous geyser, Old Faithful, and other hot springs. The national parks of Teton and Yellowstone allowed many people the chance to hike, horseback ride, or drive and stop at many vantage points to view the majesty of the mountain ranges, the beauty of the glaciers, geysers and hot springs, and the splendor of wildlife. Animals, from moose and elk, deer and eagles, and beavers and buffalo, were seen, at times up close, by conference participants. The nearby town of Jackson Hole also allowed participants to view aspects of the life and history in the region. Events, such as the annual great shoot-out (Wild West style), fair, and rodeo occurred during the conference weekend.

The banquet, held on Friday night, was a delightful evening of food, dancing, and celebration. After a hearty meal, colleagues, friends, former students, and collaborators honored Professor R. F. Casten on his 60th birthday. Anecdotes, pictures, and gifts filled a heart-felt time of celebrating and thanking Rick Casten for his contributions and support to the people and field of nuclear structure physics. The night continued with dancing and further fun until the early hours of the morning.

The final morning of the scientific program followed before the official end of the conference on Saturday, May 25, 2002. The numerous advances made in the field of nuclear structure research and the exciting future directions of the field were apparent to all participants. The current threshold in opportunities and knowledge made available with RNB facilities and new theoretical and experimental tools will continue to make the field of nuclear structure physics an exciting, dynamic, and evolving field for many years.

The conference certainly owed part of its success to the excellent guidance and planning of the Organizing Committee. The invaluable assistance of the administrative support team also made the conference, its preparation, and the submission of contributions run smoothly.

The conference proceedings of the International Conference on Nuclear Structure will be published as a forthcoming volume of the AIP Conference Proceedings.

C. Barton
CLRC Daresbury Laboratory

Exotic Clustering in Nuclei

B. Buck and A. C. Merchant
Theoretical Physics, Department of Physics, Oxford University, Oxford, UK
S. M. Perez
Department of Physics, University of Cape Town, South Africa

The presence of *light* clusters (^{3}H, ^{3}He, ^{4}He) in *light* nuclei is now well established and widely accepted [1]. The basic idea is that many states can be adequately modelled as a decomposition into two nuclei rotating round each other in their ground states or possibly in low excited levels. There is assumed to be a deep interaction potential acting between the components, while the effects of the Pauli principle are simulated by choosing a relative orbit such that the nucleons in, say, the light cluster are all above the Fermi surface of the core. With a suitably shaped potential, of a form described later, the resulting spectrum of levels breaks up into a series of quasi-rotational bands labelled by a global quantum number $G = 2n + l$, where l is the angular momentum and n is the number of nodes in the radial wave function. These ideas have now been refined and used extensively to construct models involving *heavy* clusters in *heavy* nuclei.

Our work on *light* nucleus clustering culminated in a coupled-channel treatment of ^{16}O [2], which contains many references to our earlier publications dating back to 1975.[1] In retrospect, we now see that the first indications we had that heavy clusters could play an important role in nuclei arose in an investigation of the structure of ^{24}Mg [3]. We found that a model with two ^{12}C nuclei, orbiting each other, and appearing in their ground and low excited states, produced a detailed description of virtually all the T = 0 spectrum and the related decay properties in ^{24}Mg, right up to the ^{12}C + ^{12}C breakup threshold.

Our attention was next directed to the exotic decay of actinide nuclei by Rose and Jones, who had discovered the first known example in 1984 (^{223}Ra $\rightarrow$ ^{209}Pb + ^{14}C) [4]. By 1989 this result had been unambiguously confirmed and emission of ^{14}C also observed from other isotopes of radium. In addition, ^{24}Ne emission from ^{231}Pa, ^{232}U, and ^{233}U was identified. Contrary to prevailing opinion, we took the view that the emitted nuclei were preformed in the parent nuclei and were orbiting a heavy core which in most cases would have to be an isotope of lead [5]. With this hypothesis we were able to use the same methods as for light clusters in light nuclei. We tried both a folded potential and the simpler analytic form

$$V(r) = -V_0[1 + \cosh(R/a)]/[\cosh(r/a) + \cosh(R/a)]$$

and added a Coulomb term arising from a uniformly charged sphere with $R_c = R$. Taking the global quantum number $G = 2n + l \geq 68$ for ^{14}C emission ensured that the cluster nucleons were in orbitals outside the Z = 82 and N = 126 shell closures in the core, though the exact value of G turned out not to be critical. The details of our treatment evolved over time, and we eventually settled on a cosh potential with depth 38.2A MeV, diffuseness a = 0.72fm, G = 5A, and a radius chosen to reproduce the experimental Q-value for a cluster of mass A. Then a semi-classical calculation of the decay process resulted in excellent agreement with the half-lives of all known emissions. We were also able to suggest that decays might take place preferentially to excited states of odd-A daughters [5].

We also calculated the alpha-decay of ^{212}Po by the same procedures and reproduced the observed width with similar accuracy. This led us to undertake further studies on alpha-clustering in heavy nuclei, including the remarkable fits shown in Figure 1 to the well-known Geiger-Nuttall plots and the discovery of their splitting as the neutron number increased through a magic closure [6]. The evolution of our efforts in this direction can be traced from references in our later paper on these topics [7].

Despite the initial successes in accounting for the exotic emission of heavy clusters (and alphas) from heavy

[1] We note that our task here is to present a review, in highly condensed form, of our own contribution to cluster theory in the last decade or so. We therefore make little direct reference to related work, or to other approaches such as mean field theory or the shell model, leaving such reference implicit in our quoted papers.

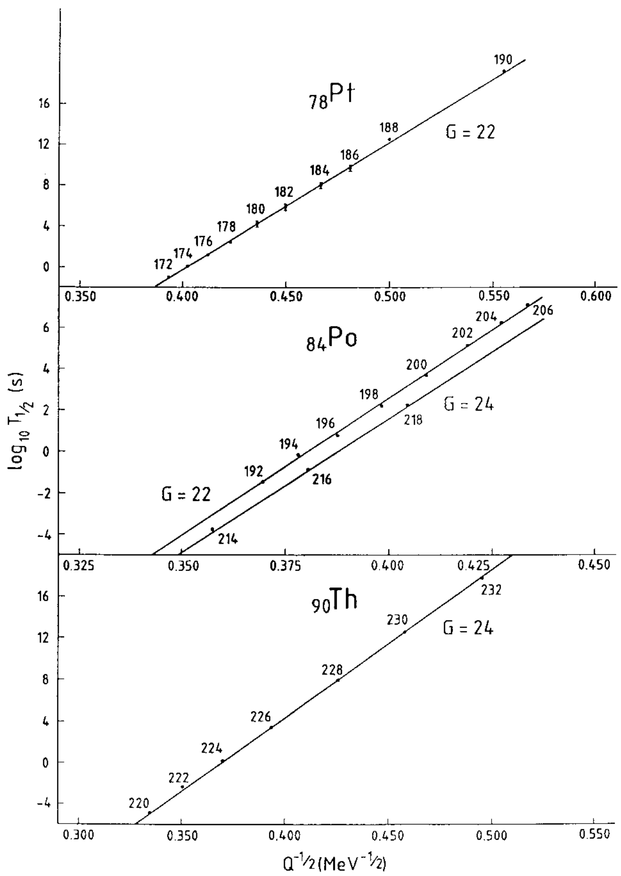

Figure 1. *Semiclassical cluster model fits (solid lines) to alpha decay half lives; from [6].*

nuclei, our potential shapes involving the cosh function did not produce correct band spectra [7]. To repair this defect we eventually proposed a much more satisfactory shape of the form

$$V(r) = -V_0\{xf(r,R,a) + (1 - x)[f(r,R,3a)]^3\},$$

where $f(r,R,a) = 1/\{1 + \exp[(r - R)/a]\}$. This, with fixed values of V_0, a, and x, maintained a good description of alpha elastic scattering potentials for ^{16}O and ^{40}Ca and of alpha decay from many heavy nuclei while simultaneously reproducing observed band spectra and E2 transition rates for the magic core plus alpha nuclei ^{20}Ne, ^{44}Ti, ^{94}Mo, and ^{212}Po [8]. Rather to our surprise, the same form also gave good results for heavy clusters; i.e., we were able to describe, simultaneously, the exotic decay widths and the spectra and electromagnetic properties of the ground state quasi-rotational bands in actinide nuclei [9]. To achieve that we used the alpha-core potential which fitted the properties of low-lying states of ^{212}Po and scaled the potential depths V_0 and global quantum numbers G = 2n + l proportionally to the cluster masses. The parameter R was then fixed in each nucleus by fitting the energy of a selected member of the ground state band. Figure 2 shows the results for the spectra of ^{222}Ra, ^{232}Th, ^{232}U, and ^{236}Pu treated as ^{208}Pb plus ^{14}C, ^{20}O, ^{24}Ne, and ^{28}Mg, respectively.

Shortly after this we realized that a single depth parameter V_0 could be used for *all* cluster calculations if it was scaled by the factor $A_1A_2/(A_1 + A_2 - 1)$, where A_1 and A_2 are the core and cluster mass numbers, respectively, i.e., essentially by the reduced mass of the binary nuclear system. The symmetry between core and cluster is discussed in [10], where it was found convenient to normalize the shape function by its value at r = 0. The only parameter left adjustable was the radius R of the potential, to be determined as specified above. The pleasant result of these modifications was a *universal* potential recipe which not only reproduced our earlier analyses of heavy nuclei exhibiting alpha and exotic clustering, but also gave good approximations for potentials describing the systems ^{4}He + ^{4}He and ^{12}C + ^{12}C.

We next began a systematic study of exotic clustering in actinides, namely the isotopes of Ra, Th, U, Pu, and Cm, using our new potential with depths V_0 and

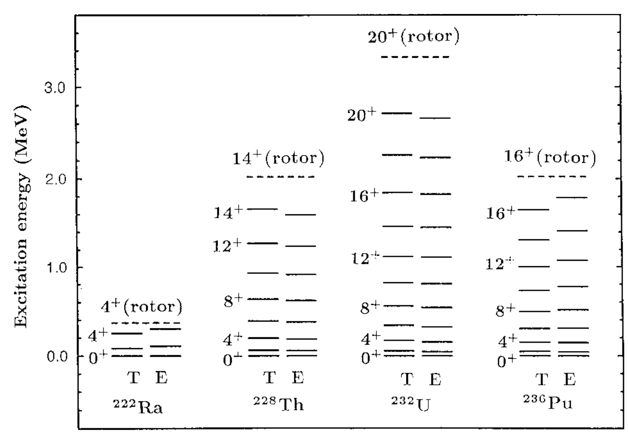

Figure 2. *Cluster model calculations of exotic cluster spectra (T) compared with experiment (E). The dashed lines show the energy of the highest known spin member of each band expected from a pure rotational model spectrum based on the $0^+ - 2^+$ energy splitting; from [9].*

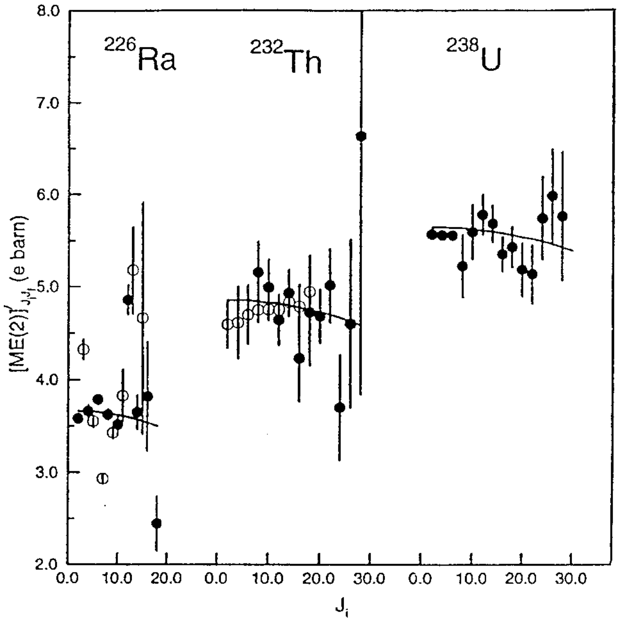

Figure 3. *Calculated (solid line) and measured (circles with error bars) values of the reduced E2 matrix elements $[ME(2)]_{JiJf}$ (e barn) for the transition $J_i \rightarrow J_f$ as functions of J_i; from [12].*

quantum numbers G scaled by the cluster masses, and in all cases the core was chosen as an isotope of Pb. We obtained good fits for the energies of the levels in the ground state $K^\pi = 0^+$ bands and also in the lowest $K^\pi = 0^-$ bands. The calculated electric multipole transition values both within and across the bands yielded fair agreement with observation. The required formulae involve the factor $\alpha = (Z_1A_2^\lambda + (-1)^\lambda Z_2A_1^\lambda)/(A_1 + A_2)^\lambda$ times the matrix elements of r^λ computed from our radial wave-functions. The most striking trend in both theory and experiment is the occurrence of a sequence of discrete jumps in the values of $B(E2;2^+ \rightarrow 0^+)$ from one isotope set to another, an example of which is shown in Figure 3 for ^{226}Ra, ^{232}Th, and ^{238}U, with these nuclei treated as a Pb core plus ^{14}C, ^{20}O, and ^{24}Ne, respectively. The matrix elements of r^2 as well as the effective charges used for these nuclei vary only slightly from nucleus to nucleus; hence the jumps in B(E2) are tracking the corresponding increments of the alpha factors as the cluster charge changes abruptly between isotope sets. The collected results for 19 nuclei are contained in [11,12] and they provide convincing evidence for the validity of our binary cluster model.

In view of the quantitative success of the preformed clusterization picture in explaining the properties of heavy nuclei we now felt it necessary to examine its relation to the standard collective model of a deformed rotating nucleus. In the latter picture it is assumed that each band has a common underlying intrinsic state and that the levels arise from rotation of the system. But the model also invokes *ad hoc* hypotheses about axial and equatorial symmetries to account for the 0^+ bands with $J = 0^+, 2^+, 4^+, \ldots$, which omit odd-J states, and similarly for the 0^- bands lacking even-J states. On the basis of such assumptions this model leads to a coherent theory of numerous observed phenomena. The drawback is that there is no satisfactory dynamical theory of the effective moments of inertia I associated with the rotating shapes, especially of their changes with J. Also, it has always been difficult to reconcile the observed B(E2) values, coming from the deformed charge distribution, with the level spacings which depend on the internal mass flows. Hence there is a need for a model which provides a dynamical reason for the band spectra, while retaining the basic ideas of the standard phenomenology. The binary cluster model, with various sizes of clusters in high orbits around a core, offers a new underpinning for rotational collectivity [13].

First, deep potentials, with the shapes we advocate, imply spectra with levels grouped into quasi-rotational bands, each corresponding to a global quantum number $G = 2n + l$. Both the potential depth and G are scaled by the cluster mass, or more generally by the reduced mass of core-cluster system, and this ensures exclusion of cluster-nucleons from the orbitals occupied by the core-nucleons. Fixed values of G lead at once to the characteristic appearance of 0^+ and 0^- bands. The even-G and odd-G bands have $l = 0^+, 2^+, 4^+, \ldots$, and $l = 1^-, 3^-, 5^-, \ldots$, respectively, since the wave function node numbers n can change only by integer steps. We further note that the bands terminate at $l = G$. Thus the cluster model suggests a simple *dynamical* explanation of the $K^\pi = 0^+$ and 0^- bands observed in many nuclei. Even more striking, this alternative view manages to combine good representations of level spacings with calculated electromagnetic observables also agreeing with experiment. As a bonus, the model enables simple calculations of half-lives for alpha and exotic decay modes.

A second interesting result of the cluster calculations concerns the wave functions generated by the Schrödinger equation for the required large values of $G = 2n + l$, a typical example of which is given in Figure 4 for

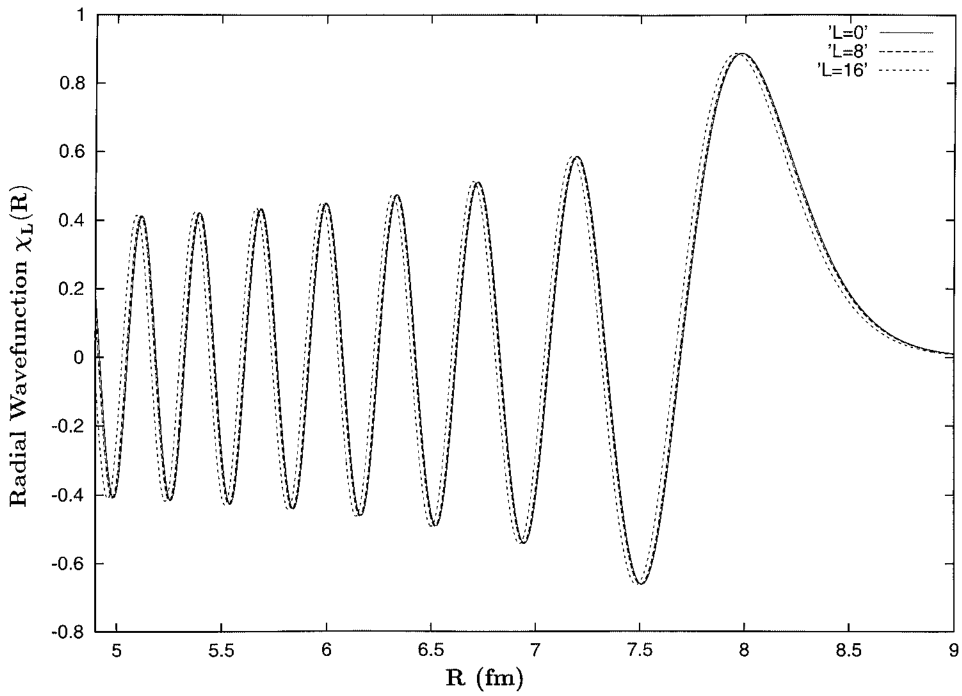

Figure 4. *Calculated radial wave functions of ^{210}Pb-^{24}Ne relative motion representing states of ^{234}U with $J^\pi = 0^+, 8^+$, and 16^+; last 16 nodes of wave functions shown; after [13].*

^{234}U. Those with low l have large n and hence very many oscillations. Except for a small region near the origin the radial functions have a virtually identical appearance and all have their largest peak outside the core nucleus radius. This, of course, corresponds to the picture of a cluster moving round the core in a high orbit. Also, the close similarity of the wave functions of the band members is quite surprising and suggests that we have here a concrete representation of the hitherto mysterious *intrinsic* state of the standard collective model. But we have to admit that our wave functions are not entirely satisfactory as yet. Their interior parts are too large and we have found that amputating them up to the last node yields good overall agreement with electric transitions without the need for effective charges. The truncated functions are very slightly state dependent, but the remaining exterior peaks are nearly identical when renormalized. A less ad hoc reduction of the amplitudes inside the core can be achieved using the technique of supersymmetry transformations [14], which removes the low-lying Pauli forbidden states while leaving the allowed state energies unchanged. We plan to investigate this problem in more detail in the future.

After formulating our cluster interpretation of heavy rotating nuclei we decided to explore its implications for odd nuclei by coupling an extra nucleon to the states of our binary model. It was known that the usual particle-rotor treatment, employing a static deformed core field, could be derived from a rotationally invariant Hamiltonian using basis states of good angular momentum at all stages, and without need for any symmetry postulates [15]. The main idea was to diagonalize analytically the interaction matrix for a nucleon, in a single particle j-state, coupled to degenerate $K^\pi = 0^+$ or 0^- bands. This leads quickly to the standard symmetrized strong-coupling state-functions and the effective mean field felt by the particle appears as a byproduct. The well-known half-integal K-bands then emerge naturally and inclusion of core-state spacings lifts their degeneracies correctly. The single j calculation is easily generalized to encompass several j-orbitals.

These general results left the actual nature of the rotational core bands unspecified. But, as already described, we now had a definite dynamical model for them, with essentially fixed intrinsic states, so we could apply the above ideas in detail to particular nuclei. Our first application was to calculate the spectrum and other observables of ^{223}Ra, modelled as ^{208}Pb + ^{14}C + n with Hamiltonian [16]

$$H = H(Pb + C) + H(Pb + n) + V(C + n).$$

The basis states were formed by coupling, to good total J, the states of the 0^+ and 0^- bands in ^{222}Ra = ^{208}Pb + ^{14}C with the easily calculated single neutron states observed in ^{209}Pb, which correspond to the orbitals ($1g_{9/2}$, $0i_{11/2}$, $0j_{15/2}$, $2d_{5/2}$, $3s_{1/2}$, $1g_{7/2}$ and $2d_{3/2}$). We then constructed the Hamiltonian matrices of the complete H, for each J, assuming that ^{208}Pb and ^{14}C remained in their ground states, and diagonalized them to produce eigenvalues and eigenvectors of possible K-bands in ^{223}Ra. By calculating the state-vectors of the bandheads as functions of the strength of the ^{14}C-n potential it becomes easy to identify the dominant parentage of each band. The resulting plots of bandhead energies are similar to the Nilsson diagrams and it is clear from our formalism that the odd neutron moves in the deformed field implied by the binary cluster structure of ^{222}Ra. The nuclear shape can be reconstructed from the model and is presented in [16]. One further technical point in the calculation is that the odd neutron is not allowed to occupy orbitals already occupied by the eight neutrons in ^{14}C. This entails the blocking of the four lowest parity-doublet bands produced by the model and the lowest allowed bands turn out to have $K = 3/2^{\pm}$, $5/2^{\pm}$ and $1/2^{\pm}$ in agreement with experiment.

In this first calculation, of considerable complexity, our results for the spectra were moderately satisfactory, giving fair indications of the locations of the low-lying bands and reasonable spacings within them. We were also able to calculate numerous gamma-ray transition strengths of E2 and mixed M1/E2 polarities, along with static moments, which matched observations quite well. But our calculated intrinsic dipole moment Q_1, which contains the factor $(Z_1/A_1 - Z_2/A_2)$ coming from the core-cluster dipole operator, was an order of magnitude too large. However, treating Q_1 as a constant parameter to be fitted, our state vectors gave a good account of the large number of measured B(E1) values. In addition, we found qualitative indication of the structural hindrance of exotic emission of ^{14}C from ^{223}Ra to the $9/2^+$ ground state of ^{209}Pb, though not quite enough to explain the preference for the decay to populate the first excited state of ^{209}Pb with spin $11/2^+$. Similar calculations were performed later to model the odd neutron nuclei ^{233}U, ^{229}Th and the odd proton nucleus ^{223}Ac, with respectable results [17].

So far we had confined our attention to the quasi-rotational bands of heavy nuclei in the actinide region. The choice of clusters and cores was there straightforward, either because the appropriate clusters are actually emitted or it seemed natural to choose a core at or near the doubly magic nucleus ^{208}Pb. We now wished to extend the model to the rare-earth region and possibly to other sections of the periodic table. Here, the selection of likely cluster-core partitions was more problematic. After several preliminary attempts to formulate a reliable method of finding the correct decomposition, we eventually arrived at a criterion of maximum stability [18]. The original strategy was to generalize the usual stability criterion for single nuclei, which picks the (charge,mass) values (Z,A) with largest deviations $D = B_A - B_L$ between the actual binding energies B_A and the energies B_L coming from the liquid drop formula. This easily identifies magic shell closures. Considering now a nucleus of fixed (Z_T, A_T), to be partitioned into pairs of nuclides with (charge,mass) values (Z_1,A_1) and (Z_2,A_2), we determined those combinations $T \rightarrow 1 + 2$ giving maxima of the expression

$$D(1,2) = [B_A(1) - B_L(1)] + [B_A(2) - B_L(2)].$$

Application of this to trans-Pb nuclei confirmed our earlier suggested partitions in that region. Although quite successful, this basic idea still required an a priori choice of what cluster masses and charges to consider and would not be useful without supporting evidence, e.g., exotic decay.

The vital clue needed to make the maximum stability method work without prior choice of clusters was already hinted at above. Experiment shows that B(E1) transitions between 0^+ and 0^- bands in heavy nuclei are very weak. This indicates that the factor $(Z_1/A_1 - Z_2/A_2)$ in the cluster dipole operator must be close to zero. Hence to good approximation we can assume the relations $Z_1/A_1 = Z_2/A_2 = Z_T/A_T$, which imply that the centres of charge and mass in the nucleus (Z_T,A_T) coincide, clearly an effect of the strong proton-neutron force. Imposing these conditions enables the plotting of the D-function against, say, Z_2 alone, for then the masses and charges of the clusters are all determined by the (Z_T,A_T) of the composite nucleus using $A_2 = Z_2(A_T/Z_T)$, $Z_1 = Z_T - Z_2$ and $A_1 = A_T - A_2$. Implementation of the idea requires that for arbitrary average $\langle Z_2 \rangle$ the "clusters" are really superpositions of several actual nuclear subunits, with Z's and N's bracketing $[\langle Z_2 \rangle, \langle N_2 \rangle]$ [18]. The continuous D-plots thus produced, an example of which is shown in Figure 5 for ^{228}Th, have maxima that indicate

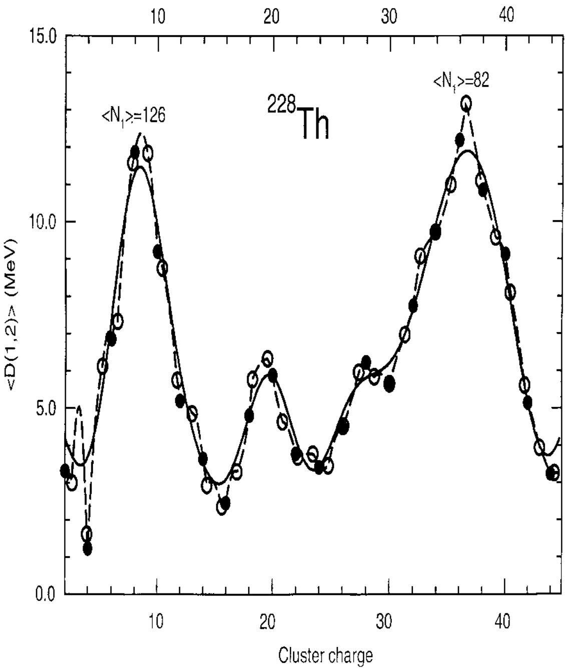

Figure 5. *Calculations of <D(1,2)> as a function of cluster charge <Z_2> for ^{228}Th. Solid circles represent isotopes, open circles isotones, the dashed line is the full calculation, and the solid line the smoothed calculation; from [18].*

likely partitions for any nucleus (Z_T,A_T). These confirm our earlier choices, and point to clusters with magic neutron numbers.

First trials of the proposed selection criteria away from the actinides were made for several isotopes of Ba, Ce and Nd. All predicted core nuclei had magic neutron number N = 82 and measured observables were well reproduced [19]. More intriguingly, as e.g. shown in Figure 5, well-developed peaks appeared in our continuous D-plots which predicted the existence in very many nuclei of rotational bands corresponding to unexpectedly heavy clusters. The implied shapes of the parent nuclei strongly suggested a cluster interpretation of the phenomenon of superdeformation, with large axis ratios. These ideas were then used to model bands in ^{194}Hg, ^{236}U, and ^{240}Pu [20]. The D-plots suggest in each case two distinct clustering modes, one corresponding to a normal ground state band, the other to an excited superdeformed band. Our cluster model thus accounts for the properties of both kinds of band in all three nuclei. We were also subsequently able to derive the simple algebraic formula for the transition quadrupole moment Q_t of a cluster band

$$Q_t = 2\ R_0^2[Z_T A_T^{2/3} - Z_1 A_1^{2/3} - Z_2 A_2^{2/3}].$$

With R_0 = 1.07 fm, this depends only on the charge-mass splits characterizing the superdeformed cluster bands, and fits the transition quadrupole moments of such bands rather closely [21].

From the above it would seem clear that well-developed cluster structures may occur in diverse nuclei. There are also further implications of the model which have not yet been fully investigated. Our current studies include an interpretation of the close similarities (sometimes approaching identity) of various bands in neighbouring nuclei as well as the derivation of new relations involving B(E2) values and excitation energies. These have resulted in the formulation of an alternative way of determining likely cluster decompositions of a nucleus independent of the D-plot technique illustrated earlier. The dipole rule, which assumes equality of the Z/A ratios for cluster, core, and parent nuclei, is still a vital ingredient in the calculations. We expect to publish reports on these developments in the near future.

In conclusion, we have demonstrated that the cluster model is a powerful tool for understanding numerous nuclear phenomena. Though simple in principle, it has required, and still requires, some additional insights to make it work universally. A good deal of evidence has now accumulated to show that the model is a valid representation of nuclear structure in many instances and that it provides an appealingly fresh view of collective behaviour. The physical picture is transparent, and easily comprehensible, while still giving a quantitative agreement with observation comparable to that achieved by more complex theories. It seems to us that, when the end results of intricate microscopic calculations often signal the buildup of spatial correlations resembling clusters, it must be pertinent to ask how far one can go by starting with fully formed clusters at the outset.

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Density Functional Theory

D. M. BRINK
Department of Physics, Oxford University

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 multidimensional 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 $\rho(\mathbf{r})$, which is a function of one position variable $\mathbf{r}$ rather than the electron wave function $\Psi(\mathbf{r}_1\sigma_1, \mathbf{r}_2\sigma_2, \ldots, \mathbf{r}_n\sigma_n)$ 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 $\rho(\mathbf{r})$.

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

$$E[\rho(\mathbf{r})] = E_K^{TF}[\rho(\mathbf{r})] + E_C[\rho(\mathbf{r})]. \tag{1}$$

The first term in (1) is the Thomas-Fermi approximation to the kinetic energy of the electrons; the second is Coulomb energy. In Thomas-Fermi theory, the kinetic energy of the electrons is approximated by

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

with the constraint that the atom contains n electrons

$$\int d^3\mathbf{r}\rho(\mathbf{r}) = n. \tag{3}$$

The Thomas-Fermi approximation for the Coulomb energy is

$$E_C[\rho(\mathbf{r})] = \iint d^3\mathbf{r}d^3\mathbf{r}' \frac{e^2\rho(\mathbf{r})\rho(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|} + \int d^3\mathbf{r}\frac{Ze^2\rho(\mathbf{r})}{r}. \tag{4}$$

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 $\rho(\mathbf{r})$ 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 $v(\mathbf{r})$ 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 $v(\mathbf{r})$. Since the Coulomb interactions are known it was concluded that the ground state density $\rho(\mathbf{r})$ 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:

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

The single particle density matrix is written in diagonal form

$$\rho(r, r') = \sum_i n_i \phi_i(\mathbf{r}) \phi_i^*(\mathbf{r}'). \qquad (6)$$

The eigenstates $\phi(\mathbf{r})$ 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 $\Sigma_i n_i = Z$. The kinetic energy of the electrons is

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

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 ρ. Kohn and Sham made the local density approximation and wrote

$$E_{XC}[\rho] = \int d^3\mathbf{r} \rho(\mathbf{r}) \varepsilon_{XC}(\rho(\mathbf{r})), \qquad (8)$$

where $\varepsilon_{XC}(\rho(\mathbf{r}))$ is the exchange correlation energy density for an electron density $\rho(\mathbf{r})$. 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 ϕ_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 *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, benzine, 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:

$$V = \sum_{i<j} v_{ij} + \sum_{i<j<k} v_{ijk}^{(3)} \tag{9}$$

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

$$v_{12} = t_0(1 + x_0 P_\sigma)\delta(\mathbf{r}_1 - \mathbf{r}_2) + \cdots + v_{12}^{so}. \tag{10}$$

The leading term is a δ-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 parameters $t_1x_1t_2x_2$. There is also a short-range spin-orbit interaction between nucleons v_{12}^{so} with a strength W_0. Skyrme's three-body force is also a zero range interaction

$$v_{ijk}^{(3)} = t_3\delta(\mathbf{r}_1 - \mathbf{r}_2)\delta(\mathbf{r}_1 - \mathbf{r}_3).$$

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 Φ. The explicit form of the energy functional is

$$E[\rho, \tau, J] = \langle\Phi | T + V | \Phi\rangle = \int H(\mathbf{r})d^3\mathbf{r}, \qquad (11)$$

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

$$\rho(\mathbf{r}) = \sum |\phi_i(\mathbf{r})|^2, \qquad \tau(\mathbf{r}) = \sum |\nabla\phi_i(\mathbf{r})|^2,$$

$$J(\mathbf{r}) = \frac{1}{r}\sum \phi_i^*(\mathbf{r})\mathbf{l}.\sigma\phi_i(\mathbf{r}). \qquad (12)$$

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

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

$$H^+(\mathbf{r}) = \frac{\hbar^2}{2m}\tau + a_0\rho^2 + a_1(\nabla\rho)^2$$

$$+ a_2\rho\tau + a_3\rho^3 + a_{so}J\rho. \qquad (13)$$

The term proportional to τ in $H^+(\mathbf{r})$ 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; $a_0 = 3t_0/8$, $a_1 = (9t_1 - 5t_2)/64$, $a_2 = (3t_1 + 5t_2)/16$, $a_3 = t_3/16$, $a_{so} = 3W_0/4$. The term proportional to ρ^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 ρ^3 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 ρ^3 term is replaced by a $\rho^{2+\alpha}$ term where $0 < \alpha \leq 1$. The second part $H^-(\mathbf{r})$ of $H(\mathbf{r})$ depends on differences of the proton and neutron densities

$$H^-(\mathbf{r}) = b_0(\rho_p - \rho_n)^2 + b_1(\nabla\rho_p - \nabla\rho_n)^2 + \cdots. \qquad (14)$$

There are five terms in H^- 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 ρ^2, the $\rho\tau$, and the ρ^α terms in (13) fix the binding energy, the density and compressibility of symmetric nuclear matter. The term proportional to $J\rho$ 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 $b_0(\rho_n - \rho_p)^2$ 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 v_{14} 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 $a_{so}J\rho$ to the density H^+ and $b_{so}(J_n - J_p)(\rho_n - \rho_p)$ to H^- were related and depended only on the parameter W_0. Nuclear radii for sequences of isotopes obtained by measuring by isotope shifts in atoms showed a 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_{so} and b_{so} 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 α giving the exponent of the density-dependent term, and a parameter x_c 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, ^{24}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 β-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 β-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 rotational bands and fission barriers in a transuranic element. Extensions to nuclei away from closed shells and especially to deformed nuclei require a generalization of the Skyrme energy functional to include a pairing force between nucleons. A very neat and simple generalization combining Hartree-Fock with a BCS pairing interaction was worked out by Vautherin in his 1973 paper [15]. Duguet et al. used Hartree-Fock-Bogoliubov theory and the Lipkin-Nogami approximate particle number projection.

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 antisymmetry 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.

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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.

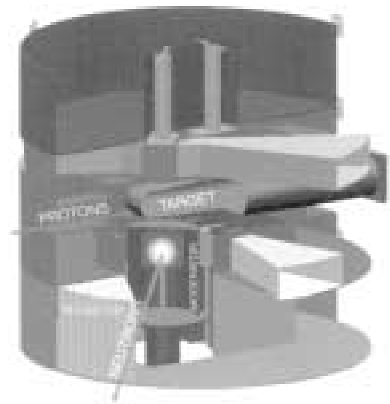

Figure 1(a). *3D view of the target, moderator, and reflector assembly.*

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 cur-

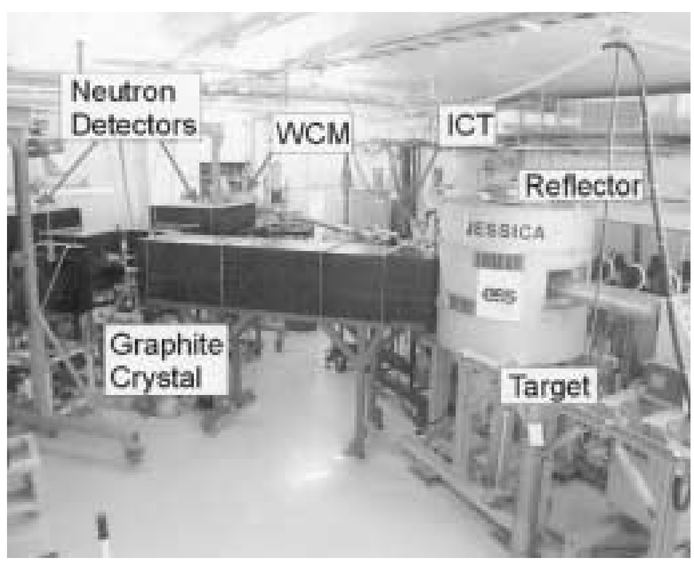

Figure 1(b). *The JESSICA Experiment at the COSY proton synchrotron in Jülich.*

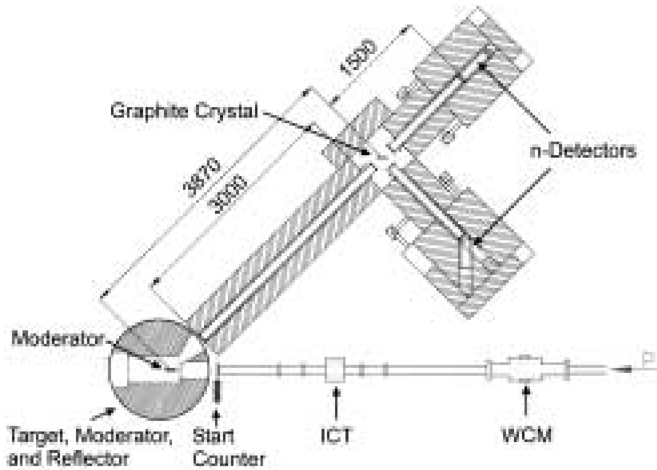

Figure 2. *Set-up of the JESSICA experiment with proton monitors, neutron detectors, scattering crystal, and target-moderator-reflector assembly.*

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

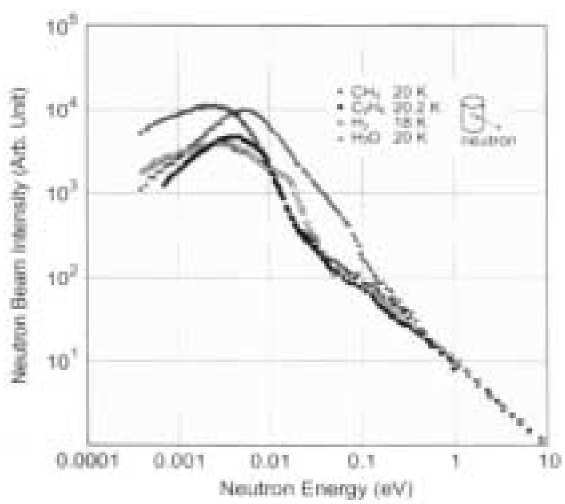

Figure 3. *Measured neutron energy spectra for various cold moderators carried out at an electron accelerator [4].*

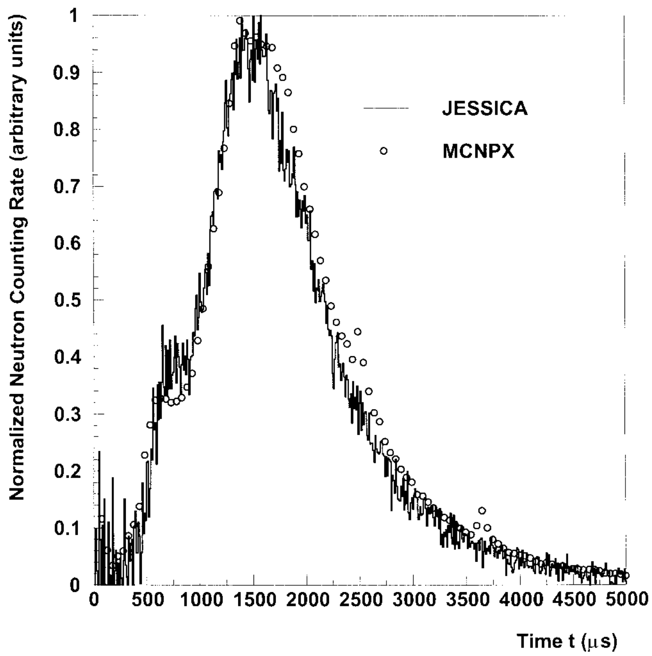

Figure 4. *Comparison of the time of flight spectrum between experimental data (solid line) and Monte Carlo simulation (open circles) for an ambient temperature water moderator.*

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 (γ, 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

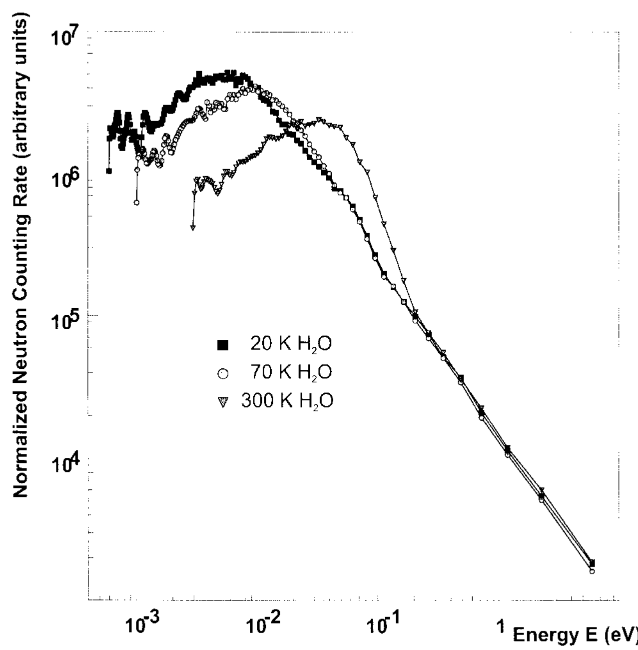

Figure 5. *Energy spectra for 20 K and 70 K ice and water at room temperature (300 K).*

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 $3 \cdot 10^{-2}$ 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 $6 \cdot 10^{-3}$ eV, for 70 K at $1 \cdot 10^{-2}$ eV, and for 300 K at $3 \cdot 10^{-2}$ 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.

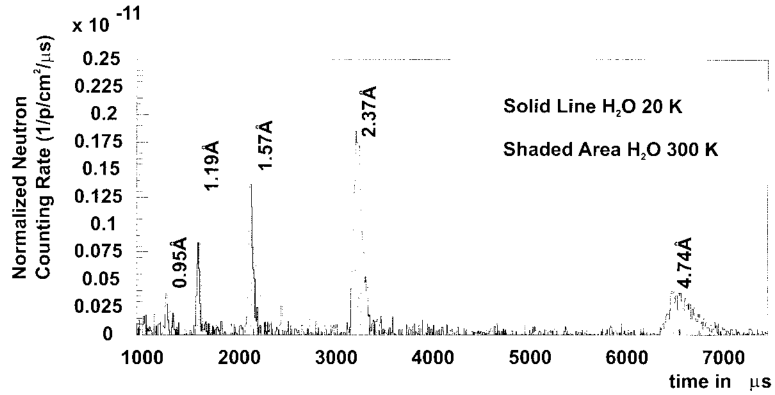

Figure 6. *Comparison of the time structure of the neutron pulses for 20 K (solid line) and 300 K (shaded area) and different wavelengths.*

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.

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K. Nünighoff for the
JESSICA Collaboration[1]

[1]H. Conrad, D. Filges, F. Goldenbaum, R.-D. Neef, K. Nünighoff, N. Paul, Ch. Pohl, H. Schaal, H. Stelzer, H. Tietze-Jaensch, M. Wohlmuther (Forschungzentrum Jülich, Germany); A. Smirnov (JINR Dubna, Russia); W. Ninaus (Technische Universtität Graz, Austria).

A Special Experiment in Cologne

In *Nuclear Physics News,* Volume 12, Number 1, it was announced that the IKP in Cologne was open to outside users provided they do their share in running the experiment. This photograph illustrates such an engagement and at the same time honors P. Kleinheinz for his contributions to our understanding of nuclear structure. In 1986 he performed an in-beam experiment (*Z. Phys. A* 324 (1986) 417), which identified double octupole states in 146Gd (Kleinheinzium) together with his young collaborators S. W. Yates, R. Julin, and B. Rubio.

Almost twenty years later most of his collaborators became full professors, but when he called them to do shifts in Cologne, they all signed up to study Kleinheinzium again with state-of-the-art instrumentation. As the photograph illustrates, it was a quite impressive team in front of A. Dewald's plunger setup: In the upper row: P. Kleinheinz, B. Rubbio, S. Lunardo A. Fitzler, J. Jolie; in the lower row: S. W. Yates, A. Algora, R. Julin, L. Caballero, R. Menegazzo, M. Piiparinnen, A. Dewald.

J. Jolie
Universität zu Köln
Köln, Germany

The Paradox in Low-Energy Few-Hadron Physics: Advancing Theory versus Experimental Phase-Out

In the last decade, due to fundamental studies of the interaction between hadrons and advances in algorithms and computational power, there has been tremendous progress in theoretical few-nucleon physics at low energies. Today work in this field has reached a high level of precision in predicting nuclear observables in the framework of a given nuclear Hamiltonian, with a wide range of implications for all nuclear physics in general and exciting prospects for the future. Progress means, on the one hand, that some questions are solved, but on the other hand new problems appear that require experimental verification for a deeper understanding. However, a dark cloud is threatening experimental programs in few-nucleon physics at low energies. Many low-energy facilities have already been shut down and the sword of Damocles is hanging over the very few remaining ones. Thus, the threatening consequence is that within a short time we will be left with only a few intermediate energy laboratories, where low-energy experiments will either be a rare exception or, even worse, impossible.

A group of concerned few-body theorists met at the University of Trento on May 20–21 to reflect upon this issue. The aim of this urgent note is to draw the attention of the greater community of physicists to this sad and quite contradictory situation and to search for solutions in order to avoid the extinction of low-energy facilities for experimental few-nucleon physics. In fact, there is an urgent need of such facilities in view of the above-mentioned theoretical progress.

Few-nucleon physics is presently experiencing an interesting period leading to the solution of increasingly complex systems linking few-body and many-body nuclear physics. However, *ab initio* calculations require microscopic interactions and currents. In recent years a lot of insight in those interactions and electroweak operators has been achieved. Thus high-precision nucleon-nucleon potentials have been developed and accurate calculations of electroweak reactions on the two-nucleon system have been carried out. These modern realistic potentials have also been successfully applied to three- and four-nucleon bound-state problems by different groups. We learned that three-nucleon forces are required to correctly predict the binding energies and excitation spectra of light nuclei up to A = 8. The microscopic nuclear interactions and currents also describe the bulk of the three-nucleon scattering data, photodisintegration, and $\vec{d} + p$ capture reactions, where the Coulomb repulsion has also been included with great precision in some of the calculations. Rapid progress towards an exact treatment of four-nucleon scattering is underway, as is development of alternative methods that reduce the complicated continuum-state problem to a bound-state like problem.

These activities have led to quite a few important findings:

- the need for a three-nucleon (3N) force for the understanding of nuclear binding;
- a deeper insight into properties of very light nuclei based on realistic nuclear forces;
- the importance of consistent electromagnetic currents and final-state interactions in interpreting electro-induced processes;
- extraction of the electromagnetic neutron form factors from electron scattering experiments with deuterium and ^{3}He targets;
- evaluation of low-energy electroweak capture processes of astrophysical relevance;
- confirmation of the α-cluster structure of ^{8}Be in microscopic calculations.

A consequence of these exciting developments is that a list of issues that need to be addressed in the near future has emerged in few-nucleon physics and where first steps are already being undertaken:

- a deeper understanding of the NN forces;
- a better insight into the spin-isospin and momentum dependence of 3N forces;
- clarification of the relation between NN and 3N forces;
- a combined and consistent foundation of many-body electromagnetic currents and nuclear forces;
- the role of relativity at low energies.

In this situation an important and interesting question remains: How are the microscopic nuclear interactions and currents related to the underlying QCD? Recent progress using chiral perturbation theory has shown links between two-nucleon and three-nucleon interactions and corresponding consistent current operators. The confirmation of this approach requires a new set of high quality data from nucleon and electron scattering experiments. In this context it will be interesting to see whether these interactions can resolve deviations of experiment and theory in four-nucleon scattering observables or additional four-nucleon forces are necessary.

Once having understood the systems with $A \leq 4$ in greater detail, one can ask whether it is possible to build a bridge to the more complex many-body physics of heavier nuclei. To that end it will be essential to study light nuclei in the mass range from A = 6 ÷ 12 with different few-body methods to address all aspects. A revival of long-existing methods and new ideas about the concept of effective interactions might play an important role in accessing these systems. In addition, an understanding of light nuclei in the valley of stability should also put the very active and fruitful field of halo nuclei on safer theoretical grounds.

We consider all the above-mentioned achievements and open questions as essential for a fundamental understanding of the strong interaction in its nonperturbative regime and of nuclei. As outlined above, we urgently need new high-precision and dedicated experiments in 3N and 4N scattering, as well as electromagnetic processes on light nuclei to guide and verify the theory. It is evident that this goal cannot be reached by just a few experiments. In order to achieve mutual stimulation, a combined and long lasting effort of both experimental as well as theoretical physicists is needed. Therefore, it is absolutely necessary to have a variety of working low-energy facilities in the near and far future.

Last but not least we would like to mention that, compared to other facilities, such low-energy facilities require in general a rather modest budget and have, due to their *human* size, also quite a high educational value for students and younger experimentalists.

H. Arenhövel, L. Canton,
J. Carbonell, A. Fonseca,
W. Glöckle, H. M. Hofmann,
A. Kievsky, W. Leidemann,
G. Orlandini, and M. Viviani

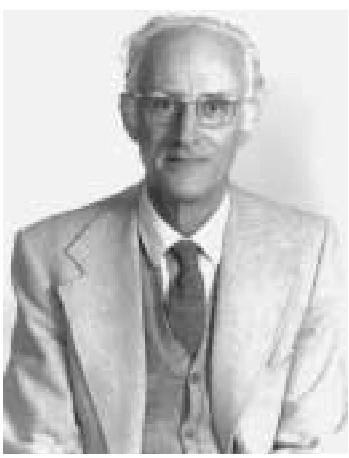
G. N. Flerov Prize

In June 2003, the Joint Institute for Nuclear Research will award the G. N. Flerov prize to the winner of the contest for outstanding research in nuclear physics. The contest is for individual participants only. The win ner will also receive $1000. Participants should send an abstract of their research, enclosing copies of major contributions, to be received by 1 February 2003 to: Dr. Andrew G. Popeko, Joint Institute for Nuclear Research, Flerov, Laboratory for Nuclear Reactions, Dubna, Moscow Region, 141980, Russia. Fax: (+7 09621) 65083, E-mail: popeko@jinr.ru.

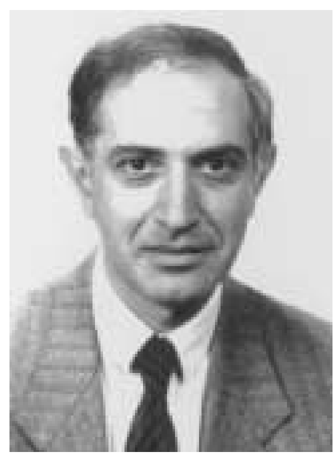
ANDREY POPEKO
Flerov Laboratory for Nuclear Reactions
Moscow, Russia

Lise Meitner Prize 2002

Awarded to Prof. James Philip Elliott, University of Sussex (UK), Prof. Francesco Iachello, University of Yale (USA), for their innovative applications of group theoretical methods to the understanding of atomic nuclei.



James Philip Elliott



Francesco Iachello

The Physics Case

The study of the discrete energy spectra of small quantum systems relates to fundamental symmetries in nature. These symmetries determine the “conserved quantities” describing the intrinsic properties of such systems and are needed in quantum mechanics to characterize the state of a system. For highly symmetric systems the number of observed characteristic energies will be strongly reduced, because many states will have the same energy. For example, different spin orientations in a spherically symmetric world are indistinguishable, but if a particular orientation in space will be preferred (e.g., due to an external magnetic field), their energy will split.

Symmetries in nuclei have played a dominant role in the development of the understanding of fundamental properties of matter. Energy spectra of atomic nuclei reflect symmetries related to the properties of the two fundamental building blocks, the proton and the neutron, which carry a half integer spin and are thus characterized by the symmetries of fermions.

The properties of the proton and neutron are very similar and can be thought of as two states of the nucleon in an abstract space, called isospin (introduced by W. Heisenberg, Nobel Prize, 1932). A rotation in isospin space transforms a neutron into a proton.

The special mathematical tool needed to describe symmetry in quantum systems is known as group theory. The symmetry of the nuclear force under rotations in spin and in isospin has led to the introduction of an even larger symmetry group (SU(4), introduced by E. Wigner, Nobel Prize, 1963). The major contribution of *J. P. Elliott* in this field came in the 1950s. He provided an understanding of the structure of the spectra of light nuclei in terms of an underlying symmetry, expressed by the symmetry group SU(3). This symmetry reflects the dynamics of a many-fermion system. The introduction of this method into nuclear physics opened new paths toward the understanding of nuclear structure in general, and in particular it allowed for the reconciliation of the spherical shell model of Maria Goeppert-Mayer and H. Jensen (Nobel Prize, 1963) with the collective and liquid drop models of A. Bohr and B. Mottelson (Nobel Prize, 1975), which existed as separate and distinct descriptions of the nucleus. The work demonstrated that dynamical symmetries occur in the energy spectra of nuclei, a concept that also influenced the early work of elementary particle physics on the structure of hadrons and that has led to the application of these concepts in nuclear, atomic, and molecular physics.

The Interacting Boson Model or Interacting Boson Approximation (IBA) was a major step in applying the concept of dynamical symmetries to the understanding of the spectra of a large number of atomic nuclei. The Interacting Boson Model (IBA) has been introduced in 1975 by *F. Iachello* in collaboration with A. Arima of the University of Tokyo, both at that time at the Kernfysisch Versneller Instituut (KVI) in Groningen (Netherlands). In the IBA, nuclear structure is described in terms of degrees of freedom involving subunits of integer spins (bosons). The concept of dynamical symmetries used in these studies is based on the fact that a symmetry may be broken in such a way as to lift the degeneracy in the energies but not alter the wave functions. A combination of the fermion and the boson degrees of freedom has led to the introduction, by F. Iachello, of super-symmetry in nuclei, which recently has been confirmed experimentally. Dynamic symmetries have also been applied by him, in the fields of elementary particle physics and molecular physics.

The description of nuclear structure based on the concepts introduced by the laureates continues to play a pivotal role in the present nuclear structure studies in which large γ-detector arrays like EUROBALL and Gammasphere are used. These concepts will be very important in the future studies of the newly accessible region of exotic nuclei (proton rich $Z \gg N$, or very neutron rich $N \gg Z$), when a new generation of radioactive beam facilities become operational.

Further Reading

R. Casten and W. Feng, *Phys. Today* **11** (1984) 26; *Physics World*, October 1999, p. 19; August 2001, p. 24.
J. P. Elliott, *J. Phys.* **G 25** (1999) p. 77.

W. von Oertzen
HMI Berlin, Germany

news from NuPECC

NuPECC Long-Range Plan

We would like to encourage you to go to the NuPECC homepage http://www.nupecc.org and

- look at the draft reports from the six working groups and
- register for the town meeting at GSI Darmstadt, January 30–February 1, 2003

Gabriele-Elisabeth Körner
NuPECC Scientific Secretary