# Nuclear Physics News

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Sunny days ahead for nuclear science? Don’t throw away your umbrella quite yet.

This has been an unusually damp season in Northern California. The second wettest March on record has been followed by an equally dismal April. Spring is on hold and pedestrians mutter darkly about global climate change, as they dodge the puddles. Only the owners of ski resorts are cheerful, with enough snow to keep the lifts running until mid-summer. The weather has been on my mind as well. It provides apt metaphors for reflection on the state of nuclear science in the early 21st century.

Reviewing recent accomplishments, we can bask in the warm sunshine of exceptional productivity. We see real advances in knowledge of new forms of nuclear matter, of nuclear currents, of neutrinos, and of the properties of nuclei far from stability. There is tremendous excitement at nuclear physics conferences around the world.

When we look to the future, however, the outlook has been much more cloudy. The funding situation in recent years has been unsettled to say the least, especially here in the United States. Budget cuts have limited beam time at user facilities, and the job market has shrunk for young scientists coming in to the field. This ill wind has not been restricted to nuclear physics; it has affected all of the physical sciences, the foundation of the technological society in which we live.

Fortunately, there are some signs of a thaw in funding here. Most important was the publication by the National Academy of Sciences, in late 2005, of a committee report entitled “Rising above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future.” Many reports are written in Washington, D.C., but this one gained unusual attention. The committee, which was chaired by Norman Augustine, the former chairman of Lockheed-Martin, was both diverse and distinguished. It included university presidents, Nobel laureates, and CEOs of Fortune 500 corporations. The participation of these corporate and academic heavyweights gave the committee more clout and a broader perspective than would have been case for a group of scientific experts alone, and mitigated the usual charges of self-interest. The report included recommendations to greatly increase the number of science teachers in the schools, to sustain and strengthen the nation’s commitment to basic research, and to make the U.S. an attractive setting to study and perform research.

The report has already had considerable impact. In his State of the Union speech earlier this year, President Bush introduced the “American Competitiveness Initiative,” which incorporated many of the committee’s recommendations, and included, among other things, a call to double investment in research in the physical sciences over the next decade. This is a significant development. Of course, we must remember that like the weather, political conditions in the U.S. are unsettled, changeable, and hard to forecast. The negotiation and compromise necessary to bring this initiative to fruition are just beginning.

Nevertheless, there is a sense of optimism in the scientific community that has not been felt in many years.

It is in this warming political climate that the Department of Energy and the National Science Foundation recently announced they will ask their Nuclear Science Advisory Committee (NSAC; the equivalent of NuPECC) to prepare a new long-range plan. This is particularly timely because, with the possibility of a growing budget, it is essential that we have a fresh, well-articulated vision of our future in order to make a strong case for our field.

By definition, NSAC plans are national in scope. However, the nuclear physics community is very much an international one. It is my hope that NSAC will make every effort to place its new long-range plan in a global context with an emphasis on international collaboration. In an era with so many political and social challenges, we in the scientific community have a special responsibility to work together to do our best to ensure a sunny and fair outlook for our children and grandchildren.

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The views expressed here do not represent the views and policies of NuPECC except where explicitly identified.
A Unified Approach to Nuclear Science at Florida State University

The Superconducting Linear Accelerator Laboratory at Florida State University is a busy, teeming place with the ongoing development of a radioactive beam facility, the construction of advanced detector systems, nuclear spectroscopy using a sophisticated array of Compton-suppressed clover gamma-ray detectors, and experiments with the finest source of polarized lithium beam in the world. However, for FSU’s nuclear experimentalists, the laboratory also serves as a home base for scientific programs at the National Superconducting Cyclotron Laboratory at Michigan State University, GANIL, Gammasphere, the Thomas Jefferson Laboratory, and the Relativistic Heavy Ion Collider. In engaging the field of nuclear science at energies ranging from keV to TeV, and in studying physics from the spectroscopy of heavy and light nuclei to hadron science and to the search for the quark-gluon plasma, FSU’s nuclear physicists cross-fertilize each other’s strengths in experimental innovation, theoretical vision, and education.

The members of the laboratory hold leadership positions throughout the nuclear physics community. Kirby Kemper was elected to the Rare Isotope Accelerator (RIA) Steering Committee in 2002 and reelected in 2005. Sam Tabor was chair of the Gammasphere Users’ Executive Committee in 2002. Tony Frawley was Run Coordinator for Run 2 of the PHENIX detector at the Relativistic Heavy Ion Collider in 2001–2002, serves on the PHENIX Executive Council, and co-chairs the committee assembled by Brookhaven management to write up the physics case for RHIC II in preparation for the next long-range plan. Mark Riley served on the U.S. Nuclear Science Advisory Committee from 1999 to 2002, was chair of the 2001 Gordon Conference on Nuclear Chemistry, has served on the GRETINA Steering Committee since its inception, and was chair of the APS Publications Oversight Committee in 2001. He is present chair of the Gammasphere Users’ Executive Committee. Paul Eugenio serves on the GlueX Collaboration Executive Board at the Thomas Jefferson Laboratory, is chair of the CLAS Hadron Spectroscopy Physics Working Groups, and serves on the CLAS Executive Coordinating Committee. He is also spokesperson for Jefferson Lab HyCLAS experiment. Ingo Wiedenhoever held an Outstanding Junior Investigator Award from the U.S. Department of Energy in 2002–2005, and is presently serving as a member of the National Superconducting Cyclotron Laboratory Users’ Executive Committee. Paul Cottle chaired this committee in 2004. Volker Crede is one of the spokespersons for the Jefferson Laboratory FROST program.

The members of the FSU Laboratory are fortunate to benefit from a longstanding fruitful collaborative relationship with the Physics Department’s nuclear theory group, which consists of four faculty members and a number of postdoctoral fellows and graduate students. The collaborations between FSU’s experimentalists and theorists cover the entire range of energies from nuclear structure physics to hadronic and relativistic heavy ion physics. The two groups share a seminar series and a coffee room as well as a floor of the Physics Department’s main building.

As of this writing, 152 students have completed their Ph.D.s at the FSU Nuclear Physics Laboratory.

Laboratory History

The FSU Accelerator Laboratory began operation in 1960 following the installation of an EN Tandem Van de Graaff accelerator. It was the second of its type in the United States. The first useful acceleration of negatively charged helium ions was achieved at FSU in 1961, and isobaric analogue resonances were identified at the facility in proton-induced reactions in 1963 [1].

The laboratory entered its second development stage in 1970 with the installation of an Super-FN Tandem Van de Graaff accelerator. At that time, the research program turned to an emphasis on heavy-ion beams. A superconducting linear post-accelerator was funded by the National Science Foundation in the mid-1980s to double beam energies, with the first experiment on the completed facility run in 1987.

The Laboratory Facility

The Super-FN tandem is injected by either a National Electrostatics SNICS-II cesium sputter ion source or a laser-pumped polarized lithium ion source. Among the beams available from the sputter source is the radioactive isotope $^{14}$C. The FSU lab is the only one in the world presently using a $^{14}$C beam. In addition, helium beams
can be produced using an rf-discharge and the same cesium charge exchange canal as the polarized lithium source. The FN tandem is equipped with a Pelletron charging system. Both the usual carbon foil strippers and a turbo-pumped recirculating gas stripper are located at the terminal of the FN tandem.

The superconducting linear accelerator consists of 12 accelerating resonators installed in 3 cryostats, plus buncher and re-buncher each located in their own cryostats. The resonators are niobium-on-copper “split-ring” resonators produced by Argonne National Laboratory. The cryostats were designed and built at FSU. All the resonators are designed for $\beta = 0.1$, except for the buncher, which is designed for $\beta = 0.06$.

**The Development of a Radioactive Beam Facility—RESOLUT**

The laboratory has constructed an in-flight radioactive beam facility named RESOLUT. The in-flight technique allows the production of large quantities of exotic ions without the limitations of the efficiency of an ion source or the chemistry of the beam material. One of the concerns associated with an in-flight facility—one that can be particularly important in experiments near the Coulomb barrier—is that the energy definition of the secondary beam is relatively poor because of the kinematic broadening induced in the production reaction. However, K. E. Rehm addressed this issue at Argonne by placing a superconducting resonator downstream of the production target. This resonator is used to sharpen the energy resolution of the secondary beam and in effect gives all reaction products the same velocity. This technique was adapted and improved for RESOLUT, which provides an increased angular acceptance for the recoil products and uses a dispersive magnetic spectrometer to select the beam of choice more cleanly, creating in effect a novel type of mass spectrometer.

A photograph of the RESOLUT facility is shown in Figure 1, and a schematic drawing of its components is displayed in Figure 2.

The experimental program at RESOLUT, which began in 2005, is directed toward studying astrophysical problems of nucleosynthesis experimentally and to study high-isospin states in stable nuclei. A neutron wall consisting of plastic position-sensitive scintillators has been constructed for use at the end of RESOLUT. The neutron wall is particularly useful for detecting neutrons from inverse kinematics ($d,n$) reactions with the radioactive beams produced by RESOLUT.

**Polarized Lithium Source**

The FSU optically pumped polarized lithium ion source (OPPLIS) uses an argon-ion laser pumped ring-dye laser at 671 nm to optically pump a lithium atomic beam in a weak magnetic field into the $M_F = 3 \Delta F = 3 \Delta I + 1/2$ ($M_s = 3 \Delta I/2$, $M_I = 3 \Delta I$) hyperfine substate. An electro-optic modulator is used to generate two strong components from the single dye laser frequency to interact with atoms in both ground-state hyperfine levels. RF transitions downbeam of the optical pumping region can be used to select other $M_F$ states. The lithium atoms are then thermionically ionized on a hot tungsten strip, extracted, accelerated

![Figure 1. Members of the RESOLUT group in front of the major components of RESOLUT. Group members include Prof. Ingo Wiedenhoever (front and center) and (from left to right) Patrick Peplowski, Eric Diffenderfer, Robert Reynolds, Allison Bernstein, Simon Brown, and Dr. Lagy Baby.](image)
to 5 keV and the passed through a cesium charge exchange cell to produce nuclear spin polarized Li$^-$ for injection into the tandem. The source has been used for producing polarized $^7$Li for measuring nuclear reaction analyzing powers of all three tensor ranks.

A schematic for the polarized lithium source is shown in Figure 3, and the source is described in more detail in Ref. [2].

Recently, OPPLIS was used to demonstrate that for low momentum transfers (<1.3 fm$^{-1}$) the analyzing powers and cross-sections for the elastic scattering of $^7$Li by a variety of targets depend only on the properties of the projectile—and not on those of the target [3]. This result shows that the properties of loosely bound radioactive beams such as $^4$He, $^8$B, and $^{11}$Li can be obtained from elastic scattering no matter what target is used as long as the momentum transfers are not too large.

**FSU γ-ray Detector Array**

The FSU Compton-suppressed γ-ray detector array consists of three Compton-suppressed “Clover” segmented germanium detectors and ten Compton-suppressed single-crystal germanium detectors. The array presently also includes several Compton-suppressed germanium systems from the Holifield Radioactive Ion Beam Facility at Oak Ridge National Laboratory.

A segmented silicon particle detector array, liquid scintillator neutron detector, and plunger for Recoil Distance Measurements are available as auxiliary detectors. The array is shown in Figure 4.

The γ-ray detector array and particle detector array were recently used to find five new states in the neutron-rich nucleus $^{20}$O using the laboratory’s $^{12}$C beam and a radioactive $^{10}$Be target in the $^{10}$Be($^{12}$C,$^{4}$He)$^{20}$O reaction [4]. Shell model calculations suggested that most of the newly observed states resulted from promotions of nucleons across the $Z = 8$ and $N = 8$ shell gaps, and that the sizes of these gaps are decreasing steadily as the neutron dripline is approached.

**Work at Major Radioactive Beam Facilities and Gammasphere**

The FSU Laboratory has a large research effort at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University and is involved with several of the major research groups there. Members of the FSU Laboratory led a collaboration that included the NSCL Gamma Group, the University of Surrey, and the University of California—Berkeley in a study of the near-neutron dripline nucleus $^{42}$Si and two neighboring nuclei using knockout reactions. The results, which were published in *Nature* [5], established the existence of the $Z = 14$ subshell closure in this nucleus and challenged the notion that this nucleus is deformed because of the hypothesized collapse of the $N = 28$ major shell closure.

Another collaboration led by FSU (with the NSCL $\beta$-decay group, the University of Tokyo, RIKEN and JAERI) led to the observation that while intruder configurations (promotions of pairs of neutrons across the $N = 20$ major shell closure) do not appear in the low-energy level structure of the

![Figure 2. A schematic of RESOLUT.](image1)

![Figure 3. A schematic of the FSU Optical Polarized Lithium Source.](image2)
$N = 17$ nucleus $^{28}\text{Na}$, they do occur at low energies in the $N = 18$ isotope $^{29}\text{Na}$ [6]. This suggests that the $N = 20$ shell closure narrows significantly in going from $N = 17$ to $N = 18$, heralding the arrival of the island of inversion, which is highlighted by the strongly deformed $N = 20$ isotones $^{30}\text{Ne}$, $^{31}\text{Na}$, and $^{32}\text{Mg}$.

The NSCL’s new sweeper magnet, which is used to study reactions in which neutrons are stripped from neutron-rich nuclei, was constructed at FSU’s National High Magnetic Field Laboratory. One of the detection systems used to detect the stripped neutrons is MoNA, the Modular Neutron Array. The array was constructed by a unique collaboration including the NSCL and FSU and several other institutions that emphasize undergraduate education.

The FSU laboratory also has active collaborations with GSI and GANIL. Members of the laboratory have been involved with the observation of proton-proton correlations observed in the two-proton radioactivity of a high spin isomer in $^{94}\text{Ag}$ at GSI [7] as well as the confirmation of a strong $N = 14$ sub-shell closure in the near-neutron dripline nucleus $^{22}\text{O}$ using inverse kinematics proton scattering at GANIL [8].

The FSU laboratory continues to be heavily involved in work using the Gammasphere array. FSU led an exhaustive study of lifetimes of high spin states of strongly deformed nuclei in the mass 135 light rare earth region using the Doppler Shift Attenuation Method [9]. The work eliminated the systematic errors that commonly occur when such measurements are performed separately and demonstrated the validity of the additivity of single-particle quadrupole moments in this mass region.

**Hadronic and Relativistic Heavy Ion Physics**

The laboratory also hosts the FSU Hadronic Physics Group, which has been deeply involved with the CEBAF Large Acceptance Spectrometer (CLAS) since its conception. FSU is very active with the study of excited...
nucleon states and the search for so-called missing baryon resonances. These missing states are predicted by quark models based on three effective quark degrees of freedom, but have not been established experimentally. The group is presently preparing for polarization experiments using polarized beams and a frozen-spin butanol target (FROST). These measurements will provide the necessary constraints to disentangle the broad and overlapping baryon states. The group is also preparing for a high statistics search for gluonic hybrid mesons and strangeonia using CLAS. These measurements are scheduled back-to-back with the polarization experiments and form the next major projects at Hall-B (CLAS) of Jefferson Lab. The search for new forms of matter drives FSU’s efforts for GlueX, a $40-million detector that will be constructed for the upgraded 12 GeV CEBAF facility at Jefferson Laboratory. The Hadronic Physics Group continues to be active with several other experiments, including E852 at the Brookhaven AGS and the Crystal Barrel at Bonn.

The long history of heavy-ion physics at the FSU accelerator led to the laboratory’s involvement in PHENIX, one of the two major detectors at the Relativistic Heavy Ion Collider. The PHENIX Ring Imaging Cherenkov (RICH) detector, the primary electron identifier, was built in the mid to late 1990s by a collaboration of FSU, SUNY Stony Brook, KEK, Wasida University, CNS (Tokyo), Nagasaki IAS, and ORNL. FSU was responsible for all but the photon detector and its electronics. The RICH gas vessel is shown in Figure 5 prior to its departure from Tallahassee for Brookhaven National Laboratory. FSU has been heavily involved in the development of Level 2 triggers for PHENIX. A member of the FSU group currently serves on the PHENIX Executive Council and heads the Level 2 Trigger effort. FSU provided the PHENIX Run Coordinator for the first full energy RHIC run in 2001/2002. The FSU group works primarily on $J/\psi$ production in heavy ion collisions as a signature of deconfinement, and is presently leading the analysis of $J/\psi \rightarrow e^+e^-$ data from Cu+Cu collisions in Run 5.

References
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Enhanced Electron Screening in Metals:  
A Plasma of the Poor Man 

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For the astrophysically important class of charged-particle-induced fusion reactions, there is a repulsive Coulomb barrier in the entrance channel of height $E_c = \frac{Z_1 Z_2 e^2}{r}$, where $Z_1$ and $Z_2$ are the integral nuclear charges of the interacting particles, $e$ is the unit of electric charge, and $r$ is the radius. Due to the tunneling effect through the Coulomb barrier at energies $E < E_c$, the fusion cross section $\sigma(E)$ drops nearly exponentially with decreasing energy $E$:  

$$\sigma(E) = S(E) E^{-1} \exp(-2\pi \eta),$$  

(1)  

where $\eta = \frac{2\pi Z_1 Z_2 e^2}{\hbar v}$ is the Sommerfeld parameter, $\hbar$ is the Planck constant, and $v$ is the relative velocity of the interacting nuclides. The function $S(E)$ contains all nuclear effects and is referred to as the nuclear or astrophysical $S(E)$ factor. In this parametrization of the cross-section it is assumed that the Coulomb potential of the target nucleus and projectile is that resulting from bare nuclei. However, for nuclear reactions studied in the laboratory, the target nuclei and the projectiles are usually in the form of neutral atoms or molecules and ions, respectively. The electron clouds surrounding the interacting nuclides act as a screening potential: the projectile effectively sees a reduced Coulomb barrier, both in height and radial extension. This, in turn, leads to a higher cross section for the screened nuclei, $\sigma_s(E)$, than would be the case for bare nuclei, $\sigma_b(E)$. There is an enhancement factor $[1,2]$,  

$$f_{ab}(E) = \frac{\sigma_s(E)}{\sigma_b(E)} = \exp(\pi \eta U_e/E) \geq 1,$$  

(2)  

where $U_e$ is an electron-screening potential energy. This energy can be calculated from the difference in atomic binding energies between the compound atom and the projectile plus target atoms of the entrance channel, or alternatively from the acceleration of the projectiles by the atomic electron cloud. For energy ratios $E/U_e > 1000$, shielding effects are negligible, and laboratory experiments can be regarded as essentially measuring the bare cross-section: $\sigma(E) \equiv \sigma_b(E)$. However, for $E/U_e < 100$, shielding effects begin to become important for understanding and extrapolating low-energy data. Relatively small enhancements arising from electron screening at $E/U_e = 100$ can cause significant errors in the extrapolation of cross-sections to lower energies, if the curve of the cross-section is forced to follow the trend of the enhanced cross-sections, without correction for the screening. Note that for a stellar plasma, the value of the bare cross-section $\sigma_b(E)$ must be known because the screening in the plasma could be quite different from that in the laboratory nuclear-reaction studies, that is, $\sigma_p(E) = f_p(E) \sigma_b(E)$, where the plasma enhancement factor $f_p(E)$ together with $\sigma_b(E)$ must be explicitly included for each situation. A good understanding of electron-screening effects in the laboratory is needed to arrive at reliable $\sigma_s(E)$ data at low energies (for independent $\sigma_s(E)$ data, see indirect methods such as the Trojan-Horse-Method [3]). An improved understanding of laboratory electron screening may also help eventually to improve the corresponding understanding of electron screening in stellar plasmas, such as in our sun. According to Eq. (2) one expects an exponential enhancement at low energies in the laboratory, which can be described by a single parameter $U_e$.  

Experimental studies of fusion reactions involving light nuclides ([4] and references therein) have shown the expected exponential enhancement of the cross-section at low energies, which could be described by a single value for $U_e$. However, the observed enhancements were in several cases larger (up to about a factor 2) than could be accounted for from available atomic-physics models, that is, the adiabatic limit $U_{\text{ad}}$.  

Recently, the electron screening in d(d, p)t has been studied for deuterated metals, insulators, and semiconductors, that is, 58 samples in total ([6–8] and references therein). As compared to measurements performed with a gaseous D2 target ($U_e = 25 \pm 5$ eV [5]; $U_{\text{ad}} = 2 \times 13.6$ eV = 27.2 eV), a large screening was observed in all metals (of order $U_e = 300$ eV, i.e. a factor 10 higher than $U_{\text{ad}}$), whereas a small (gaseous) screening was found for the insulators and semiconductors.  

Suggested solutions of the large enhancements including aspects such as stopping power, beam intensity, thermal...
motion, channeling, solid state properties, and Fermi shuttle acceleration mechanism were not successful [7]. Finally, an explanation of the large screening in metals was suggested [7] by the Debye plasma model applied to the quasi-free metallic electrons. The electron Debye radius around the deuterons in the lattice is given by

\[ R_D = (\varepsilon_0 k T / e^2 n_{\text{eff}} \rho_a)^{1/2} = 69 (T / n_{\text{eff}} \rho_a)^{1/2} [\text{m}] \]  

with the temperature \( T \) of the quasi-free electrons in units of K, \( n_{\text{eff}} \) the number of these electrons per metallic atom, and the atomic density \( \rho_a \) in units of atoms/m\(^3\). With the Coulomb energy of the Debye electron cloud and a deuteron projectile at \( R_D \) set equal to \( U_e = U_D \), one obtains

\[ U_D = 2.09 \times 10^{-11} (n_{\text{eff}} \rho_a / T)^{1/2} [\text{eV}] \]  

For \( T = 293 \text{ K} \), \( \rho_a = 6 \times 10^{28} \text{ m}^{-3} \), and \( n_{\text{eff}} = 1 \) one obtains a radius \( R_D \), which is about a factor 10 smaller than the Bohr radius of a hydrogen atom; furthermore, one obtains \( U_D = 300 \text{ eV} \), the order of magnitude of the observed \( U_e \) values. A comparison of the calculated and observed \( U_e \) values led to \( n_{\text{eff}} \) values, which were for most metals of the order of one. The acceleration mechanism of the incident ions leading to the high observed \( U_e \) values is thus the Debye electron cloud at the rather small radius \( R_D \).

The \( n_{\text{eff}} \) values have been compared with those derived from the Hall coefficient: they agreed within experimental uncertainties for all metals with known Hall coefficient. Another critical test of the Debye model is the predicted temperature dependence, \( U_D \propto T^{-1/2} \), that is, a decrease of \( U_D \) with increasing temperature, which was experimentally verified (Figure 1).

Furthermore, the Debye energy \( U_D \) should scale with the nuclear charge \( Z_t \) of the target atoms. The prediction was verified [9–11] in \(^7\text{Li}(p,\alpha)\alpha\) and \(^6\text{Li}(p,\alpha)^3\text{He} \) \( (Z_t = 3) \), \(^9\text{Be}(p,\alpha)^6\text{Li} \) and \(^8\text{Be}(p,\alpha)^7\text{Li} \) \( (Z_t = 4) \), \(^{50}\text{V}(p,n)^{50}\text{Cr} \) \( (Z_t = 23) \), and \(^{176}\text{Lu}(p,n)^{176}\text{Hf} \) \( (Z_t = 71) \), always for pure metals and alloys. The data demonstrate that the enhanced electron screening occurs across the periodic table and is not restricted to charged-particle-induced reactions among light nuclides studied so far [4]. The \(^7\text{Li}\) and \(^6\text{Li}\) data (Figure 2) demonstrate with high precision the isotopic independence of the electron screening effect, that is, the same \( U_e \) value for the \(^7\text{Li}\) and \(^6\text{Li}\) nuclides, particularly in the cases of the Li metal and PdLi\(_x\) alloys. The two reactions with neutrons in the exit channel demonstrate further that the electron screening is an effect in the entrance channel of the reaction and not influenced by the ejectiles of the exit channel, that is, by the charged particles of the exit channel studied so far [4].

Finally, the Debye model predicts a dependence on the nuclear charge of the target, \( U_D \propto Z_t \); the prediction was verified in the \(^{4}\text{He}(p,\alpha)^4\text{He} \) studies in metals \( (Z_t = 2) \): taking a typical value of \( U_e = 300 \text{ eV} \) for the d+d fusion reaction in metals at \( T = 290 \text{ K} \), one expects for \(^{4}\text{He}(p,\alpha)^4\text{He} \) the Debye value \( U_D = Z_t U_e(d+d) = 600 \text{ eV} \), consistent with observation \( U_e = 680 \pm 60 \text{ eV} \).

It should be noted that the Debye model is used to calculate the effects of electron screening on fusion reactions in a stellar plasma, \( f_r(E) \). Using a metallic plasma the Debye model was tested successfully with respect to all parameters entering the model. One may thus call metals “a plasma of the poor man.” An improved theory is highly desirable to explain why the simple Debye model appears to work so well. Without such a theory, one may consider the Debye model as a parametrization of the data, with an excellent predictive power.

There is another important prediction of the Debye model concerning radioactive decay of transuranic nuclides in a metallic environment. In general, for the \( \alpha \)-decay and \( \beta^+ \)-decay one expects a shorter half-life due to the acceleration mechanism of the Debye electrons for these positively charged particles similar as for the protons, deuterons or...
3He in the fusion reactions, whereas for the β−-decay and e-capture process one predicts a longer half-life (here: deceleration of the negatively charged particles). For example, if the α-decay $^{210}\text{Po} \Rightarrow \alpha + ^{206}\text{Pb}$ with $E_\alpha = 5.30$ MeV and $T_{1/2} = 138$ days occurs in a metal cooled to $T = 4$ K, one arrives at $U_2 = Z_2Z_1U_e(d+d)(290/4)^{1/2} = 2 \times 82 \times 300\text{eV} \times 8.5 = 420$ keV, where we used again a typical value of $U_e = 300$ eV for the d+d fusion reaction in metals at $T = 290$ K. The enhancement factor then gives $f_{\text{lab}} = 265$, and thus the half-life is shortened to 0.5 days. For the biologically dangerous transuranic waste $^{226}\text{Ra} \Rightarrow \alpha + ^{222}\text{Rn}$ ($E_\alpha = 4.78$ MeV, $T_{1/2} = 1600$ years) an analogous calculation leads to $T_{1/2} = 1.3$ years. Experiments are in progress to test these predictions. If these predictions should also be verified, one may have a solution to remove the transuranic waste (involving all an α-decay) of used-up rods of fission reactors in a time period of a few years. Finally, a reduced half-life of α-emitters such as $^{238}\text{U}$ and $^{232}\text{Th}$ in a metallic environment may have important corrections in their use as cosmo-chronometers [2] (i.e., the age of the elements) as well as in understanding the flux of geo-neutrinos using the Kamland detector [12] (i.e., the energy source of the earth).

References
Laboratory Studies of Stardust

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Introduction
Since the 1950s it has been established that carbon and all heavier elements are produced in stars and that these elements are produced in different stellar sources with very different isotopic ratios [e.g., 1]. Although many stellar sources must have contributed material to the solar system, it was believed that this material had been thoroughly mixed during solar system formation and resulted in very uniform isotopic ratios. As a consequence, signatures of individual stars had been completely obliterated and the solar system or “cosmic” abundances of elements and isotopes, although providing an important touchstone for stellar nucleosynthesis, represented only an average of distinct stellar sources. This situation has been dramatically changed with the discovery in 1987 that primitive meteorites contain tiny grains of pristine stardust. These grains condensed in the outflows of evolved stars and in supernova ejecta, survived interstellar travel and solar system formation, and are preserved in certain meteorites [2–5]. Their presolar, stellar origin is indicated by their isotopic compositions, which encompass a vast range and are completely different from that of the solar system. The grains can be located in and extracted from their meteoritic hosts and studied in detail in the laboratory. Because a given grain is a piece of a star, it can provide information on stellar evolution and nucleosynthesis, galactic chemical evolution, physical conditions in stellar atmospheres, dust processing in the interstellar medium, and condition during solar system formation. Since the discovery of the first presolar grains, their study has grown into a new kind of astronomy, complementing traditional astronomical observations. After a general overview and discussion of laboratory analysis techniques I will concentrate on issues of nucleosynthesis and topics of nuclear physics interests (sections 5–8). The reader interested in obtaining more detailed information is referred to some reviews on presolar grains [2–7].

Isolation of Presolar Grains
The first hints of the survival of presolar signatures in solar system materials came from isotopic anomalies, isotopic ratios different from those dominating the solar system, in hydrogen and the noble gases neon and xenon. However, these hints were largely ignored and it was not until the discovery of anomalies in oxygen, a major rock-forming element [8], that the idea of survival of presolar material in primitive meteorites was taken seriously. However, it turned out that the solids exhibiting isotopic anomalies in oxygen (and, as it was soon found, in many other elements) had formed in the solar system and only inherited presolar signatures from their precursors. It took more than a decade to find bona fide stardust that had condensed in stellar sources. This feat was achieved by Ed Anders and his colleagues at the University of Chicago by, as Anders put it, “burning down the haystack to find the needle” [9]. In this approach, chemical dissolution and physical separation techniques were used to track the carriers of anomalous, so-called exotic, noble gas components and led to the separation of presolar diamond [10], silicon carbide (SiC) [11,12], and graphite [13]. These phases are not only high-temperature phases that must have had a condensation origin, but are also chemically resistant and thus could be isolated by harsh chemical treatment.

Although these carbonaceous phases carried exotic noble gases, which aided in their discovery, and although almost all SiC and graphite grains are of stellar origin, the identification of presolar oxide grains is more difficult. The reason is that the solar system is oxygen-rich (i.e., has O > C), leading to the formation of oxygen-rich minerals from processed, that is, isotopically homogenized, material, which constitute a large background. Identification of presolar O-rich grains requires isotopic measurements of individual grains in the ion microprobe (see section 4). Separation of oxide phases such as corundum (Al₂O₃) and spinel (MgAl₂O₄) by chemical processing still helps, because the fraction of presolar grains among these phases is much higher (1–2%) [14,15] than among silicates, where
only one grain out of 5,000 grains, and that only for grains smaller than 1 μm, is of presolar origin [16].

Types of Presolar Grains

In spite of the grains’ low abundance, their small size, and the background of isotopically normal grains of solar-system origin, an ever increasing number of different types of presolar minerals have been identified. Table 1 lists presolar grain types, their abundances, sizes, stellar sources, as well as nucleosynthetic signatures carried by the grains. Nanodiamonds are the most abundant, but they are only ~2.5 nm in size, precluding analysis of individual grains. Their presolar nature rests on the fact that they carry anomalous Xe and Te, but their average C isotopic ratio is normal (i.e., solar). Thus it cannot be ruled out that only a fraction of the diamonds have a stellar origin.

All other grain types are large enough that they can be analyzed as single grains for their isotopic compositions. Although silicates have the second-highest abundances, they have been discovered only in the last couple of years because of the overwhelming presence of isotopically normal silicates [16,17]. The abundance of oxides is also relatively high but only among sub-μm grain in the most primitive meteorites. Silicon carbide is the best studied grain type because almost pure SiC separates can be produced by chemical processing of meteorites, and because trace element concentrations are high enough so that many elements can be analyzed in addition to C and Si. Average grain sizes are less than 1 μm but grains up to 20 μm have been found. Figure 1 a shows an SEM image of an unusually large grain. Analysis in the ion microprobe has shown enormous ranges in the isotopic compositions of individual grains (Figure 2) and has led to the classification of different sub-types according to the C, N, and Si isotopic ratios of the grains [18]. Mainstream, Y, and Z grains most likely originated in C-rich Asymptotic Giant Branch (AGB) stars. Grains of type X come from supernovae, grains of type A+B probably from J stars and/or from post-AGB stars that have undergone a very late thermal pulse, and a few grains appear to have a nova origin. Silicon nitride grains are

Table 1. Presolar grain types.

<table>
<thead>
<tr>
<th>Grain type</th>
<th>Abundance’ ppm</th>
<th>Size μm</th>
<th>Stellar sources</th>
<th>Nucleosynthetic processes* exhibited by grains</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nanodiamonds</td>
<td>1400</td>
<td>0.002</td>
<td>SNe</td>
<td>r, p</td>
</tr>
<tr>
<td>Silicates in IDPs</td>
<td>~900</td>
<td>≤1</td>
<td>RGB and AGB</td>
<td>Core H</td>
</tr>
<tr>
<td>Silicates in meteorites</td>
<td>180</td>
<td>≤0.5</td>
<td>RGB and AGB</td>
<td>Core H, CBP</td>
</tr>
<tr>
<td>Oxides</td>
<td>110</td>
<td>0.15–2</td>
<td>RGB, AGB, SNe</td>
<td>Core H, CBP, HBB, Shell H, He, s</td>
</tr>
<tr>
<td>Mainstream SiC</td>
<td>14</td>
<td>0.3–20</td>
<td>AGB</td>
<td>Core H, Shell H, Shell He, s</td>
</tr>
<tr>
<td>SiC type A+B</td>
<td>0.25</td>
<td>0.5–5</td>
<td>J stars?</td>
<td>Shell He and H</td>
</tr>
<tr>
<td>SiC type X</td>
<td>0.15</td>
<td>0.3–5</td>
<td>SNe</td>
<td>H, He, O, e, s, n-burst</td>
</tr>
<tr>
<td>Graphite</td>
<td>1</td>
<td>1–20</td>
<td>SNe, AGB</td>
<td>H, He, O, e, s, n-burst; Core H and He</td>
</tr>
<tr>
<td>Nova grains (SiC, gr.)</td>
<td>0.001</td>
<td>~1</td>
<td>Novae</td>
<td>Ex H</td>
</tr>
<tr>
<td>Si nitride</td>
<td>0.002</td>
<td>≤1</td>
<td>SNe</td>
<td>He, O</td>
</tr>
<tr>
<td>TiC</td>
<td>~0.001</td>
<td>0.01–0.5</td>
<td>SNe, AGB</td>
<td>He, O, e</td>
</tr>
</tbody>
</table>

*Abundances (in parts per million) vary with meteorite type. Shown here are the maximum values.

found in SiC-rich residues. They are extremely rare and have the isotopic signatures of SiC X grains, thus have a SN origin.

The separation of graphite is more complicated than that of SiC [19]. Most presolar graphite grains are larger than 1 μm (Figure 1b) and range up to 20 μm in size. They have been separated according to density [19]. Low-density grains have isotopic signatures that indicate a SN origin [20], whereas high-density grains seem to have an origin in C-rich AGB stars of low metallicity, that is, stars that were born with low abundances of “metals” (all elements heavier than He) [21]. Many graphite grains contain tiny sub-grains of titanium-, zirconium-, and molybdenum-rich carbides, cohenite (Fe₃C), kamacite (Fe-Ni) and elemental iron [22,23]. These grains must have condensed before the graphite and in some cases apparently acted as condensation nuclei (Figure 1c).

Analytical Techniques

Presolar grains have been analyzed for their size and morphology (SEM), internal structure (TEM), elemental (SIMS, Synchrotron XRS) and isotopic (SIMS, RIMS) compositions. Measurements of isotopic ratios are most important and by far most efforts have been devoted to them. Two basic types of isotopic analysis techniques have been applied, “bulk” analysis, the analysis of collections of large numbers of grains, and single grain analysis.

In spite of the low abundances of diamond, SiC and graphite in meteorites, chemical and physical separation provides essentially pure samples with enough grains for bulk analysis. Bulk analysis has been performed by Gas Mass Spectrometry for C, N, and the noble gases [24,25] and by Thermal Ionization Mass Spectrometry (TIMS) for the heavy elements Sr, Ba, Nd, Sm, and Dy [18]. Although only averages over many grains are obtained by these measurements, they make it possible to determine isotopic ratios of trace elements, which cannot be obtained on single grains. Measurements can be done on grain size and density separates, for gas MS by stepwise heating (pyrolysis) or combustion in an oxygen atmosphere.

Information on individual stars can be obtained by the analysis of single grains and correlations of isotopic ratios of several elements can serve to obtain the stellar history of a given grain. The technique of choice is Secondary Ion Mass Spectrometry (SIMS) with the ion microprobe. Single grain analysis revealed a tremendous range of isotopic ratios (see Figure 2). It also led to the identification of new grain types such as corundum and spinel [26] and silicon

Figure 1. Secondary electron (a and b) and transmission electron (c) microscope images of presolar grains. (a) This large SiC grain shows euhedral features. (b) Graphite grain with smooth, shell-like surface (“onion type”). (c) TEM micrograph of a microtome slice of a presolar graphite grain. The TiC grain in the center of the graphite spherule apparently served as a condensation nucleus. Scale bars in a and b are 1 μm, in c 100 nm.
nitride [27], as well as of rare sub-populations of SiC grains. Although most isotopic measurements in the past have been made on >1 μm grains, a new type of ion micro-probe, the NanoSIMS (Figure 3) allows analysis of grains down to 100 nm in size. It was instrumental in the discovery of presolar silicates in interplanetary dust particles [17] and primitive meteorites [16]. Laser ablation and Resonant Ionization Mass Spectrometry (RIMS) has been applied to the isotopic analysis of the heavy elements Sr, Zr, Mo, Ru, and Ba in single presolar SiC and graphite grains [28–30]. The unique advantage of this technique is its high ionization efficiency and the fact that a chosen element can be ionized selectively at the exclusion of any isobaric interferences. Thus it is possible to measure Zr isotopes in the presence of Mo and vice versa. Single grain measurements of He and Ne isotopes have been made by laser heating and gas MS [31].

**s-process Nucleosynthesis**

The agreement of the distribution of $^{12}\text{C}/^{13}\text{C}$ ratios found in carbon stars [32] with that in mainstream SiC grains indicates an origin in such stars. Further evidence is provided by the grains’ N isotopic ratios and the presence of radioactive $^{26}\text{Al}$ (deduced from excesses in its daughter $^{26}\text{Mg}$) and $^{22}\text{Ne}$ [24]. However, the most convincing evidence is obtained from the s-process patterns exhibited by all the heavy elements whose isotopic compositions have been measured to date (Figure 4). AGB stars have long been implicated as the main source of nuclei produced by the s-process, the slow capture of neutrons at neutron densities that are low enough that unstable isotopes can decay before another neutron is added [e.g., 33,34]. The evolution of the heavy elements thus progresses along the valley of stability. Two reactions provide neutrons in AGB stars: $^{13}\text{C}(\alpha,n)^{16}\text{O}$ and $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$. The first occurs under radiative conditions in the intershell between the H- and He-burning shells between thermal pulses. It is responsible for most of the s-process production of the heavy elements.

**Figure 2.** Nitrogen and carbon isotopic ratios of individual presolar SiC grains. Because rare grain types have been identified by special automatic imaging searches, the number of grains of different types do not correspond to their relative abundances in meteorites. These abundances are given in the legend. The dotted lines indicate the solar (terrestrial) isotopic ratios.

**Figure 3.** NanoSIMS, a new type of ion microprobe with high sensitivity and high spatial resolution. In this instrument a primary ion beam (Cs$^+$ or O$^-$) is focused onto the sample and by sputtering produces secondary ions. These ions are accelerated, separated according to their mass in a double-focusing magnetic mass spectrometer, and simultaneously detected in five different electron multipliers.
The second reaction occurs during the thermal pulses, lasts for a much shorter time, and results in much higher neutron densities [for details see Ref. (33)].

Figure 4 shows the isotopic patterns of heavy elements measured in bulk samples of SiC, which are dominated by mainstream grains. These patterns are characteristic of the s-process and for all elements except Dy agree very well with theoretical models of s-process nucleosynthesis in low-mass AGB stars [29,35]. The isotopic patterns allow the determination of different stellar parameters such as neutron exposure, temperature, and neutron density [18]. These parameters in turn depend on stellar mass and metallicity as well as on the neutron source. For example, the measured Ba patterns indicate a neutron exposure half of that inferred for the solar system. Another example is provided by the abundance of $^{96}$Zr, which is sensitive to neutron density because of the short half life (64 d) of $^{95}$Zr. The low $^{96}$Zr measured in individual grains indicates that the $^{22}$Ne($\alpha,n$) neutron source must have been weak, excluding intermediate-mass (M > 3M$\odot$) AGB stars as parent stars of mainstream SiC grains [29].

One interesting consequence of isotopic measurements in presolar SiC grains was that some results motivated nuclear astrophysicists to determine neutron-capture cross-sections with high precision. Discrepancies between Ba and Nd isotopic patterns measured in presolar SiC and the results of model predictions led to the suggestion that the cross-section used in the theoretical calculations were
incorrect. This suspicion was confirmed by subsequent improved cross-section determinations that successfully resolved the discrepancies [36–38].

Grains from Supernovae

For a given presolar grain the stellar source is unknown and must be inferred from the grain’s isotopic composition. From astronomical observations it was clear that RGB and AGB stars and supernovae were the most likely sources of the grains. A rare sub-type of SiC, the X grains have isotopic signatures that indicated a SN origin. These grains have large excesses of $^{28}\text{Si}$ relative to the heavier Si isotopes and most have $^{12}\text{C}$ and $^{15}\text{N}$ excesses (see Figure 2). Such signatures are predicted for different layers of core-collapse (Type II) supernovae [39,40]. The smoking gun for a SN origin of X grains was provided by the finding that they contain evidence for the presence of radioactive $^{44}\text{Ti}$ ($T_{1/2} = 60\text{ y}$) and $^{49}\text{V}$ ($T_{1/2} = 337\text{ d}$) at the time of their formation [41,42]. Both of these isotopes are only produced in supernovae, mostly in a layer that contains almost pure $^{28}\text{Si}$. Evidence for a SN origin is also found in low-density graphite grains in the form of $^{15}\text{N}$, $^{18}\text{O}$, and $^{28}\text{Si}$ excesses as well as evidence for the initial presence of $^{41}\text{Ca}$ and $^{44}\text{Ti}$ [20]. Silicon carbide X grains exhibit a Mo isotopic pattern that is completely different from that found in mainstream grains (Figure 5). Interestingly, it is not the pattern expected for the r-process (rapid addition of neutrons at very high neutron densities) but has been successfully explained by a neutron-burst model at intermediate neutron densities [43]. A neutron burst is predicted to occur in a narrow O-rich zone of Type II supernovae and can account for the Mo pattern in X grains [40].

Although the overall isotopic signatures of grains are consistent with theoretical predictions, the grain data present fundamental problems. One is that these signatures are found in completely different layers of the supernova: the high $^{28}\text{Al}/^{27}\text{Al}$ ratios found in X grains in the He/N zone, high $^{12}\text{C}/^{13}\text{C}$ and $^{18}\text{O}/^{16}\text{O}$ ratios in the underlying He/C zone, high $^{15}\text{N}/^{14}\text{N}$ ratios at the bottom of this zone, high neutron densities (n-burst) at the top of the underlying O/C zone, $^{28}\text{Si}$, $^{44}\text{Ti}$, and $^{49}\text{V}$ in the Si/S zone ($^{44}\text{Ti}$ and $^{49}\text{V}$ also in the underlying Ni core). It is still unclear how these different layers can be mixed together to produce the isotopic signatures observed in the grains, in particular in view of the fact that a huge layer consisting mostly of O lies between the C-rich layers and the Si/S layer. Another puzzle is why most of the SN grains identified so far are carbonaceous (SiC and graphite) and why only a handful of O-rich grains of a SN origin have been identified (Figure 6). Supernovae are predicted to contain far more O than C. Furthermore, theoretical models fail to predict in detail many isotopic ratios found SN grains [20]. Thus it is clear that the study of presolar grains provides new and fundamental challenges to nuclear astrophysicists.

Short-lived Radioisotopes

Many presolar grains contain evidence for the initial presence of short-lived, now extinct isotopes in the form of large...
excesses in the daughter isotopes of these radionuclides. In many cases these excesses are enormous so that there is little doubt that they are of radiogenic origin. I have already mentioned $^{44}$Ti and $^{49}$V. They are only produced in supernovae, both by α-rich freeze-out, $^{44}$Ti also by Si burning, in the Si/S and Ni zones. Both are of general astrophysical interest for different reasons, $^{44}$Ti because there is a chance that γ-rays from its decay can be detected in remnants of recent SN explosions, $^{49}$V because the initial presence of this isotope with a half-life of only 337 days implies grain condensation in SN ejecta on a time scale of a couple of years. Because neutron capture in the He/C zone can also produce $^{49}$Ti excesses [39,40], this signature by itself is no proof for initial $^{49}$V. However, the correlation between $^{49}$Ti excesses and the V/Ti ratio established its presence beyond any doubt [42].

Two other short-lived isotopes for which evidence was found in SN grains are $^{41}$Ca ($T_{1/2} = 1.05 \times 10^5$ y) [44] and $^{26}$Al ($T_{1/2} = 7.3 \times 10^5$ y) [for a summary see Ref. (3)]. In contrast to $^{44}$Ti and $^{49}$V, these two radionuclides are also produced in AGB stars and have, in fact, been detected in grains with an AGB origin. Inferred $^{41}$Ca/$^{40}$Ca (from $^{44}$K excesses) and $^{26}$Al/$^{27}$Al (from $^{26}$Mg excesses) ratios are much higher in SN grains than in grains from AGB stars. In SN grains the former range up to $1.6 \times 10^{-2}$, in agreement with theoretical predictions for n-capture production in the He/C, C/O, and the O-rich zone of SNII [39,40]. The latter range up to 0.6 in X grains; the highest ratios are predicted for the He/N zone, where $^{26}$Al is produced by proton capture on $^{26}$Mg. $^{41}$Ca/$^{40}$Ca measured in hibonite (CaAl$_2$O$_4$) grains from AGB stars [45] range up to $2 \times 10^{-4}$, in good agreement with theoretical predictions for n-capture production in the He shell. Inferred $^{26}$Al/$^{27}$Al ratios in mainstream SiC grains (up to $2 \times 10^{-3}$) agree with predictions for production in the H shell of AGB stars [e.g., 46]. However, ratios in many oxide grain (corundum, spinel, hibonite, silicate) are much higher, as will be discussed in the next section.

A short-lived isotope for which evidence has been only found in grains from AGB stars is $^{99}$Tc ($T_{1/2} = 2.1 \times 10^5$ y). RIMS analysis of Ru isotopes in single mainstream SiC grains revealed s-process patterns with depletions in all Ru isotopes relative to s-process-only $^{100}$Ru [30]. Whereas all measured ratios are in good agreement with AGB models, $^{98}$Ru shows systematic excesses, which have been successfully explained by incorporation and decay of $^{99}$Tc in the grains. It is fitting that a signature of this elements, whose presence in stars [47] was the first astronomical evidence for stellar nucleosynthesis, has now been found in stardust studied in the laboratory.

**Evidence for Stellar Mixing**

The isotopic analysis of presolar grains provides evidence for mixing processes in their stellar sources. I already mentioned the fact that SN grains carry isotopic signatures that have their origin in very different stellar zones. Their presence in individual grains implies mixing of these zones, although the details of these mixing processes are still not understood [20]. Another example where isotopic ratios measured in presolar grains indicate mixing in stars is provided by the O isotopic ratios of O-rich grains (Figure 6). The O isotopic composition of Group 1 grains can be explained by core H burning and the first (and second) dredge-up whereby different $^{17}$O/$^{16}$O ratios indicate different stellar masses [48]. Group 3 grains mostly come from low- and Group 4 grains from high-metallicity stars. However, the large $^{16}$O depletions in Group 2 grains cannot be produced by standard models and an extra mixing process called cool bottom processing (CBP) has been proposed to explain them [49]. In this process, assumed to occur on the RGB and AGB, material from the convective envelope is believed to circulate to hot regions close to the H-burning shell where $^{16}$O is destroyed by $^{16}$O$(p,\gamma)^{17}$N. Such extra mixing has also been invoked to explain low $^{12}$C/$^{13}$C ratios and $^3$Li and $^3$He anomalies in RGB stars [50].

Additional evidence for CBP is given by the inferred $^{26}$Al/$^{27}$Al ratios found in many oxide grains, which range up to 0.1

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**Figure 6.** Oxygen isotopic ratios measured in individual O-rich presolar grains. The four groups defined by Nittler et al. [14] are indicated. The dotted lines indicate the solar (terrestrial) isotopic ratios.
[14,45,51]. However, standard models of H shell burning in AGB stars result in ratios of $\sim 2 \times 10^{-3}$ [46,52]. Consequently, CBP has also been invoked to account for the high $^{26}$Al/$^{27}$Al ratios in oxide grains. In their model Nollett et al. [53] use two parameters to characterize CBP, the circulation rate, which mostly affects the $^{18}$O/$^{16}$O ratio in the envelope, and the temperature reached by the circulated material, which mostly affects the $^{26}$Al/$^{27}$Al ratio. Not all AGB stars experience CBP and one of the subjects of current research is which stars did and which ones did not. The parent stars of mainstream SiC grains apparently did not. Is it possible that CBP prevented O-rich stars from becoming carbon stars, so that evidence for effects of CBP on $^{26}$Al/$^{27}$Al ratios are only seen in O-rich but not C-rich grains?

Conclusions

The study of presolar dust grains in the laboratory has become a new branch of astronomy. The grains provide information on isotopic ratios that could not be obtained from stars. Of special interest are results that do not agree with stellar models and thus trigger the introduction of new models (e.g., CBP), the measurement of cross sections (Ba, Nd), or the search for new processes not considered before (neutron burst). The field is vigorously expanding and technical advances are expected to yield new surprises.

References

Lattice QCD at Non-Vanishing Temperatures and Chemical Potentials

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Introduction

Quantum Chromo-Dynamics (QCD) describes the physics of strong interactions. These phenomena are in many cases non-perturbative. A particularly interesting sector of the strong interactions is at extreme conditions. With increasing temperatures ($T$) we expect a transition at some $T = T_c$. The dominant degrees of freedom are hadrons in the low temperature phase and colored objects in the high temperature phase. Present lattice results suggest a cross-over and a critical point at some non-vanishing $T$ and chemical potential ($\mu$).

Because we are mostly interested in the physics around $T_c$, non-perturbative methods are necessary among which lattice QCD is the most systematic. There are at least two serious difficulties with lattice simulations. The first one is connected to the lightness of the quark masses. The cost of computations increases strongly as the quark masses decrease, therefore most lattice results were obtained with unphysically large quark masses. The second difficulty is connected to the continuum limit. Calculations are always performed at a finite lattice spacing ($a$). In order to get physical results, we have to take the $a \to 0$ limit. Because, for example, for the equation of state (EoS) the computational costs scale as $a^{-13}$ it is not surprising that up to very recently most results were obtained only at one set of lattice spacings.

The situation is much easier in the case of the pure gauge theory. The first problem does not exist because the quark masses are infinite. There are continuum extrapolated results, for example, for the equation of state, both with unimproved and improved lattice actions and they show nice agreement [1–3]. There are also numerous EoS results for the full theory with dynamical quarks [4–7], which will be discussed in the following.

For a long time it was believed that no physical answer can be given to questions with non-vanishing baryonic densities. The reason for that is the infamous sign problem, which spoils any Monte-Carlo method based on importance sampling. Recently, new techniques were developed, which are able to cover small to moderate baryonic chemical potentials at non-vanishing temperatures (chemical potential is used to set the baryonic density).

In this article recent results on non-vanishing densities and the determination of the EoS when approaching the physical quark mass and continuum limit are presented.

Lattice Formulation, Non-Vanishing Temperatures and Densities

Thermodynamical quantities can be obtained from the partition function, which can be given by a Euclidean path-integral:

$$Z = \int DU D\bar{\Psi} D\Psi \exp \{-S_E(U, \bar{\Psi}, \Psi)\}$$

(1)

where $U$ and $\bar{\Psi}, \Psi$ are the gauge and fermionic fields and $S_E$ is the Euclidean action. The lattice regularization of this action is not unique. There are several possibilities to use improved actions that have the same continuum limit as the unimproved ones. The advantage of improved actions is that the discretization errors are reduced.

Usually $S_E$ can be split up as $S_E = S_g + S_f$ where $S_g$ is the gauge action containing only the self interactions of the gauge fields and $S_f$ is the fermionic part. The gauge action has one parameter, the $\beta$ gauge coupling, whereas the parameters of $S_f$ are the $m_q$ quark masses and $\mu_q$ chemical potentials. For the fermionic action the two most widely used discretization types are the Wilson and staggered fermions.

For the actual calculations finite lattice sizes of $N_x \times N_t$ are used. The physical volume and the temperature are related to the lattice extensions as:

$$V = (N, a)^3, \quad T = \frac{1}{N, a}$$

(2)

Therefore lattices with $N_t >> N_x$ are referred to as zero temperature lattices whereas the ones with $N_t > N_x$ are
finite temperature lattices. Because the gauge coupling $\beta$ has the largest influence on the lattice spacing, it essentially determines the temperature (increasing $\beta$ increases $T$).

For large homogeneous systems the pressure is proportional to the free energy density. Unfortunately the free energy density $(-T/V \log Z)$ cannot be measured directly. We can only measure the derivatives of $\log Z$ with respect to the parameters of the action. Then, with an integration we can obtain the pressure. This method is known as the integral method for calculating the pressure. In order to remove the divergent zero-point energy we have to subtract the pressure measured on zero temperature lattices. Further thermodynamical quantities can be derived directly from the pressure. For example, the energy density ($\epsilon$), entropy density ($s$), and speed of sound ($c^*_s$) have the following relation with the pressure:

$$\epsilon = T \frac{dp}{dT} - p, \quad s = (\epsilon + p)T, \quad c^*_s = \frac{dp}{d\epsilon}.$$  \hspace{1cm} (3)

Although QCD at finite chemical potential ($\mu$, which as already mentioned, is used to set non-vanishing baryonic density) can be formulated on the lattice [8], standard Monte-Carlo techniques cannot be used at $\mu \neq 0$. The reason is that for non-vanishing real $\mu$ the functional measure—thus, the determinant of the Euclidean Dirac operator—is complex. This fact spoils any Monte-Carlo technique based on importance sampling. Several suggestions were studied earlier to solve the problem. Unfortunately, none of them was able to give physical answers for non-vanishing densities. About three years ago new techniques appeared, with which moderate chemical potentials could be reached on the lattice.

One of the most popular ideas [9,10] was to produce an ensemble of QCD configurations at $\mu = 0$ and at the corresponding transition temperature $T_c$ (or at any other physically motivated point for which importance sampling works). Then one determined the Boltzmann weights [11] of these configurations at $\mu \neq 0$ and at $T$ lowered to the transition temperatures at this non-vanishing $\mu$. An ensemble of configurations at a transition point was reweighted to an ensemble of configurations at another transition point.

**Line of Constant Physics**

Lattice calculations of the EoS are usually performed with a fixed $N_f$ and then, because in a fixed temperature range $N_f$ is inversely proportional to the lattice spacing, the continuum limit can be approached by increasing $N_f$.

Keeping $N_f$ constant means that the temperature can only be varied by changing the lattice spacing. This is usually achieved by varying the gauge coupling. If we want to keep, for example, the quark masses constant then the dimensionless lattice mass parameters $(am_q)$ have to be tuned accordingly. This defines the line of constant physics (LCP) in the parameter space.

If we keep the mass parameters constant and do not follow the LCP—which is the case in most EoS lattice studies—then we have to face the following unphysical situation. Cooling down two systems, one at $3T_c$ and one at $T_c$ to zero temperature, the quarks in the former case will be 3 times heavier. In this approach not $m_q$ but $m_q/T$ is kept constant.

**Previous Results on the Equation of State**

There are numerous lattice results for the EoS using dynamical quarks. However, in all cases the quark masses—for computational reasons mentioned in the introduction—were set to higher values than their physical one. The first results were obtained with staggered fermions. Calculations were performed by the MILC collaboration [4,5] and by Karsch, Laermann, and Peikert from Bielefeld [6]. The first calculation with Wilson fermions was done by the CP-PACS collaboration [7].

Staggered results are shown on Figure 1. No LCP was used in these cases, which means that the curves correspond to constant $m_q/T$, that is, increasing quark masses with increasing temperature. Figure 2 shows the EoS obtained with Wilson fermions for $N_f = 4$ and 6. The lowest quark mass used here corresponds to a pion mass of 500 MeV. The LCP was used in this analysis.

In the last years small nonzero chemical potentials [9,10] have also been used to determine the EoS [12–15].

Recently, at the lattice conference both the MILC collaboration [16] and the RBC–Bielefeld collaboration [17] reported on their ongoing work in QCD thermodynamics.

Although the published results all apply QCD with dynamical quarks they still have several weaknesses:

1. In all cases, unphysical quark masses were used, which results in unphysical pion masses. Because the transition temperature is higher than the physical mass of the pion, but smaller than the pion masses used in these calculations, it might be important to use physical values.

2. The works with staggered fermions did not use the line of constant physics, which results in an unphysical dependence of the hadron masses on the temperature.
3. A known problem with staggered fermions is the taste symmetry violation, which causes a non-physical non-degeneracy of the pion masses. This non-degeneracy disappears in the continuum limit, but it is still large for the lattice spacings used in these calculations.

4. The approximate R algorithm [18] was used for the calculations with 2, 3, or 2 + 1 flavors of staggered fermions. This algorithm has an intrinsic stepsize that leads to systematic errors in the results. In order to eliminate this systematics an extrapolation to zero stepsize should be performed. None of the previous works have done such an extrapolation. It should be mentioned that due to the subtraction in the calculation of the pressure the error coming from the typically used finite stepsizes is comparable with the result itself.

5. The discretization errors are still probably large. This is especially true for temperatures around and below $T_c$ where the lattice spacing of $N_t = 4$ lattices can be as large as 0.3 fm.

6. The determination of the physical scale is not always unambiguous. Ref. [6] uses, for example, the string tension, which is—strictly speaking—not an existing quantity in full QCD because at large distances the string breaks and a meson pair is produced.

### New Results with Physical Quark Masses, Equation of State

In the following the new results obtained in collaboration with Y. Aoki and K.K. Szabó are presented. Details of this work are found in Ref. [20]. We have determined the EoS for two sets of lattice spacings, $N_t = 4$ and 6. We improved on all points listed earlier.

**Lattice action, LCP**

The lattice action we used was a combination of the tree-level Symanzik-improved gauge action and the stout-improved fermionic action [21]. The stout improvement is known to reduce the taste symmetry violation significantly.

As mentioned earlier, using an approximate algorithm without performing the necessary extrapolations is dangerous. Instead we used the exact rational hybrid Monte-Carlo (RHMC) algorithm [22,23].
The quark masses were set to their physical values so that the meson masses agree with their physical values up to a few percent. Moreover, the physical quark masses were kept constant while increasing the temperature, that is, we followed the LCP.

In order to give the EoS in \(T/T_c\) units, we had to find the ratio of the scales at the different simulation points. For this we matched the static quark–antiquark potential for the different points at an intermediate distance. \(T_c\) was defined as the turning point of the isospin number susceptibility \([20]\).

The precise determination of \(T_c\), that is, connecting the scale to physical quantities, will be the subject of a subsequent publication.

Results

In order to present the \(N_t = 4\) and 6 results on the same plots we rescaled all quantities in the following way. At infinite temperatures all quantities should approach their free Stefan-Boltzmann limit \((c)\). This limit is, however, different in the continuum \((c_{\text{cont}})\) and on lattices with some fixed \(N_t(c_N)\). Therefore all results are scaled with a factor \(c_{\text{cont}}/c_N\) so that they could be compared with the continuum Stefan-Boltzmann limits.

Figure 3 shows the pressure and the energy density normalized by \(T^4\). For comparison, the Stefan-Boltzmann limit is also shown. Similarly, one can determine the entropy density, speed of sound, and quark number susceptibilities \([20]\).

**New Results with Physical Quark Masses, Critical Endpoint**

A critical point is expected in QCD on the temperature versus baryonic chemical potential plane. Our goal in this section is to determine the location of this critical point.

The lattice action we used was the unimproved staggered action with physical quark masses (it means, that the pion and kaon masses take approximately their physical values).

The partition function of lattice QCD with \(n_f\) degenerate staggered quarks is given by the functional integral of the gauge action \(S_g\) at gauge coupling \(\beta\) over the link variables \(U\), weighted by the determinant of the quark matrix \(M\), which can be rewritten \([9]\) as

\[
Z(\beta,m,\mu) = \int DU \exp\left[-S_g(\beta,U)\right] \quad \text{det}(M(m,\mu,U))^{1/4} = \int DU \exp\left[-S_g(\beta,\mu,U)\right] \quad \text{det}(M(m,\mu,U))^{1/4} \times \left[\exp\left[-S_g(\beta,\mu,U) + S_g(\beta,\mu,U)\right]\right]^{1/4}
\]
where $m$ is the quark mass, $\mu$ is the quark chemical potential and $n_f$ is the number of flavors. For non-degenerate masses one uses simply the product of several quark matrix determinants on the 1/4-th power. Standard importance sampling works and can be used to collect an ensemble of configurations at $m_w$, $b_w$, and $m_w$ (with, e.g., $\text{Re}(m_w) = 0$ or non-vanishing isospin chemical potential). It means we treat the terms in the curly bracket as an observable—which is measured on each independent configuration—and the rest as the measure. By simultaneously changing several parameters, for example, $b$ and $m$ one can ensure that even the mismatched measure at $b_w$ and $m_w$ samples the regions where the original integrand with $b$ and $m$ is large. In practice the determinant is evaluated at some $m$ and a Ferrenberg-Swendsen reweighting [11] is performed for the gauge coupling $b$. The fractional power in Eq. (4) can be taken by using the fact that at $m = m_w$ the ratio of the determinants is 1 and the ratio is a continuous function of the chemical potential. The details of the determinant calculation can be found in Ref. [10].

In the following we keep $\mu$ real and look for the zeros of the partition function on the complex $\beta$ plane. These are the Lee-Yang zeros [19]. Their $V \to \infty$ behavior tells the difference between a crossover and a first order phase transition. At a first order phase transition the free energy $\propto \log Z(\beta)$ is non-analytic. Clearly, a phase transition can appear only in the $V \to \infty$ limit, but not in a finite $V$. Nevertheless, the partition function has Lee-Yang zeros at finite $V$. These are at “unphysical” complex values of the parameters, in our case at complex $\beta$-s. For a system with a first order phase transition these zeros approach the real axis in the $V \to \infty$ limit (the detailed analysis suggests a $1/V$ scaling). This $V \to \infty$ limit generates the non-analyticity of the free energy. For a system with crossover the free energy is analytic, thus the zeros do not approach the real axis in the $V \to \infty$ limit.

Figure 4 shows $\text{Im}(\beta_{\text{end}})$ as a function of $\mu$ enlarged around the endpoint $\mu_{\text{end}}$. The picture is simple and reflects the physical expectations. For small $\mu$-s the extrapolated $\text{Im}(\beta_{\text{end}})$ is inconsistent with a vanishing value, and the prediction is a crossover. Increasing $\mu$ the value of $\text{Im}(\beta_{\text{end}})$ decreases, thus the transition becomes consistent with a first order phase transition.

Setting the scale leads to the final results of the analysis. As we already discussed, the quark masses, used to determine the endpoint, correspond approximately to their physical values. The pion to rho mass ratio, extrapolated to our $T \neq 0$ parameters, is 0.188(2) (its physical value is 0.179), whereas the pion to K mass ratio in the same limit is 0.267(1) (its physical value is 0.277).

Figure 5 shows the phase diagram in physical units, thus $T$ as a function of $\mu_B$, the baryonic chemical potential (which is three times larger then the quark chemical potential). At $\mu = 0$ the transition between the hadronic and
quark-gluon plasma phases is a cross-over. As we increase the chemical potential the transition temperature decreases, but the transition itself remains a cross-over. At a given endpoint chemical potential the transition is a second order one. For even larger chemical potentials the transition temperature further decreases and the transition becomes a first order one. The curvature of the crossover line separating the QGP and the hadronic phases is given by

$$T/T_c = 1 - \frac{Cm^2}{T_c^2}$$

with $C = 0.0032(1)$.

The endpoint is at $T_h = 162 \pm 2$ MeV, $\mu_E = 360 \pm 40$ MeV.

Summary

Previous results using either staggered or Wilson fermions were discussed. They suffer from several weaknesses.

New results on the EoS were presented. Our analysis attempted to improve on previous analyses by several means. We used for the lightest hadronic degree of freedom the physical pion mass. We used two different sets of lattice spacings ($N_t = 4, 6$). The system was kept on the line of constant physics (LCP) instead of changing the physics with the temperature. Due to our smaller lattice spacing and particularly due to our stout-link improved fermionic action the unphysical pion mass splitting was much smaller than in any previous staggered analysis. An exact calculation algorithm was applied.

We presented results for the pressure and energy density. In a similar way results for the entropy density, speed of sound, and the isospin and strangeness susceptibilities can be obtained.

Although a continuum extrapolation could already be performed with the current data, because the $N_t = 4$ lattices are rather coarse (especially around and below $T_c$) it would be safer if the EoS on even finer lattices ($N_t = 8$) were obtained. Such an analysis would be a major step toward the final results for the equation of state.

We also discussed the overlap-improving multiparameter reweighting technique, in order to calculate physical observables at non-vanishing temperatures and chemical potentials. A critical point is expected in QCD on the temperature versus baryonic chemical potential plane. Using the above lattice method for $\mu \neq 0$ we studied dynamical QCD with $n_f = 2 + 1$ staggered quarks of physical masses on $N_t = 4$ lattices. We used physical quark masses in this analysis. Our result for the critical point is $T_E = 162 \pm 2$ MeV and $\mu_E = 360 \pm 40$ MeV. The continuum limit extrapolation is also missing in this case.

Acknowledgments

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The computations [25] were carried out at Eötvös University on the 330 processor PC cluster of the Institute for Theoretical Physics and the 1024 processor PC cluster of Wuppertal University.

Figure 4. $\text{Im} (\beta^2)$ as a function of the chemical potential.

Figure 5. The phase diagram in physical units. Dotted line illustrates the crossover, solid line the first order phase transition. The small square shows the endpoint. The depicted errors originate from the reweighting procedure. Note, that an overall additional error of 1.3% comes from the error of the scale determination at $T = 0$. Combining the two sources of uncertainties one obtains $T_E = 162 \pm 2$ MeV and $\mu_E = 360 \pm 40$ MeV.
References

Experiments with Stored Relativistic Exotic Nuclei at the FRS-ESR Complex

Introduction

For almost three decades, storage and cooler rings have been indispensable tools for atomic, nuclear, and high-energy physics. While electrostatic storage rings (ELISA at Aarhus, Denmark; CSR at Heidelberg, Germany) are specialized for the lowest beam kinetic energies, electromagnetic rings cover the energy range from the Coulomb barrier (ASTRID at Aarhus, Denmark; TSR at Heidelberg, Germany; CRYRING at Stockholm, Sweden) up to the relativistic regime (CELSIUS at Uppsala, Sweden; COSY at Jülich, Germany; IUCF at Bloomington, USA). The past LEAR machine, the present AD (both located at CERN in Geneva, Switzerland), and the future FAIR-facilities HESR and FLAIR will provide antiproton beams at relativistic and low energies (from a few MeV down to rest).

The experimental storage ring ESR of GSI at Darmstadt, Germany, is the only existing storage-ring facility for experiments with radioactive, highly charged ions. This is due to the worldwide unique combination with an in-flight separator, the FRagment Separator FRS [1]. The investigation of exotic nuclei in a heavy-ion storage and cooler ring opens up a new field of precision experiments. Already the first experiments showed the discovery potential for nuclear structure and astrophysics [2–4] The high charge states strongly affect those decay channels of radioactive ions, which involve the atomic cloud, such as electron conversion and electron capture branches, but also led to the discovery of new decay modes like the beta-decay to bound states of the released electron [5]. Mapping of wide ranges of the mass surface benefits from the large variety of cocktail beams provided by the FRS and the ESR’s capability to act as a high-resolution multi-turn mass spectrometer.

Planned in the 1980s, the FRS-ESR complex has stimulated many technical forefront developments and yielded several physics highlights since the beginning of its operation in the early nineties. Some of the important achievements of the first-generation experimental program at FRS-ESR will be presented in the following.

Novel Methods

Energetic secondary beams are produced by projectile fragmentation in peripheral collisions of relativistic heavy-ion beams and by fission of uranium beams after electromagnetic excitation in the production target of the FRS. This low excitation-energy fission is particularly interesting because it leads to hitherto inaccessible, neutron-rich nuclides [6]. Subsequent separation in-flight allows one to inject mono-isotopic beams or well-defined cocktail beams of exotic nuclei into the ESR. At typical energies of 400–800 MeV/u the ions are fully stripped off their electrons when penetrating through matter, because the velocity is similar to or even exceeding the orbital electron velocities, thus leading to bare nuclei or to few-electron ions. The beam quality of the separated fragments can be considerably improved by stochastic precooling [7] and electron cooling in the ESR [8]. While stochastic cooling is best suited for beams with large longitudinal momentum spread (of the order of several permille to percent), electron cooling leads to highest phase-space densities and a final relative velocity spread of the order of 10^-7. Cooling times of few seconds can be reached, see Figure 1. At intensities below a few thousand ions Coulomb-ordered, crystalline beams [8,9] are formed. Depending on the residual gas composition and pressure and on the cooler electron current, stored beams have typical lifetimes of about one hour (for the heaviest species such as bare uranium nuclei) up to about one day (for lighter nuclei such as neon) and can thus be observed for long times.

In the last years the experimental progress was intimately connected with the development of new and challenging measurement and detection methods such as time-resolved Schottky spectrometry [11], the operation of the ESR in the isochronous mode [12] (a mode that is usually avoided for circular accelerators, because it lacks phase focusing and leads to unstable operation), and a fast, ultra-high-vacuum compatible time pick-up detector [13] including a data acquisition system that employs ultra-fast signal sampling (sampling rates up to 20 giga-samples per second are used for the recording of signals from the time pick-up detector). Both, the time pick-up detector and time-resolved Schottky spectroscopy reach the ultimate sensitivity for single ions and are therefore ideal diagnostic tools for experiments with weak secondary beams. The Schottky noise power is proportional to the beam intensity.
Decay studies can be performed with a time resolution of about one second. Based on these developments, two new, complementary techniques, have been, for example, pioneered for direct mass measurements: Schottky Mass Spectrometry (SMS) [14,15] andIsochronous Mass Spectrometry (IMS) [16,12]. SMS is based on cooled beams and employs time-resolved Schottky spectroscopy for analysis of the intensities and revolution frequencies of the ions, see Figure 2. The cooling time is the limiting parameter for the accessible half-lives of the order of about one second. IMS fully profits from the short separation times of an in-flight system (few 100 ns) and allows the time-of-flight mass measurement within few microseconds.

**Example Results**

**Mapping the Mass Surface**

Both methods, SMS and IMS, are capable of mapping large areas of the nuclear mass surface with typical accuracy between 30...100 keV. Figure 3 shows a part of those nuclides, whose mass was experimentally determined at FRS-ESR for the first time. In one of the runs, neutron-deficient nuclei were produced by bismuth fragmentation [11], and with SMS the masses of almost 465 different isotopes were directly determined, more than 170 of them were previously unknown. Some additional 107 new masses could be obtained by using the links of α-chains, leading to one of the most important results of these experiments: the location of the proton-drip-line in the region of francium [15,17]. Moreover, the shell gap energy of neutron-deficient lead isotopes was probed and yielded new insights on the deformation effects in this area [17,18].

IMS is suited to investigate very short-lived nuclides such as uranium fission products with millisecond half-lives or even less. With primary-beam intensities of $2 \times 10^9$ uranium ions per spill the measurements reach presently out up to e. g. $^{135}$Sn. The new mass data in the vicinity of closed shells ($N = 50.82, Z = 28.50$) and in particular in the vicinity of double shell closures contribute to the investigation of isospin dependence of shell and pairing effects [19] and the long-standing question of possible shell quenching. The potential prospects of combined FRS-ESR experiments are illustrated with the new isotope $^{235}$Ac in the right part of Figure 2, indicating its simultaneous first identification, mass determination and half-life measurement [20].

**Half-Lives, New Decay Modes**

Some nuclear decays involve atomic electrons and are thus altered by changes of the ionic configuration. The most dramatic modifications occur in $^{163}$Dy, a stable nucleus when dressed, but radioactive when fully ionized. It decays to $^{163}$Ho$^{1+}$ with a half-life of $T_{1/2} = 48 \pm 5$ days [5]. The reason is the changing Q-value from a negative to a positive value. Sounding paradoxical, the difference of atomic ionization energies of the now missing shells of mother...
and daughter ion is additionally available for the nuclear decay. This effect led to the discovery of a long predicted new decay mode: the beta-decay to bound states \[ \beta^b \] in 207\(^{+}\)Tl, where the emitted electron becomes bound in an inner atomic shell of the daughter nucleus. This two-body beta-decay is the time-reversed orbital electron capture. Together with the FRS, these basic experiments were recently extended to secondary beams, which ideally allow the choice of the best-suited candidates (in terms of Q-value, half-life, branching ratios, etc.). Studying the bound-state beta-decay \( \beta^b \) it is possible to obtain a wealth of unique information \[ \beta^b \]: total and partial \( \beta^b \)-decay rates, the \( Q_{\beta^b} \)-value, and the “Fermi-function,” which is the ratio of bound and continuum electron wave function at the origin. This function has been probed for \( \beta^- \)- and electron-capture decay, but never before for \( \beta^+ \)-decay. For the first time a branching ratio of this new decay mode was measured, the result is shown in Figure 4. The newly available phase-space of the empty electron shells leads to an additional decay branch and a half-life which is shorter by 11%.

Besides decays involving leptons, also hadronic decays such as proton- and \( \alpha \)-radioactivity are expected to vary characteristic properties. The missing electron screening of the nuclear charge distribution results in an increased Coulomb-barrier height and thus to reduced decay probabilities. Depending on the Q-value, this effect may alter the decay rates by up to 100%, which will be an issue for coming studies.

**Applications in Nuclear Astrophysics**

Origin and evolution of the chemical elements and the explanation of the observed stellar, in particular the Solar abundance pattern(s) belong to those questions in astrophysics, where nuclear data add key contributions. Charged-particle fusion reactions account for the abundances of nearly all metals up to the iron group, whereas almost all isotopes beyond iron are created from captures of free neutrons. Once the macroscopic parameters (seed material, densities, temperature, entropy, etc.) of quiescent burning phases of stellar plasmas and thermonuclear runaways are settled, the nucleosynthesis pathways, their endpoints, time scale, energy production and the final abundance pattern are mainly governed by nuclear reaction cross sections, mass-differences, and beta-decay rates. Masses play a crucial role because, for instance, the r-process follows a trail in the chart of nuclei, which is characterized by a neutron-separation energy of \( \approx 2 \) MeV.
Network calculations rely on data of up to about 6,000 nuclei. Schottky and Isochronous Mass Spectrometry, capable of probing large fractions of the mass surface rather than isolated spots, are extremely valuable to test mass predictions over a wide range of proton and neutron numbers, to stimulate improvements and to allow for extrapolations into unknown territory. It is also obvious, that at typical temperatures \( kT \approx 30 \text{ keV} \) (s-process) or \( >100 \text{ keV} \) (r-, rp-process), nuclear disintegrations occur mainly from bare nuclei or highly-charged ions, leading to significantly changed decay rates, in extreme cases decay channels may even become totally blocked, others may appear newly. Age-dating techniques and nuclear cosmo-chronometers, mostly used to put lower limits on the age of the Galaxy, are clearly affected by these environmental effects and still suffer from some uncertainties. Reliable data are thus needed.

**Summary and Outlook**

The tremendous research potential of storage-ring experiments with unstable beams has been pioneered at the FRS-ESR facility. Novel techniques, such as electron and stochastic cooling for relativistic heavy ions, Schottky and Isochronous Mass Spectrometry, first tests for elastic scattering off internal targets and novel experimental studies probing the dielectronic recombination, decay-studies of bare exotic nuclei and high-precision atomic-structure and QED-studies with highly charged ions [24] are only the most prominent examples to mention. Further exciting results are expected from new combined fragment-separator-storage-ring facilities, which will become operational soon, such as the HIRFL project at Lanzhou, China, and at RIKEN, Japan. The FRS-ESR facility described here serves as a model for these new facilities and simultaneously as the prototype for the upcoming NUSTAR facility comprising of the fragment-separator and storage-ring complex at FAIR [25,26]. The intensity gain of the new synchrotrons, the increased transmission of the SUPER-conducting FRagment Separator SUPER-FRS [1] for fission fragments (while preserving the characteristic mono-isotopic selectivity and single-particle sensitivity) and improved acceptance and cooling capabilities will allow nuclear-structure studies on nuclei which are presently out of reach, such as r- and rp-process nuclei, and neutron-rich drip-line nuclei up to the nickel region.

Increased performance is expected from a system of collector and storage-cooler rings, each of them equipped with unique instrumentation and specialized for dedicated experiments. The fast stochastic cooling acts on a time scale of typically 100 ms and leads to efficient storage and cooling of neutron-rich fission fragments. The CR collector ring is optimized for efficient capture and fast phase-space reduction of the fragment beams from Super-FRS and for Isochronous Mass Spectrometry with “hot” secondary

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**Figure 3.** Newly measured masses from SMS (large squares) compared with models. Absolute deviations from the HFB (left), HF+BCS (center) and FRDM (right) models are illustrated on the chart of nuclides [10].
beams, thus allowing to measure masses of species with half-lives down to a few microseconds with a precision of typically $\delta m \approx 50$ keV. The stochastically pre-cooled beams will be transferred into the new experimental storage ring NESR for precision mass measurements ($\delta m \approx 10$ keV, lower half-life limit $T_{1/2} \approx 50$ ms) and decay studies employing time-resolved Schottky Mass Spectrometry. Pure isomeric beams can be produced in favourable cases (half-lives exceeding $\approx 1$ s, excitation energies in excess of $\approx 1$ MeV).

Reaction studies in storage rings are typical second-generation experiments, which require the increased luminosities. A novel heavy-ion-electron collider will provide purely electromagnetically interacting probes for the Coulomb excitation of exotic nuclei [27]. Electrons permit single-step excitation to well-defined states. With conventional methods such experiments are restricted to stable nuclei, whereas the collider technique provides much cleaner conditions and gives access to exotic nuclei. The experiments will probe dipole strength distributions, shell structure, charge distributions and form factors by means of elastic and inelastic electron scattering. New opportunities for nuclear-structure studies arise from hyperfine interaction and isotope-shift measurements, for example, by the interaction with monochromatic photons from lasers or by the dielectronic recombination [28] of nuclei in an electron target of the NESR. Antiprotons colliding with exotic nuclei are a new hadronic probe to unravel nuclear matter distributions. Thus, new methods and new probes will open up a new field for precision experiments. An exciting new era is to be expected.

Figure 4. Left: first direct observation of bound-state beta-decay: traces of bare mother nuclei $^{206m, g}$Tl$^{81+}$ and hydrogen-like bound-beta-decay daughter $^{206}$Pb$^{81+}$, recorded and observed with time-resolved Schottky spectroscopy for approximately 20 min. Right: branching ratio of bound-state and continuum-state beta-decay as a function of $Q$-value for a nucleus with atomic number $Z=81$ (solid line) compared with the experimental value for the decay of bare $^{207}$Tl$^{81+}$ (data point, error bars are smaller than the symbol size).

References
facilities and methods

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12th Euroschool on Exotic Beams, 25 August–2 September 2005, Mainz, Germany

In summer 2005, the 12th Euroschool on Exotic Beams was held in Mainz, Germany. This school series started out in the 1990s at Leuven, Belgium. It is intended for doctoral students and post-docs working on physics and techniques related to radioactive ion beams. Since 2000 it has travelled to various places in Europe (Jyväskylä, Les Houches, Valencia, and Surrey). The next school will be held at ECT* in Trento, Italy, 11–15 September 2006.

This year’s school at Mainz brought together more than 70 students from 19 different, mostly European, countries, with both genders almost equally represented. It is a good practice of the school that lecturers and students live at the same location. Besides the lectures, there is ample time and opportunity for discussions and the exchange of ideas. The lectures were given by well-known specialists from universities and research laboratories in Europe and America. Among the main courses was a basic introduction on heavy-ion accelerators and on specific aspects of theoretical and experimental nuclear physics with exotic nuclei. A special session was devoted to the sustainability of nuclear energy and a comparison of various electricity supply options. During a poster exhibition students presented their own research work and could learn from each other. The one-day visit to a European large-scale research facility led the school this year to GSI at Darmstadt. Here, the attendees inspected the accelerator and experimental facilities. In particular, they learned about specific advantages of cancer therapy with heavy-ion beams. They recognized their future opportunities with the broad physics program addressed by the upcoming FAIR project.

A boat trip to the most scenic part of the Rhine river between Mainz and Koblenz provided a recreational break during the lecture program. The atmospheric farewell evening combined typical local food with live folksongs from different countries, presented by both lecturers and students. This balanced combination of hard work and leisure made the Euroschool on Exotic Beams an unforgettable event for all participants.

For more information on the Mainz school, including the program and the given lectures, see http://www-linux.gsi.de/~scheid/euroschool-05/home.htm. The Euroschool on Exotic Beams is funded by the EU under contract number HPCF-2001-00101-01.

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GSI Darmstadt
The 12th International Conference on Capture Gamma-Ray Spectroscopy and Related Topics

The 12th International Conference on Capture Gamma-Ray Spectroscopy and Related topics (CGS-12) was hosted by the University of Notre Dame from Monday, 5 September to Friday, 9 September 2005. The University of Notre Dame du Lac, founded in 1842 by a priest of the Congregation of Holy Cross, is an independent, national Catholic university located in a rather picturesque part of Indiana adjacent to the city of South Bend and approximately 90 miles southeast of Chicago. The conference was preceded by a one-day workshop on Nuclear Isomers organized by Professor Yang Sun on Sunday, 4 September 2005. The conference program was lively and interactive with a large number of women and young scientists giving invited talks. The conference theme varied across current topics in Nuclear Structure, Nuclear Symmetries, Nuclear Reactions with stable as well as radioactive ion beams, Nuclear Astrophysics, Tools of Nuclear Science from instrumentation to facilities, as well as Applications of Nuclear Science. The last meeting of the series, CGS-11, was held in Pruhonice near Prague in the Czech Republic in 2002. Some of the other conferences were held in Santa Fe, NM, USA (1999); Budapest, Hungary (1996); Fribourg, Switzerland (1993); Asilomar, USA (1990); Leuven, Belgium (1987); Knoxville, TN, USA (1984); Grenoble, France (1981); Brookhaven, USA (1978); Petten, the Netherlands (1974); and Studsvik, Sweden (1969).

More than 150 scientists from 23 countries attended this conference. The program was rather densely packed for five and a half full days with many excellent contributions from the speakers as well as those who presented their posters, making this conference a big success.

There are enormous changes in the field of interest for this conference over time. A main emphasis of the field has shifted toward Nuclear Astrophysics and toward other applications of nuclear science. New facilities have come on line specifically using neutrons with n_TOF at CERN, Geneva and DANCE at Los Alamos National Laboratory. Another pleasant surprise for us was the participation of significant numbers of women at this meeting.

The conference program at CGS-12 was scheduled to avoid any parallel sessions enabling all the participants to be a part of the entire program. In a special evening session—assisted by other spirits—we included a session on “Data for Nuclear- and Astrophysics Application” to address the needs of the collection, compilation and dissemination of nuclear data in our field. This was perhaps one of the liveliest sessions of the conference. An emerging trend is the shift toward web-based data bases and compilations. In addition to the existing nuclear data bases on nuclear structure and reaction cross-sections, new databases addressing are emerging for the special needs of reaction-rates for nuclear astrophysics.

A special session of the conference was dedicated to the memory of our dear friend, colleague, and one of the founding members of neutron capture spectroscopy, Dr. David D. Warner. Dave Warner was a member of the International Advisory Committee, one of the main invited speakers to CGS-12 and the first person to have registered on-line to attend CGS-12. Dave Warner was not only influential in developing the program in Nuclear Physics in the UK but also in Europe as well as the USA. He was on the advisory and executive committees of every facility in Europe, including the GSI-FAIR project, NuPecc, and the initial stages of planning for the Rare...
Isotope Accelerator in the US. Dave was a great friend, mentor, and colleague and he is missed more than we can say in words.

Professor Steven Yates of the University of Kentucky in Lexington funded a prize of $500 to be awarded to the best poster presented by a post-doctoral fellow or a graduate student. The Founder’s Award was inaugurated in honor of the memories of Jean Kern, Raman Subramanian, and Gabor Molnar. All three of them have played crucial roles in establishing the CGS series of conferences as well as hosting one of the former symposia for CGS. The best posters were chosen by the selection committee consisting of Professors Art Champagne (University of North Carolina at Chapel Hill), Alejandro Frank (UNAM—Mexico City, Mexico), and Jan Jolie (University of Koeln, Germany). The committee had a tough time deciding on a winner and they suggested splitting the prize among two graduate students. The winners were Hye Young Lee and Smarjit Triambak; both are presently graduate students at the University of Washington in Seattle working with his advisor Alejandro Garcia. Hye Young Lee works in Nuclear Astrophysics at the University of Notre Dame with her advisor Michael Wiescher.

The CGS-12 welcoming reception was held in the courtyard of the University of Notre Dame Snite Museum of Art with live music provided by the Nuclear Jazz Quartet. The collections of the Snite Museum of Art place it among the finest university art museums in the USA. The galleries were open for the conference participants and a special exhibit was held for CGS-12. The Fritz & Millie Kaeser Mestrovic Studio Gallery of the museum featured the BRANCACCI PROJECT—PHASE ONE.

In this series of murals, Bill Sandusky, professor of art at Saint Mary’s College (Notre Dame) had reinterpreted the fresco cycle painted in the Brancacci Chapel of Santa Maria del Carmine in Florence, Italy by Masaccio, Masolino, and Filippo Lippi, painted between about 1424 and 1480. Prof. Sandusky was available in the gallery on Sunday evening for a gallery talk and questions.

The conference excursion was to view the architectural styles of Chicago. We traveled by coach from Notre Dame to Chicago where we boarded “Chicago’s First Lady.” The
boat took us on an architectural roundtrip on the Chicago river and we got a humbling view of the skyscrapers of the Windy City. The conference dinner was served on the boat and the return from the lake was facing Chicago’s silhouette at night from Lake Michigan.

The conference ended with an impressive performance of “A Universe of Dreams” with the Ensemble Galilei with National Public Radio’s Neal Conan. The performance consisted of music, poetry, and stories with projected images from the Hubble Space Telescope capturing our imagination. The members of the advisory and program committees met for dinner in the Golden Dome at Notre Dame. The outcome was a unanimous decision to have the next conference in Cologne, Germany for the 2008 meeting. Professor Jan Jolie of the “Universität zu Köln” has agreed to organize the next conference. We are looking forward to 13th International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics (CGS-13)!

DR. ANDREAS WOEHR AND PROF. ANI APRAHAMIANT
Chair of CGS-12


The international conference entitled Frontiers In NUclear STructure, Astrophysics and Reactions (FINUSTAR) was held on the Aegean island of Kos, Greece, on September 12–17, 2005. The venue was the Kos International Convention Center (KICC) at the Kipriotis Village Resort. It was organized by the Institute of Nuclear Physics of the National Center for Scientific Research “Demokritos,” Athens, the Department of Physics of the University of Jyväskylä, Finland, and the Department of Physics of the National Technical University of Athens.

FINUSTAR covered a wide spectrum of research activities, both theoretical and experimental, in nuclear structure, nuclear astrophysics, and nuclear reactions. Although these research directions refer to different sub-communities of nuclear physics, the interplay between these fields has been strengthened over the last years mainly by utilization of common instrumentation and research facilities. The aim of FINUSTAR was to gather researchers from these scientific “brotherhoods” into closer contact in order to discuss common problems, present recent results, get informed about the latest developments in theory as well as the most recent achievements in instrumentation. To meet these goals, FINUSTAR included a long list of topics:

- Nuclear structure at the extremes
- Collective phenomena and phase transitions
- Nuclear masses and ground state properties
- Synthesis and structure of heaviest elements
- Mean field theories, shell model, cluster models, and molecular dynamics
- Nucleosynthesis in the cosmos and nuclear physics aspects
- Weak-interaction processes
- Nucleon scattering as a probe for nuclear structure
- Nuclear reactions off stability and indirect methods
- Reaction dynamics at low and intermediate energies
- Radioactive and exotic beams
- Facilities and instrumentation for the future

The conference was attended by 160 physicists from all 5 continents with a fair representation of all the major nuclear physics laboratories in the world. It featured 144 contributions, 80 of them given as oral and 64 as poster presentations. Ninety-two of them were based on experimental and 52 on theoretical results. The presentations were of excellent quality and invoked lively
and instructive discussions. Also worth mentioning is the impressively high percentage of young researchers among the speakers. The proceedings are to appear in AIP Conference Proceedings, Vol. 831.

In light of the enthusiastic response of the international nuclear physics community to FINUSTAR, we are planning to organize the second one of the series in the autumn of 2007.

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Workshop on the Physics of Compressed Baryonic Matter

About 130 theorists and experimentalists from 16 countries participated in a workshop on compressed baryonic matter that took place at GSI on December 15 and 16, 2005. The goal of the workshop was to review the physics of strongly interacting matter under extreme conditions, and to discuss future perspectives, theoretical and experimental, of the physics at high baryon density.

Tetsuo Hatsuda (Tokyo) opened the scientific session with a review of the present understanding of the QCD phase diagram. He identified four major phases: the hadronic phase at low temperatures $T$ and small baryon chemical potential $\mu_B$ where chiral symmetry is broken; the deconfined Quark-Gluon Plasma (QGP) phase at high $T$ and/or large $\mu_B$ where the quarks are asymptotically free; a phase of pre-formed pairs bound by strong residual forces located between the hadronic and the QGP phase; and a color superconducting phase at very low $T$ and very large $\mu_B$.

Recent developments in Lattice QCD calculations at finite baryon chemical potential $\mu_B$ were reported by Frithjof Karsch (Brookhaven/Bielefeld) and Zoltan Fodor (Wuppertal). In the calculations—which correspond to a pion mass well above the physical value—one finds a critical endpoint at $\mu_B \approx 300–400 \text{MeV}$, a first-order phase transition for larger and a crossover for smaller values of $\mu_B$. Clearly the discovery of the first-order phase transition and/or the critical endpoint would represent a major milestone on the way toward a quantitative understanding of strongly interacting matter.

Wolfram Weise (Munich) presented an effective field theoretical model for QCD thermodynamics, which includes features of both deconfinement and chiral symmetry restoration. In comparison with lattice QCD results he finds good agreement for observables like the quark number density for nonzero quark chemical potential.

The structure of compressed baryonic matter in the interior of compact stars was discussed by Fridolin Weber (San Diego). At baryon densities above 2 or 3 times saturation density one expects exotic states like hyperon matter, kaon or pion condensed matter, or quark matter. It was stressed that the composition of a pulsar core depends both on mass and on spin frequency. Dirk Rischke (Frankfurt) discussed conditions at low temperatures and very high quark chemical potentials ($\mu_q > 1 \text{GeV}$) where quark matter is predicted to form a color superconductor due to the attractive quark–quark interaction.

Ralf Rapp (Texas A&M University) addressed theoretical aspects of another fundamental goal of heavy-ion physics: the search for the onset of chiral symmetry restoration in hot and dense matter. He discussed possible consequences of chiral symmetry restoration on the in-medium spectral function of low mass vector mesons, which is relevant for dilepton spectroscopy in heavy-ion collisions. Recent experimental results were presented by Romain Holzmann (GSI) for the HADES collaboration, by Oliver Busch (GSI) for the CERES collaboration, and by Gianluca Usai (Cagliari) for the NA60 collaboration. Of particular interest is the invariant mass distribution of dimuon pairs measured by NA60, which indicates that the in-medium spectral function of the rho meson is broadened but not shifted in mass.

Burkhard Kämpfer (Dresden) discussed the properties of mesons and baryons using QCD sumrules. He explored the competition between the quark condensate and the 4-quark
condensate in different channels. In particular, he finds that the in-medium properties of the D-meson are sensitive to changes of the quark condensate.

A crucial ingredient needed for a quantitative interpretation of data from heavy-ion reactions are phenomenological models that describe the dynamics of nucleus–nucleus collisions. Christian Fuchs (Tübingen) and Elena Bratkovskaya (Frankfurt) reviewed the status of kinetic transport theory. The calculations predict that high baryon densities of up to 10 times nuclear density and energy densities of 5–6 GeV/fm³ are reached in central Au+Au collisions already at beam energies of 25 AGeV. The transition from hadronic matter to deconfined matter of quarks and gluons is expected above a critical density of about 1 GeV/fm³.

Adrian Dumitru (Frankfurt) discussed the status of non-equilibrium chiral hydrodynamics calculations. In the case of a first-order phase transition he predicted inhomogeneities in the energy density distribution that should effect the collective flow and hadron abundances. Yuri Ivanov (Moscow) presented results of multi-fluid hydrodynamics calculations. He showed trajectories in the QCD phase diagram for central Au+Au collisions at different beam energies. According to the calculations, the conditions in the fireball are close to the critical point (as predicted by QCD lattice calculations) at beam energies around 30 AGeV.

Claudia Höhne (GSI), who presented an overview on strangeness production data measured at the CERN-SPS, discussed the excitation function of the kaon-to-pion ratio measured in Pb+Pb collisions that exhibits a peak at a beam energy of 30 AGeV. This observation is not reproduced by transport calculations or by statistical models. A similar but less pronounced structure is found in the lambda-to-pion ratio reflecting the transition from baryon to meson dominated matter around 30 AGeV. Moreover, the NA49 collaboration measured the kaon-to-pion ratio event-by-event and observed nonstatistical fluctuations at a beam energy around 20 AGeV. Such fluctuations are expected to occur in systems close to the critical point, in analogy with critical opalescence in macroscopic systems.

Volker Koch (Berkeley) considered fluctuations to be a key observable both for the critical point and for a first-order phase transition. In the second case, one expects spatial fluctuations (“blob formation”) due to spinodal instabilities in the phase coexistence region. Moreover, he stressed the role of strangeness-baryon number correlations as a signature for the nature of the deconfined phase (“simple” QGP versus bound state QGP).

Volker Friese (GSI) presented the plans for the heavy-ion collision program of the Compressed Baryonic Matter (CBM) experiment at the future Facility for Antiproton and Ion Research (FAIR). The CBM measurements will focus on rare probes containing heavy quarks, for example, open and hidden charm, and on penetrating probes, for example, dilepton pairs from light vector meson decays. Hadronic probes, including (multi strange) hyperons, as well as fluctuations and correlations of bulk matter particles such as pions and kaons, will also be measured. The goal is to obtain a comprehensive picture of the high net-baryon density region of the phase diagram of strongly interacting matter. In this sense the CBM research program is complementary to the heavy-ion experiments at RHIC and LHC where matter at high temperatures and small net baryon densities is explored.

The final session of the workshop was devoted to the discussion of a planned White Book on the physics of dense baryonic matter. The aim of this document is to review the status of theory and experiment, to discuss the relation between physics questions and observables, and to map out a strategy for future research. Misha Stephanov (Chicago), Jorgen Randrup (Berkeley), and David Blaschke (Rostock) reported on a first draft of the book that was prepared by three working groups. The next draft of the White Book will be discussed at the workshop on “The Physics of High Baryon Density,” which will take place at the ECT* in Trento from May 29 to June 2, 2006.

The presentations of the workshop can be found at http://www-aix.gsi.de/conferences/cbm2005-Dec/
Physics Opportunities with EURISOL

The proposed EURISOL radioactive beam facility is an ambitious leap beyond the capabilities of any current ISOL facility in the world (see http://www.eurisol.org). EURISOL is intended to produce and accelerate isotopes spanning the broadest possible range of isospin and masses. It promises to open up an entire new vista for nuclear physics and have a significant bearing on many other fields of science, including condensed matter, atomic, particle, and astrophysics.

The EURISOL Design Study, a 4-year project funded under the European Union’s 6th Framework Programme, is part of the roadmap toward the construction of the final facility. The Design Study is undertaking preparatory work on the various elements of the facility (high-intensity proton driver, target-ion sources, postaccelerator, etc). As such a major project as EURISOL has to be driven by science, an integral part of the Design Study is the “Physics and Instrumentation” Task. As part of the planned work program of this Task, a workshop was held at ECT* in January. The aim of the workshop was to identify some of the areas of physics in which EURISOL could uniquely advance our knowledge. To achieve this, the workshop set out to attract speakers and participants representing diverse fields at the frontiers of nuclear physics research.

Over 40 scientists from 12 different countries participated in the workshop in the stimulating atmosphere of the ECT* in Trento. Throughout the workshop a considerable fraction of the time was given over to lively open discussions of the ideas presented by the speakers, many of whom were among the younger members of our community. Time was also devoted to debating more general issues, including various aspects of the user needs (especially in terms of the postaccelerated beams) and a proposal to form an ISOL user group to draw together the future EURISOL research community.

The detailed program of the workshop, including a slide report, can be found at http://ns.ph.liv.ac.uk/eurisol. Although the topics addressed in the presentations covered a broad spectrum of the nuclear physics research that is likely to figure at the EURISOL facility, it is evident that the science program is continuously evolving. New ideas are always welcome, so if you have something to contribute or want to get involved, please get in touch!

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Proton–Proton Correlations Observed in Two-Proton Radioactivity of $^{94}$Ag

Since 1960, the spontaneous break-up of atomic nuclei by emission of two protons was expected to proceed via simultaneous emission of a pair of protons coupled into a $^2$He cluster. Recently, Ivan Mukha and colleagues made the surprising observation [1] of a case of two-proton radioactivity characterized by emission of the protons either in the same or opposite directions. At the GSI research center in Darmstadt, Germany, the lightest known isotopes of silver, $^{94}$Ag, was synthesized by using nuclear reactions between accelerated $^{40}$Ca ions and $^{58}$Ni atoms. After purification by on-line mass separation the $^{94}$Ag nuclei were implanted into a catcher positioned in a highly segmented array of silicon and germanium detectors. The simultaneous two-proton emission was identified for a long-lived (0.4 s), high-spin state of $^{94}$Ag. This ($21^+$) isomer is also known to undergo one-proton decay [2], thus making it the first nucleus exhibiting one- as well as two-proton radioactivity. Both disintegration modes were unambiguously identified by “tagging” on $\gamma$ rays that are known to de-excite the high-spin states populated in the daughter nuclei $^{93}$Pd and $^{92}$Rh, respectively.

The observed two-proton decay is unexpectedly fast. This result as well as the directional correlation observed for the emission of the two protons are interpreted as indicating a very large, prolate (cigar-like) deformation of the parent nucleus, with the emission of protons occurring either from the

![Figure 1](image-url)

**Figure 1.** Upper panel: Partial two-proton decay half-life ($T_{1/2}$) of $^{94}$Ag ($21^+$) as a function of the nuclear deformation parameter $\alpha$, which is the ratio of the long to the short axes of the ellipsoid. Model estimates for the two-proton decay proceeding as simultaneous three-body breakup (black curves) and quasi-classical $^2$He decay (grey curves) are shown for the angular momenta $L=6, 8, 10$. The nuclear shapes corresponding to the derived deformations are displayed for the $L=6$ calculation. The experimental $T_{1/2}$ value is shown by the dotted line (marked as “Exp.”), the grey region indicating the experimental uncertainty. Lower panel: Intensity $W$ predicted for the two-proton emission as a function of the angle $\theta$ between one emitted proton and the long ellipsoid axis (thick grey curve) [1].
same or from opposite ends of the “cigar.” This first measurement of correlation data in two-proton radioactivity calls for further experimental studies of the properties of this truly exotic isomer as well as for a more quantitative theoretical description of the observed two-proton decay behavior.

References
2. I. Mukha et al., Observation of Proton Radioactivity of the (21$^+$) High-Spin Isomer in $^{94}$Ag, Phys. Rev. Lett. 95, 022501 (2005).

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The South East European Nuclear Physics Network (SEENet)

In view of the key role that nuclear science plays in the technological development of our society, a group of 16 nuclear physicists from 10 Institutes and Departments from South-East European (SEE) Research Centres and Universities agreed to establish the South East European Nuclear Physics Network (SEENet). The first SEENet meeting was held on September 16, 2002 at the Physics Department of the University of Sofia, Bulgaria. A second meeting took place six weeks later at the Faculty of Sciences of the Istanbul University, Turkey, where a Memorandum of Understanding (MoU) was signed by the representatives of (a) the Faculty of Physics of the University of Sofia, Bulgaria, (b) the Institute of Nuclear Research and Nuclear Energy (INRNE), Sofia, Bulgaria, (c) the Rudjer Boskovic Institute (RBI), Zagreb, Croatia, (d) the Physics Department of the University of Zagreb, Croatia, (e) the Institute of Nuclear Physics of the National Centre for Scientific Research “Demokritos,” Athens, Greece, (f) the National Institute for Physics and Nuclear Engineering (NIPNE), Bucharest, Romania, (g) the University Politecnica of Bucharest, Romania, (h) the Vinca Institute of Nuclear Science, Belgrade, Serbia-Montenegro, (i) the Department of Physics of the University of Novi Sad, Serbia-Montenegro, and (j) the Faculty of Sciences of the Istanbul University, Turkey.

According to the signed MoU, SEENet aims at

- Creating a users network of SEE groups that carry out research in SEE nuclear physics installations and European Large Scale Facilities (LSF) and enhancing SEE regional and European collaborations.
- Performing mapping studies on Nuclear Science and Technology in SEE according to NuPECC and other European organization’s guidelines.
- Promoting both independent nuclear research activities in SEE and activities complementary to those at LSF.
- Facilitating training in Nuclear Science and Technology for graduate students and young scientists by providing access to SEENet member laboratories and LSF.
- Facilitating the access to the funding instruments of the European Commission for network members.
- Enhancing the interaction of the scientific groups involved by organizing workshops, conferences, and schools on Nuclear Science and Technology.

SEENet has a Members Council (MC) consisting of representatives of all member institutions as well as a Steering Committee (SC) comprising the national representatives (one scientist from each SEENet country). The Steering Committee elects a Chair and a Vice-Chair for a 2-year period that is renewable.

So far, SEENet meetings have been organized at the Department of Physics of the University of Novi Sad, Serbia-Montenegro (May 2003), NIPNE (Bucharest, Romania, May 2005) and the Institute of Nuclear Physics of NCSR “Demokritos,” Greece (Athens, November 2005). In addition, SEENet has grown and now includes three additional members: (a) the Faculty of Applied Physics of the National Technical University of Athens (NTUA), Greece, (b) the Physics Department of the Aristotle University of Thessaloniki, Greece, and (c) the Department of Atomic and Nuclear Physics of the University of Bucharest, Romania. The SEENet meetings paved the way for forming the proposal for a South-Eastern Nuclear Physics network activity as an integral part of EURONS I3 [1]. Another important outcome was the decision to take specific measures for the integration of SEE nuclear physics groups in the European research area both in terms of research activities and funding.
As mentioned earlier, SEENet is now a network activity of EURONS I3. As such it has undertaken to provide the European nuclear physics community and the EC with two reports. One will include an account of the research activities carried out by SEE nuclear physics groups at European LSF. The other will feature a mapping of nuclear science in the SEE region. For the preparation of the reports, SEENet has formed three working groups on Physics, Infrastructures and Education, respectively. Each working group consists of six members, one from each SEENet country, acting as national conveners. The purpose of the two reports is not only to highlight the broad scientific potential of the SEE nuclear physics community, which includes more than 400 nuclear physicists, but also to emphasize the problems related to the operation of the existing SEE infrastructures and the lack of proper mobility schemes. These problems have been identified by all SEENet members and are listed in the “Position Letter On Nuclear Science in South-Eastern Europe” that was produced during the last SEENet meeting in Athens (November 2005). This letter can be found on the SEENet website [2] together with the MoU and the minutes of all SEENet meetings.

Looking back at the course of events following the first SEENet meeting in Sofia and the first expression of concern about the future of Nuclear Science in SEE (article by Dimiter Balabanski [3]), one cannot but appreciate the determination of the SEENet community to contribute decisively to the efforts of the broader European nuclear physics community. In fact, more than 100 nuclear physicists from SEE are actively involved in key nuclear physics experiments running in European LSF, and many others are participating in design studies of future nuclear physics instrumentation and infrastructures. At the same time, SEENet is keen on promoting collaborations between SEE nuclear physics groups performing measurements in the regional accelerator laboratories, which provide research opportunities and training for young physicists. One such example is the joint effort of the 5 MV Tandem Accelerator Facility of the Greek National Research Centre “Demokritos,” Athens, the 9 MV FN Tandem Laboratory of the National Institute for Physics and Nuclear Engineering (NIPNE) in Bucharest, Romania, the University of Sofia, Bulgaria, and the University of Istanbul, Turkey, both on an experimental and theoretical level. This intense collaboration is based on a long-term research program on Nuclear Astrophysics and Nuclear Structure. Another significant SEE event worth mentioning is the Balkan School on Nuclear Physics, which has been organized in different countries of the region for the past 10 years. The 5th Balkan School will be held in Brasov, Romania [4] this summer.

From a personal viewpoint, the most important achievement of SEENet is that it has managed to make funding agencies in the South-Eastern European countries aware of the scientific potential of the nuclear physics communities in the region. As a result, three SEE countries: Greece, Romania, and very recently Croatia, joined NuPECC in 2005. This provided an opportunity for the broader European nuclear physics community to become acquainted with the problems the SEE scientific community faces related to funding and decaying infrastructures. In recognizing these problems and appreciating the high-level scientific potential and the vital role of the SEE region in future activities of the international nuclear physics community, NuPECC has embarked on a series of discussions on possible actions and initiatives that would lead to upgrading the nuclear physics installations in SEE and would enhance the involvement of SEE groups in funding schemes within the upcoming 7th Framework Program (FP7).

As SEENet and NuPECC member, I look forward to a promising future full of challenges and opportunities for nuclear science in SEE and in this direction the support of the entire European nuclear physics community is imperative.

References
1. http://www.gsi.de/EURONS

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IUPAP Young Scientist Prize in Nuclear Physics

This prize was established by IUPAP in 2005 at the time of the General Assembly in Capetown, South Africa.

The purpose of this prize, which consists of $1,000, a medal, and a certificate citing the recipient’s contributions, is:

To recognize and encourage very promising experimental or theoretical research in nuclear physics, including the advancement of a method, a procedure, a technique, or a device that contributes in a significant way to nuclear physics research, by a scientist within eight years of obtaining the Ph.D. (or equivalent) degree.

Nominations by one or two nominators (and distinct from the nominee) are open to all experimental and theoretical nuclear physicists. Three prizes will ordinarily be awarded at the time of the tri-annual International Nuclear Physics Conference. However, the selection committee may, given the circumstances, decide to award only two prizes or in a special situation only one prize, in which cases the monetary award will be inversely proportionally larger.

Nominations are due October 1 of the year preceding the International Nuclear Physics Conference and are valid only until then. It will be extremely helpful to the selection committee to receive at least two additional letters supporting the nomination that detail the expected significance of the contributions of the nominee to nuclear physics. It is also appropriate to submit additional materials such as published articles that underline the expected significance of the nominee’s contribution to nuclear physics. It is important that the selection committee has the specific information that allows it to determine what the nominee has contributed and how this contribution is expected to impact the field.

Nominations are to be sent by the deadline to the chair of the IUPAP Commission of Nuclear Physics (C12). For particulars please check the IUPAP website: www.iupap.org under “commissions.” The next International Nuclear Physics Conference will be held June 3–8, 2007, in Tokyo, Japan.

Next deadline for nominations: October 1, 2006. Nominations should be sent to: Dr. Walter F. Henning, Chair of the IUPAP Prize Selection Committee, GSI, Planck Strasse 1, D-64291 Darmstadt, Germany.