Contents

Editorial ..............................................................................................................................................................3

Laboratory Portrait
The Cyclotron Institute at Texas A&M University
by Robert Tribble ............................................................................................................................................ 5

Feature Article
Using a Square Well to Introduce Nuclear Physics
by Sophie Heinrich and Jean-Luc Sida .......................................................................................................... 11

Facilities and Methods
AGATA: The Advanced Gamma Tracking Array
by J. Simpson and R. Krücken ...................................................................................................................... 15

Francium Developments at Stony Brook

Impact and Applications
Selected Isotope Applications in Cosmochemistry and Geochemistry
by Chris J. Ballentine and Ian Lyon ............................................................................................................. 22

Meeting Reports
by Andrea Vitturi ........................................................................................................................................... 28

International Symposium on Physics of Unstable Nuclei
by Dao Tien Khoa, Vo Van Thuan, Nguyen Dinh Dang, Shigeru Kubono, and Nguyen Van Giai ........... 29

Obituary ...........................................................................................................................................................30

News from EPS/NPB .......................................................................................................................................31

Calendar ...........................................................................................................................................................32

Cover illustration: A view of the K500 superconducting cyclotron at Texas A&M University, looking from the beam line switchyard toward the accelerator.
Precarious Careers, Uncertain Futures

I graduated with a degree in physics in a southern country where the possibilities of obtaining a permanent job as a researcher are rather insignificant. Like many of those who have left their country of origin to work in a foreign laboratory, I started out years ago on an unintentional path of no return. Taking advantage of Spanish national grants and of the European programs of mobility, I have worked in five different nuclear physics and astrophysics groups in three different countries (Germany, France, and Belgium). Since 1998, I have been at the cyclotron laboratory at Louvain-la-Neuve, but I do not have a permanent position. This itinerant life has demanded from me a certain degree of flexibility, adjusting myself to the work program, conditions, and facilities offered, and learning new skills, from vacuum techniques to theoretical models. Taking as mine the glory or the misery of the groups of which I have been a member over the years, I have had the chance to discover a lot about human nature. It has been an extremely rich adventure. The drawback is sometimes, but fortunately not always, weak support from the local groups when applying for a position. In a natural way, those who have graduated from and received their Ph.D. degree in the group are preferred. This is a commonly accepted practice in all the universities where I have been and one of the disadvantages of mobility. It may be unnecessary to mention that the link with the home institute, if it existed at all, is broken when one works abroad for many years.

Being a foreigner has not normally been an obstacle for me, but I have found that being fluent in the language of the country is a must if one wants to be accepted and to play a role in the research activities of the group. Moreover, I have not been treated differently than my male colleagues. Being a woman has been neither a difficulty nor a benefit for my research career. At least, this is what I have perceived. I think it has been irrelevant, as it should be. But I realize that this is not always the case. In general, it will be a significant improvement when being a woman will not be a disadvantage (but also not an advantage) in getting a job. A step forward will be achieved when gender will be considered a marginal feature and positive discrimination will not be needed anymore. On the other hand, the reality of so few women in key positions in nuclear physics is a problem common to other research fields and it deserves a real debate within the scientific community. It reflects a typical impasse within our society, which is amplified when one takes into account the need for a permanent position near the place where the life partner works and the children go to school.

Coming back to my own experience, even though my employment situation is fairly unstable, I feel fortunate. After 15 years in nuclear physics, I am still doing what I like, in a state-of-the-art laboratory with a friendly environment, in a pleasant country, and with productive and enjoyable collaborations. When planning future work, I have learned to pay little attention to ill augurs and, in spite of the everyday uncertainty about financial support, I still enjoy nuclear physics. However, it is not easy to carry out research under these conditions. Sometimes I believe that I have completely misjudged my choice of career and I would not suggest that others follow my example. Many of the people from my generation, and especially those coming after, do not know other possible ways of doing research than this one: surviving from one grant to the next, carrying on from one contract to another. Our future in nuclear physics is uncertain.

We all know brilliant young researchers who have been forced, not without bitterness, to leave nuclear physics for a more secure job in the private sector or who have totally changed their research area in order to get a position. These lost researchers could have been the building blocks of nuclear physics in future years. Hearing or writing myself about the bright future of nuclear structure in Europe seems unreal to me sometimes. The reality in Europe is that the number of permanent positions in nuclear physics is decreasing every year. As hard as it is to believe, it may well happen that a commission that examines the applications for permanent positions in physics does not include a nuclear physicist among its members. This is certainly anomalous and alarming. Although other fields in physics and, in general, in science may well suffer from the same illness, nuclear physics has specific problems today. In spite of

The views expressed here do not represent the views and policies of NuPECC except where explicitly identified.
all the funding employed to build up and to develop nuclear physics research facilities in Europe (sometimes gargantuan enterprises with correspondingly gargantuan budgets), little attention is given to keeping a stable and sufficient number of permanent professionals to drive the projected research. Needless to say, we need the experimental facilities. But more than ever, we need dedicated researchers who do not have to struggle to keep their jobs. Because, like it or not, we are short of talented minds.

Are there people out there with hidden motivations for preventing nuclear physics from being well represented? Certainly internal quarrels with other physics disciplines create damage and are a significant waste of energy and time. But I believe that the loss of permanent positions is, among other things, the result of many years of nuclear physicists resting on their laurels, of the many nuclear physics “microgroups” being isolated, serving particular interests rather than a common coordinated goal (in spite of the considerable efforts of NuPECC and of the more recent research initiatives), and a deficient, or even nonexistent, publicizing of the benefits of nuclear physics to society. It is also a problem of lack of lobbying at the European, national, and regional levels.

How does one build a solid scientific program for the future without firm foundations? I do not think it can be done. I do not have the solution, but we, the entire community, may still do something. Do not ignore the problem. Do not accept it as a calamity. Do not stay passive in your corner. Take advantage of your position and use your imagination to react now. Otherwise, when our senior colleagues retire and the current Ph.D. students (if any are left) are gone, no one will be there to work on fundamental nuclear physics research. On that day there will be no one to blame except those who had the responsibility to act but did not.

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The Cyclotron Institute at Texas A&M University

Overview

The Texas A&M University Cyclotron Institute is jointly supported by the U.S. Department of Energy and the State of Texas. The centerpiece of the Institute is a K500 superconducting cyclotron, from which first beams were extracted in 1988. Today, with two electron-cyclotron-resonance (ECR) ion sources, the accelerator can produce a wide variety of beams: those with intensities of at least 1 enA range in energy up to 70 MeV/A for light ions and to 12 MeV/A for heavy ions such as U. For the past decade the cyclotron has averaged more than 6500 hours of operation per year.

The Cyclotron Institute was initiated by Texas A&M University just over 40 years ago. In the early 1960s a proposal was funded jointly by the Atomic Energy Commission, the R.A. Welch Foundation (a private foundation headquartered in Houston, TX), and the State of Texas to construct an 88" cyclotron. Construction of the accelerator was completed by 1967 and first beams were obtained from it in 1968. The 88" cyclotron operated continuously until 1986, when it was decommissioned, just prior to when first beams were obtained from the new superconducting cyclotron.

In 1980, Texas A&M University and the Welch Foundation jointly funded the construction of the K500 superconducting cyclotron. The accelerator was built by Institute staff in a building addition that provided room for the cyclotron vault and new experimental areas. Since completing the cyclotron, Institute staff have designed, constructed, and upgraded the ECR sources used for injection into the accelerator as well as ancillary equipment used downstream from it. Figure 1 shows a schematic layout of the cyclotron and experimental areas. The complement of sophisticated state-of-the-art detectors and spectrometers provides the instrumentation necessary for research in the areas of nuclear structure, fundamental interactions, exotic nuclei, nuclear astrophysics, intermediate-energy reaction dynamics, nuclear thermo-dynamics, the nuclear equation of state, atomic physics, and applied nuclear science. Approximately 100 Institute members—scientists, engineers, technicians, support staff, graduate students, and undergraduates—are involved in these programs.

In addition to a broad research program in nuclear science based on the K500 cyclotron, Institute researchers are involved in collaborations at several other laboratories in North America including Brookhaven National Laboratory, Argonne National Laboratory, and TRIUMF. Below we provide some details about the ongoing projects.

Fundamental Interactions

In recent years, the Institute has...
developed an on-line facility specially designed for precision measurements of short-lived nuclides. Currently it is focusing on the study of superallowed $0^+ \rightarrow 0^+$ nuclear $\beta$ decay, which is a highly sensitive probe of the vector part of the weak interaction. Measurements of the lifetime, branching ratio, and decay energy for such transitions yield a direct determination of the weak vector coupling constant, $G_V$, provided that small radiative corrections are properly accounted for. From $G_V$, it is possible to establish a very precise value for $V_{ud}$, the up-down element of the Cabibbo–Kobayashi–Maskawa (CKM) quark-mixing matrix of the minimal electroweak standard model. Not only does nuclear $\beta$ decay yield the most precise determination of $V_{ud}$ but that result is the most precise of any element in the CKM matrix. It also leads to the most demanding available test of CKM unitarity, a fundamental tenet of the standard model. Strikingly, the test fails by more than two standard deviations, a provocative outcome that has motivated the quest for even greater precision in the determination of $V_{ud}$ (and of $V_{us}$, the other key element in the test).

The precision-measurement facility is mounted at the end of MARS. An isotope of interest, produced from heavy-ion bombardment of a cooled hydrogen gas target, appears as a beam at the focal plane of MARS. It is extracted into air, degraded in aluminum, and then stopped in a thin mylar tape. The combination of electromagnetic separation in MARS and range separation in the degrader results in sample impurity levels below 0.1%. A fast tape transport system moves collected samples repetitively to a shielded counting location where the activity can be counted. Typical precision on half-life results is 0.04%, while branching ratios can be determined to 0.15%. Results from studies of $^{22}$Mg and $^{34}$Ar decay with this facility have already appeared [1, 2]. How these results impact on the structure-dependent radiative corrections is shown in Figure 2.

**Isoscalar Giant Resonances and Nuclear Compressibility**

The first conclusive measurements of the isoscalar giant monopole resonance (GMR) in nuclei were made by Institute researchers in the late 1970s. Since then, we have focused on obtaining more detailed information about them. The experimental program is based on the MDM magnetic spectrometer and focal plane detectors, which allow us to use small-angle (including 0°) inelastic scattering with both light-ion and heavy-ion beams at about 60 MeV/A. Figure 3 shows the excellent peak to continuum ratio for the data as well as giant monopole and isoscalar dipole distributions derived from the data. The isoscalar GMR and isoscalar giant dipole resonances...
(ISGDR) are of particular interest because their energies are directly related to the compressibility of the nucleus \( (K_A) \) and, ultimately, to the compressibility of nuclear matter \( (K_{NM}) \). \( K_{NM} \) is an important quantity for both nuclear physics and astrophysics, as it is one of the key ingredients needed to understand neutron stars. Using Hartree–Fock random-phase-approximation calculations, the theoretical program at the Institute explores the relationship between \( K_A \) and \( K_{NM} \) as well as the comparison between model predictions and experimental strength functions.

From the inelastic-scattering measurements, we have obtained GMR and ISGDR strength distributions up to very high excitation energy \( (E_x \sim 30–40 \text{ MeV}) \) in many nuclei \[4\]. Both the mass and isotopic dependence of GMR and ISGDR strength functions are being studied under circumstances in which 100% (or nearly 100%) of the GMR strength has been located in 18 nuclei from \(^{24}\text{Mg}\) to \(^{208}\text{Pb}\), which include four isotopic series. Calculations that use \( K_{NM} \sim 230 \text{ MeV} \) generally give GMR energies consistent with the data.

**N/Z Dependence of Nuclear Interactions**

The neutron-to-proton ratio \( (N/Z) \) of reaction partners affects both the dynamics and the thermodynamics of heavy-ion collisions. Predictions have suggested that: (1) the difference in the chemical potential between neutrons and protons will change the thermodynamics governing the decay of excited nuclear matter when the \( N/Z \) ratio is changed; (2) a neutron-rich system will undergo a type of distillation resulting in a low density or “gas” phase, which carries much of the neutron enrichment, and a high density or “liquid” phase that is more

**Figure 3.** Recent results from inelastic scattering of \( \alpha \)'s on \(^{116}\text{Sn}\) with the MDM spectrometer set at 0°. The spectrum shows excellent peak to continuum ratios. The GMR and ISGDR distributions obtained from the data are also shown.
symmetric; and (3) the dynamics of reactions leading to excited nuclear systems will depend on N/Z.

Institute researchers are studying these N/Z dependencies in heavy-ion reactions by comparing what happens during collisions of different isotopes, such as $^{20}$F, $^{20}$Ne, and $^{20}$Na. Measurements with light and medium-mass heavy-ion beams are being carried out with the FAUST detector system located at the back of either MARS or BigSol [5]. The measurements are shedding light on how N/Z affects the deep-inelastic transfer process and are providing new information on ways to produce neutron-rich heavy residues.

**Properties of Hot Nuclei**

Experiments are being carried out to determine the thermodynamic properties of very excited “hot” nuclei produced in intermediate-energy heavy-ion collisions in order to explore (1) the nuclear equation of state under nonnormal conditions; (2) the nature of the “liquid–gas” phase changes in strongly interacting, finite quantum systems; and (3) the relationship of such changes to those in bulk nuclear matter. Our focus is on developing ways to extract direct information on the extent to which equilibration of various degrees of freedom is realized and to understand the dynamical and thermodynamical evolution of the interaction region. If a collision produces sufficient thermal and/or compressional shock, the hot composite nucleus that results may expand to low density, then cluster and disassemble. If this multifragment disassembly is that of a thermally and chemically equilibrated nucleus, information on critical behavior and the liquid–gas phase change in nuclear matter should be accessible [6].

To pursue this research, Institute staff constructed the NIMROD detector, a $4\pi$ charged-particle array located inside a $4\pi$ neutron calorimeter. The NIMROD array, in addition to providing high geometric coverage, has low detection thresholds and a large dynamic range for light charged-particle detection and allows isotopic identification to at least $Z=10$, as shown in Figure 4.

**Nuclear Astrophysics**

Over the last decade we have seen an explosion of new information in astrophysics, ranging from a glimpse at the earliest events in our universe to a more detailed view of the continual evolution in stellar systems that surround us. Cosmology theories tell us that, within an instant after the Big Bang, nuclear synthesis was driving the evolution of the universe. To understand this evolution we require information about a wide range of nuclear reactions, many of which involve an unstable nucleus capturing a proton or an alpha particle and transmuting to a new unstable nucleus. Until the recent advent of radioactive-ion beams, it was nearly impossible to study such reactions in the laboratory. Now, Institute researchers are using...
radioactive beams produced in MARS to learn more about some of the important nuclear reactions governing the behavior and evolution of our own sun and other stars.

The approach that has been developed involves a combination of radioactive-beam-induced reactions with conventional nuclear-physics techniques. The strength of the asymptotic wave function—the asymptotic normalization coefficient, or ANC—is determined from a peripheral transfer reaction. Then the ANC is used to determine the reaction rate for direct proton-capture reactions at stellar energies. This technique has been used to determine stellar-capture rates for reactions such as \(^7\)Be\((p,\gamma)\)^8B, the sole source of high-energy neutrinos from our sun \([7]\); \(^{11}\)C\((p,\gamma)\)^12N, an important reaction to bypass the triple \(\alpha\) process in massive stars \([8]\); and \(^{19}\)N\((p,\gamma)\)^20O, one of the reactions in the hot CNO cycle. Measurements with stable beams and targets have also been performed.

**Ion Interactions**

The ion-interactions program is currently addressing three topics: (1) electron capture and loss by fast, high-Z ions, (2) cross sections for K-vacancy production in heavy-ion-atom collisions, and (3) x-ray satellite structure arising from multiple ionization in heavy-ion-atom collisions. The first topic is motivated partly by a fundamental interest in the collision dynamics of ionization and charge-exchange processes in fast, heavy-ion collisions and partly by the current need for electron-loss cross sections in order to evaluate the prospects of heavy-ion inertial fusion as a possible energy source. Also, a detailed knowledge of electron-capture and -loss cross sections is required for the accurate calculation of projectile charge-state distributions, a problem of particular importance in accelerator design.

The accurate theoretical prediction of cross sections for K-vacancy production, our second topic, has been a longstanding goal in the field of ion-atom collisions. Institute researchers have been performing systematic measurements of K-vacancy production cross sections in a continuing effort to explore their dependence on projectile energy and atomic number, and upon target atomic number. Recent work on this topic has disclosed large discrepancies between theory and experiment for projectiles with atomic numbers greater than 10 \([9]\). For the third topic Institute researchers are performing high-resolution measurements of the L x-ray spectrum of holmium to examine the satellite multiplet structure and to deduce the associated distributions of L-, M-, and N-shell vacancies.

**Radiation Effects**

Over the past decade, use of our facility to test the response of electronic components to radiation has grown steadily to the point that it now occupies about 20% of the available beam time. The major motivation for tests is to certify components for space flights. Solar flares, cosmic rays, and the Earth’s Van Allen belts serve as natural sources of space radiation. Such ionizing radiation can “upset” the normal function of semiconductor devices “upset” can be measured in the laboratory with beams of high-energy ions, such as those accelerated by the K500 cyclotron. The Radiation Effects Facility (REF) end station consists of dosimetry and energy-degrader systems with computer-controlled device staging at test locations in both air and vacuum.

**Nuclear Theory**

Nuclear theorists at the Institute attempt to explain phenomena that are observed in nuclear interactions at a wide range of energies, from those available at the K500 cyclotron to those at RHIC. In one area of study, the theory group has proposed various ways to study the nuclear symmetry energy in collisions with radioactive beams, including measurements of both the preequilibrium neutron/proton ratio and of two-nucleon correlation functions and the production of light clusters. They have found that these observables are sensitive to the density dependence of the nuclear symmetry energy, an essential property required for an understanding of the structure of radioactive nuclei and of many important issues in nuclear astrophysics. At higher energies, such as those at GSI, the group has suggested that new information about the nuclear equation of state can be obtained from subthreshold kaon production. These theoretical studies are based on a relativistic transport model, RVUU, developed at Texas A&M University \([10]\). This model has been extended further to probe the physics of hot dense matter produced in heavy-ion collisions at the even-higher energies available from the AGS at Brookhaven National Laboratory. For relativistic heavy-ion collisions at RHIC, the group has developed a hybrid model that includes both initial partonic and final hadronic interactions. It has been used to extract signals of the quark-gluon plasma, which is expected to be produced in these collisions.
Research Outside the Laboratory

Cyclotron Institute scientists also participate in the BRAHMS and STAR collaborations at RHIC, the TWIST and superallowed-beta-decay collaborations at TRIUMF, and the CPT collaboration at Argonne. The BRAHMS group focuses on the study of very high rapidity phenomena, especially in \( p-p \) collisions. The STAR group focuses on studies of high-transverse-momentum phenomena and the spin of the proton. Early results show that high-transverse-momentum particle production is strongly suppressed in Au–Au collisions at RHIC, indicating that the medium created is very dense and dissipative [11]. Future plans include measurements of the gluon polarization in the proton. TWIST will determine the Michel parameters that characterize the space-time structure of muon decay to a few parts in \( 10^4 \). Any deviation from expectations of the standard model would require the introduction of right-handed weak currents or other new physics. The beta-decay studies at TRIUMF and the mass measurements undertaken with the CPT collaboration at Argonne complement our local superallowed beta-decay program by providing results that are not accessible here.

Future Directions

Over the past few years, Institute staff members have developed a plan to upgrade the present facility to one that would yield high-quality radioactive beams directly from the K500 superconducting cyclotron. The first stage of the plan involves recommissioning the 88" (K150) cyclotron. Intense light-ion and heavy-ion beams from that cyclotron will be used to produce radioactive ions, which will then be slowed down in a He-gas stopper and collected by ion guides as \( 1^+ \) ions. A \( 1^+ \)-to-\( n^+ \) ECR ion source will then be used to produce the highly charged radioactive beams for reacceleration in the K500 cyclotron. The project will cost around $4 million and take about three years after initial funding to complete. It is envisioned that many aspects of the project will provide valuable input to RIA development. Details can be found in a white paper on our website at http://cyclotron.tamu.edu/.

References


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In reviewing the promotion and teaching of nuclear science (PANS), we present an approach that has worked well with French students in a third year master’s class. We use a nuclear square well to explain the shell model. This approach is attractive, as it stems largely from one observation: that nuclear radii vary as $A^{1/3}$. Students are able to make calculations unassisted and also address questions such as the evolution of energy levels with nuclear mass, the nonexistence of mass 5 and 8 stable nuclei, or the shell closures and magic numbers.

Herein, we present a few worked examples and give a very simple program (see box) for finding the single-particle energy levels in the nuclear square well.

We are certainly not the only ones doing that, and we do not claim that it is something new since this model has been used for a long time; it is just a natural and very coherent way to introduce the nuclear shell structure realm.

Why the Nuclear Mean Field Could Be Approximated by a Square Well

Our aim is to build a toy model, ruled by only a few principles, that yet captures the essence of the nuclear world. The following fundamental assumption will serve as the basis: stable nuclei may be treated as spheres with sharp edges that grow with $A$, the number of nucleons. To be consistent, we thus have to use a nuclear attractive force which is fastly saturating; for reasons of straightforwardness, we choose a zero-range interaction. A nucleon is then submitted to a potential proportional to the negative of the nuclear density of its nucleus. The nuclear density, and therefore the mean potential, can be approximated by a step function with a constant height and a width $R$ varying as $A^{1/3}$.

How to estimate the depth of the potential? Since, a priori, we don’t know the magnitude of that well, we use the evolution of the nuclear radius within the framework of the Fermi gas model to solve the inverse problem. For $A$ free particles closed in a sphere of radius $R_0 A^{1/3}$, the Fermi energy associated is equal to $53 \text{ MeV}/R_0^2$. Assuming the standard value of $R_0 = 1.2 \text{ fm}$ and taking into account the mean binding energy per nucleon assumed at $8 \text{ MeV/nucleon}$, this leads to a potential felt by a nucleon, independent of the mass of the nucleus, equal to $45 \text{ MeV}$ [1].

Program to find the nuclear square well eigenstates with Mathematica®

This file will calculate and plot the working function $W$ (Figure 2), corresponding to an orbital momentum $l=0$ (noted $ll$ at the end of the program) and a mass $A=208$ (noted $aa$). Changing $ll$ and/or $aa$, one can calculate any level for any nuclei.

$$\begin{array}{l}
\text{rzero} = 1.2 \\
\text{rmasse} = 931 \\
\text{hbar} = 197.3 \\
\text{vzero} = 53 / \text{rzero}^2 + 8 \\
\text{Rayon[a_]} = \text{rzero}^2 a^{1/3} \\
\text{z1[a_,e_]} = \text{Sqrt}[2.*\text{rmasse}/\text{hbar}/\text{hbar}]*\text{Rayon[a]} \\
\text{z2[a_,e_]} = \text{Sqrt}[2.*\text{rmasse}/\text{hbar}/\text{hbar}]*\text{Rayon[a]} \\
\text{h[1_,zz1_]} = \text{BesselK}[1 + 1/2, \text{zz1}]/\text{Sqrt}[\text{zz1}] \\
\text{j[1_,zz2_]} = \text{BesselJ}[1 + 1/2, \text{zz2}]/\text{Sqrt}[\text{zz2}] \\
\text{W[1_,a_,e_]} = ((\text{z1}[a,e]-z2[a,e]*[l+1,z2[a,e]])/(l[l+1,z2[a,e]-z1[a,e]*[l+1,lz1[a,e]])/(h[lz1[a,e]])) \\
\text{ll} = 0 \\
\text{aa} = 208 \\
\text{Plot}[1/W[ll,aa,e],\{e,0,vzero\}]
\end{array}$$

* This $W$ function is different from the previous one. It has been built to increase the contrast and to avoid spurious divergences.
The nuclear square well is now clearly defined (Figure 1), and from that potential, we may obtain the single-particle energy eigenstates for any given nucleus of mass $A$.

**Solving the Equations**

With such a potential, spherical symmetry is assured, so the radial and angular variables $r$, $\theta$, $\phi$ could be separated, and the wave function of the states is the product of a radial function and a spherical harmonic $[2]$. The radial function is the Bessel function $j_l$ inside the well and the Hankel function $h_l$ outside $[2]$. Using recurrent relations between Bessel functions, the continuity of the two functions and of their derivatives at the surface of the well imposes the following condition:

$$W \equiv z_1^2 j_l(z_1) h_l(z_1) - z_2^2 h_l(z_2) j_l(z_2) = 0$$

with $z_1 = \sqrt{\frac{2mE}{\hbar^2} a}$ and $z_2 = \sqrt{\frac{2m(V_0-E)}{\hbar^2} a}$,

where $a$ and $V_0$ are the ridge and depth of the well, $m$ is the nucleon mass, and $E$ is the energy of the eigenstate of orbital momentum $l$.

For a given orbital momentum $l$, the energy of the states will be given by the zeros of the $W$ function. We use $1/W$ to show graphically, from the computer, the solutions as divergences. This allow us to build the single-particle levels for any nuclei. In Figure 2, we can see the different $s$-states for a square well corresponding to lead.

**Wave Functions and Densities**

As the spherical harmonics are tabulated $[3]$, the total wave functions could be calculated, like for the lead $2d$ level, which is displayed in Figure 3, where the particular projection of the angular momentum $m=0$ is plotted in the plan ($r$, $\theta$). We can also show that the principal quantum number, like $n=1$, $2$ or $3$ used in Figure 2, corresponds to the number of nodes of the wave function of the states.

The nuclear density is now determinable by squaring the wave function. For instance, we have extracted the $^{206}$Pb density, shown in Figure 4, as decomposed into its orbital angular momentum components. The contribution to the total density of each occupied state is determined taking into account the $(2l+1)$ degeneracy of the $l$ states, the spin degeneracy, and the constitution (N, Z) of the nucleus. The protons and neutrons are being considered into two separated but identical wells (the reduction of the proton well, coming from Coulomb interaction, can eventually be added).

The radial wave function outside the well is a function like $h(r) = \exp(-\sqrt{\alpha E} r)/\sqrt{\alpha E} r$, where $E$ is the energy of the state. For low binding energies ($E \sim 0$), the wave function and so the density of probability will extend over a large region of space. Even with this simple model, we are able to illustrate some new effects that emerge for nuclei near the limits of stability.

**Level Evolution with Masses**

We can obtain the energy levels for any nucleus, giving the mass number $A$ and a chosen orbital momentum $l$. The levels are not at fixed positions and we can follow the
evolution of levels with mass, as given in Figure 5. The last bound level for light nuclei is close to the Fermi energy, so there are no possible excited states below threshold, whereas for heavy nuclei, the Fermi level is deep inside the well, which allows many possible bound excited states.

This level energy dependence with mass implies a natural dependence on nuclear binding energies. The total binding energy of a nucleus may be thought naively to be the sum of the individual single particle energies. However, since as one increases the mass, a given l-state appears at a deeper energy, an overall constant binding energy per nucleon is not incoherent.

This is a fundamental difference between the square well and the infinite potential such as the harmonic oscillator: the latter is mass independent and all levels of fixed energy are bound.

Examples

Inexistence of Mass 5 and Mass 8 Nuclei

The observation of the nonexistence of mass 5 and mass 8 stable nuclei is important not only to nuclear physics but also to astrophysics. Astrophysicists have for a long time noticed the premature abortion of nucleosynthesis a few minutes after the big bang, being able to build up nuclear species only to mass 7. Indeed, the stop of big bang nucleosynthesis is mainly due to the lack of stable isotopes of mass 5 and 8.

This inexistence is explained naturally using our toy model. Let’s calculate the energy levels for a mass 5 nuclei. The energy levels of this nucleus are calculated looking for \( l = 0 \) and \( l = 1 \) solutions. One \( l = 0 \) state exists at -19 MeV, but there happen to be no \( l = 1 \) bound states in such a model for mass 5 nucleons. This is not specific to \( R_0 = 1.2 \text{ fm} \) and \( V_0 = \ldots \).
45 MeV but true for every reasonable value of \( R \), with its associate \( V_c \).

The situation for mass 8 is slightly different. The necessary levels to build mass-8 nuclei do exist, since our program indicates an \( l = 0 \) state existing at 24 MeV and an \( l = 1 \) state at 5 MeV. The total binding energy of such a nucleus would be -116 MeV. However, the transmutation of \(^7\)Be into two \(^4\)He tends to readily occur, given that the binding energy of the \(^4\)He nucleus (about –65 MeV in our calculation) would lead to a deeper potential for the two-\(^4\)He system. Further, the energy available in this decay is sufficient to overcome the Coulomb barrier (acting as a confining potential in this case); the reaction lies some 12.5 MeV above the barrier. Hence, primordial \(^7\)Be nuclei were doomed to always decay.

**Shell Model for Heavy Nuclei**

For a heavy nuclei like lead, the order of the levels is 

\text{(1s)(1p)(1d)(2s)(1f)(2p)(1g)(2d)(1h)(3s)(2f)(1i)(3p)}.

This order of the states leads to shell closures 2-8-18-20-34-40-58-68-90-92-138-138. . . . These, however, are not the observed magic numbers of nuclei. They correspond, in fact, to the magic numbers of metallic clusters: 8, 20, 40, 58, 92, 138, . . . [4]. Like nucleons in nuclei, the atoms of metallic clusters are subject to a short-range force, so the square well is also a good approximation for such a system.

One important ingredient is missing in the case of nuclei: it is the spin-orbit potential, first introduced by the Nobel prize winners Mayer and Jensen. By adding a spin-orbit potential to the nuclear square well, they were able to reproduce the nuclear magic numbers. This could be repeated by students fairly simply, given the form of the spin-orbit term such as –L.S, which induces a splitting of the levels and a new sequence where the numbers 2, 8, 20, 28, 50, 82, 126 appear like shell closures. While such a simple version may not give the correct large energy gap, it is sufficient for the purpose of this project.

**Summary and Conclusion**

As a pedagogical tool, this toy model presents many advantages compared to other ones. It could be used interactively within a classroom environment and easily managed by students with mathematical libraries. In addition, these ones particularly appreciate the realism of a finite well (which, unlike infinite potential models, explains naturally the emergence of levels with the increase in mass) and the logical reasoning used here: the primary observation of the A \( \frac{1}{3} \) dependence of the nuclear radius leads directly to the shells in the nucleus, with the exception of the required addition of a spin-orbit term. Furthermore, this model is as rich as it is simple; while we have shown only a few examples, others can be done, including the calculation of super heavy elements by the addition of a Coulomb term to reduce the proton well or the estimation of the probability of a proton decay in the radioactivity of \(^4\)He.

In the end, this model, used as a heuristic tool, appears to be a precious help to students trying to learn the "nuclear way of reasoning" by themselves.

**Acknowledgment**

We warmly thank M. Cassé, A. Drouart, S. Karataglidis, and E. Tryggestad for their help in the preparation of this article.

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facilities and methods

AGATA: The Advanced Gamma Tracking Array

For decades, the study of the gamma-ray decay of the quantal states of the atomic nucleus has played a pivotal role in discovering and elucidating the wide range of phenomena manifested in its structure. Each major technical advance in gamma-ray detection devices has resulted in significant new insights into the structure of nuclei. To date, these advances have culminated in two state-of-the-art $4\pi$ arrays of escape-suppressed spectrometers, Euroball in Europe and Gammasphere in the USA.

With the advent of the first generation of radioactive beam facilities, dedicated medium-size detector arrays (e.g., MINIBALL and EXOGAM in Europe) have been constructed with the specific aim of studying the electromagnetic radiation from reactions of fast-moving, short-lived exotic nuclei, with beam intensities several orders of magnitude lower than what is typically used at stable beam facilities.

The global consensus of opinion now is that the next major step in $\gamma$-ray spectroscopy involves abandoning the concept of a physical suppression shield and achieving the ultimate goal of a $4\pi$ Ge ball through the technique of $\gamma$-ray energy tracking in electrically segmented Ge crystals [1, 2]. The resulting spectrometer will have an unparalleled level of detection power to nuclear electromagnetic radiation. Its sensitivity for selecting the weakest signals from exotic nuclear events will be enhanced by a factor of up to 1000 relative to its predecessors (Figure 1, left side). It will have an unprecedented angular resolution making it ideally suited for high-energy resolution even at velocities of the emitting nuclei up to 50% of the velocity of light (Figure 1, right). It is therefore superbly suited to be used in conjunction with the new generation of radioactive beam accelerators or existing stable beam facilities.

High-precision $\gamma$-ray spectroscopy is one of the most powerful probes of the structure of excited nuclear states and so the impact of a massive increase in the efficiency and sensitivity in this area will be far-reaching, both in the study of nuclear structure and in the closely related disciplines of nuclear astrophysics and fundamental interactions.

The new challenges for nuclear spectroscopy which provide the

Figure 1. Left: Plot of the spectroscopic sensitivity as a function of spin for various arrays showing the evolution of gamma-ray detection technology. The large gain provided by a $4\pi$ tracking array, such as AGATA, is clearly shown. Right: Simulated spectrum for ca. 2.5 MeV $\gamma$-rays emitted from a source that moves with 20% of the velocity of light. A resolution of 8 keV is expected for AGATA, which should be compared with 80 keV (the broad structure) for a current generation large array, e.g., EUROBALL.
impetus for AGATA are emerging principally from the new generation of high-intensity radioactive ion beam facilities currently being developed worldwide. These provide beams with energies spanning the Coulomb energy regime, typical of the European ISOL facilities (SPIRAL, REX-ISOLDE), to the intermediate and relativistic energy regimes of fragmentation facilities, such as SIS/FRS at GSI. AGATA is vital for these laboratories and for the planned major new facilities at, e.g., GSI and for EURISOL. In the Coulomb energy regime the classical reaction types (Coulomb excitation, transfer, deep-inelastic, or compound reactions) will become possible using increasingly more exotic radioactive beams allowing essentially all facets of nuclear structure to be probed in hitherto inaccessible regions of the nuclear chart. At intermediate energies, between 50 and 200 A MeV, Coulomb excitation can be employed to pick out states connected to the ground state by sufficiently strong electromagnetic matrix elements, up to and including the highly excited giant resonances. At even higher beam energies the single particle structure of ground state and excited states of the most exotic nuclei can be probed by means of knock-out and Coulomb break-up reactions. At these energies secondary fragmentation becomes a powerful tool to create very exotic fragments that are excited to relatively high spins of more than 30h. Finally, the rarest species, closest to the drip lines, can be studied using decay spectroscopy after implantation. This massive increase in experimental access to phenomena in unexplored regions of the nuclear chart, offered by the new generation of exotic beam facilities, can only be fully exploited with the matching leap in experimental sensitivity offered by AGATA.

The combination of high-efficiency, high-resolution γ-spectroscopic studies and exotic beams will allow a very rich physics program to be addressed that covers the full gamut of topics which currently engage the nuclear physics research community. The study of structure at the very limits of nuclear stability is crucial in order to answer some of the most pressing questions in the field. These include the isospin dependence of the effective nuclear interaction, the ability to explain collective phenomena from the properties of the individual nucleons, and the limits of nuclear existence and indeed Mendeleev’s table of the elements. In the last decade, it has become clear that many of our preconceptions of nuclear structure have to be revised. Nuclear radii are not always proportional to $A^{1/3}$; instead, neutron-rich nuclei develop a diffuse region of neutron “skin” or “halo” which can extend much further. The values of the magic numbers of the nuclear shell model for neutrons and protons are no longer sacrosanct: the strength of the $T = 0$ part of the nucleon–nucleon interaction means that the position of the neutron (proton) shell closure varies with the proton (neutron) number. The number of neutron-rich nuclei which can exist is far greater than anticipated: improvements in the treatment of the self-consistent nuclear problem, including more realistic estimates of correlations and clustering, predict a neutron drip line which seems to be constantly receding. AGATA will focus on all these aspects through studies of, for example, (i) proton-rich nuclei at and beyond the proton drip line and the extension of the $N = Z$ line, (ii) neutron-rich nuclei towards the neutron drip line in medium heavy elements, and (iii) the heaviest elements towards new super-...
heavy elements. The response of nuclei to angular momentum and temperature will be investigated by, for instance, ultrahigh spin states produced in extremely cold reactions, metastable states at high spins and at very large deformation, and multiphonon giant resonances as well as other high-temperature phenomena, such as quantum chaos.

A γ-ray tracking system involves measuring the position and energy of every γ-ray interaction in a detector so that the scattering path and sequential energy loss of each individual γ-ray can be deduced using the Compton scattering formula; see Figure 2. The full energy of the event can then be reconstructed without the losses due to suppression shields, which covered nearly half the solid angle in the previous generation of spectrometers. The realization of such a system will require highly segmented germanium detectors and digital electronics. This device will have wide-ranging applications in medical imaging, astrophysics, nuclear safeguards, and radioactive waste monitoring, as well as introducing a new plateau of detection capability for nuclear structure studies.

Given the importance of this development and its far-reaching implications, it is not surprising that developments are taking place in Europe and in the USA to realize this new type of instrument. In Europe a collaboration (consisting of 40 partners from over 10 countries) has already been established to construct the 4π γ-ray tracking spectrometer called AGATA. This collaboration has recently signed a memorandum of understanding for the first phase of the project to perform the research and development necessary to finalize the technology for γ-ray tracking and hence fully specify the full 4π spectrometer. In the USA a research program called GRETA (Gamma-Ray Energy Tracking Array) is fully underway [2].

The AGATA project [1] is based on the technological achievements obtained in recent years by the European γ-ray spectroscopy community and especially within the European TMR Network Project Development of γ-Ray Tracking Detectors for 4π γ-Ray Arrays [4], in which a proof of concept for the novel technique of γ-ray tracking has been achieved. In order to prove the feasibility of a full 4π γ-ray tracking spectrometer a demonstration of the new technology with a subarray, the so-called AGATA demonstrator, is needed that is sufficiently large to carry out experiments and hence validate the concept. The full 4π AGATA array will consist of either 120 or 180 36-fold segmented individually encapsulated Ge crystals (see Figure 3), closely packed together in groups of three in a common cryostat. The encapsulated detector technology builds on the development made for the cluster detectors of Euroball and Miniball [5]. The signals from each segment as well as from the central contact are used for the determination of the position of the interaction points [6, 7]. Here the shape and size of the real charge signal collected in one segment together with the mirror image charges in the neighbouring segments are needed for a position resolution significantly better than the segment size. Note in Figure 3 the difference between the physical segments, given by a perpendicular cut from the central contact to the outer contact border, and the effective segments, given by the real charge.

Figure 3. Thirty-six-fold segmented, encapsulated Ge detector (top right). The lower right shows the calculated effective segments, indicated by different shading. Their shape is obtained by releasing a test charge at each position in the detector and determining on which outer segment the charge is collected. On the left, the calculated position sensitivity in depth (l), radial (r), and azimuthal (φ) direction is indicated. The highest sensitivity is reached near the effective segment boundaries due to the maximum of the induced signals into the neighbouring segment.
collection geometry. The interaction position is determined by an iterative algorithm that compares the measured pulse shapes with a database of reference pulse shapes [7]. Here the particular challenge lies in the deconvolution of multiple interactions within one segment as well as real and induced charge signals in one segment.

Research and developments is required to specify and investigate options for signal processing. This involves the use of digital electronics and processing to extract energy, time, and interaction positions within the detector. The energy is extracted from the digitized preamplifier signals using a so-called moving window deconvolution (MWD) algorithm [8]. The impact of the fully digital processing can be seen in Figure 4. The top shows the raw pre-amplifier signals at an event rate of 40 kHz. Analogue signal processing would lead to a lower energy resolution due to signal pile-up. Applying the MWD algorithm extracts clean signals, shown in the middle. The amplitude of these signals is equal to the collected charge. The digital processing thus allows pile-up events to be disentangled, enabling event rates of up to 50 kHz. The individual segments will be triggered by the signal from the core contact of each crystal where a very low threshold can be achieved.

The AGATA collaboration aims to build a demonstrator subarray of up to 5 detector modules, with each module containing three 36-fold segmented detectors. The demonstrator will have a purposely built digital electronics and data acquisition system, and the collaboration will develop and refine the algorithms for energy, triggering, timing, and position determination, and for tracking. As well as proving the tracking concept and power of the full array, this demonstrator, which will be available for experiments in 2007, will be a powerful spectrometer in its own right.

Concluding, we would like to emphasize the enormous impact that AGATA will have on the exploration of nuclear structure at the extremes of isospin, proton number, angular momentum, and temperature. This radically new device will constitute a dramatic advance in γ-ray detection sensitivity that will enable the discovery of new phenomena, which are only populated in a tiny fraction of the total reaction cross section or of nuclei that are only produced with rates of the order of a few per second or less. Its unprecedented angular resolution will facilitate high-resolution spectroscopy with fast and ultrafast fragmentation beams giving access to the detailed structure of the most exotic nuclei that can be reached. Finally, the capability to operate at much higher event rates will allow the array to be operated for reactions with intense γ-ray backgrounds, which will be essential for the study of, for example, transuranic nuclei.

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Figure 4. Digitized preamplifier signals for a detector rate (core signal) of 40 kHz. Top: the deconvoluted signals after using the moving window deconvolution (the energy is obtained by averaging over the flat top of the signal (insert)). Bottom: the response of a triggering algorithm (Slope Condition Counting, SCC) is shown [8].
Francium Developments at Stony Brook

The radioactive element francium is of great interest in many laboratories because, as an alkali, it is the heaviest atom in which the atomic properties can presently be calculated to better than 1%. The electron–nucleus interactions in heavy atoms are stronger than in lighter alkalis and are more sensitive to weak interaction effects in nuclei, such as anapole moments, electric dipole moments, and other parity-violating effects. The ability to trap large numbers of atoms, >10^6, would make possible precision measurements of these effects.

Stony Brook [1] and Legnaro [2] now have the capability to produce and trap radioactive Fr produced with heavy ion reactions, and experiments are planned at KVI (Groningen) and at TRIUMF. There is also interest in using cold atomic beams to look for atomic parity-violating effects [3].

The number of trapped atoms, N, is given by N=I·η·τ, where I is the initial Fr beam intensity, η the trapping efficiency, and τ the lifetime of an atom in the trap. At Stony Brook, we initially worked with Fr beams of the order of 10^5 Fr/sec. The lifetime of the trap is determined by the quality of the vacuum, with τ≈10^2 sec for pressures ≈10^-9 Torr. In our initial work, the trapping efficiency was of the order of 10^-2, so we would typically have about 10^3-4 atoms in the trap.

In the last year, a new approach to trapping has made an order of magnitude improvement in the trapping efficiency [4]. Along with evolutionary improvements in the Fr production and vacuum, we can now trap 10^5 atoms routinely, and when everything is working optimally, should be able to achieve 10^6 trapped atoms. Figure 1

Figure 1. Detail of the new trapping system with pivoting neutralizer.

Figure 2. New Fr beam transport system.
facilities and methods

shows the new apparatus, conceived by Eduardo Gomez and constructed by Gomez and Seth Aubin in our laboratory. The system works in “batch” mode, with Fr accumulating on a cold neutralizer for a fixed time. After accumulation, the neutralizer is rotated so that it covers the only opening in the trapping cell, and the neutralizer is then heated to evaporate the Fr atoms into the cell. Because there are no exit holes, the Fr has longer to be trapped in the cell before either it is lost to a defect in the cell coating or it finds the small cracks around the neutralizer to diffuse out of the cell. With this system, the overall trapping efficiency is now >1%. The “batch” nature of the trap is ideal for the planned transfer to a second trap. If the second trap has a much longer lifetime, then the number accumulating there will be proportional to that lifetime, and even larger numbers of atoms should be accumulated.

Another problem that we had with our original trapping system was that because the target was located within about 2m of the trap, the neutron background precluded our working at the trap, and everything had to be remotely controlled, or tediously changed by turning off the beam and entering the target room. We have solved this problem with the new setup, which is shown in Figure 2. The primary 100 MeV 18O beam from the Stony Brook LINAC impinges on a Au target, which is in the shielded target room, while the trap and all of the laser systems are in a separate laboratory. The Fr activity is transported as an ion beam through a small hole in the shielding wall, and the low-energy alpha, beta, and gamma activities are easily shielded in the trapping area.

The target is heated by the beam and by an auxiliary heater to just below the melting point for fast diffusion of the Fr to the Au surface, where it is emitted as an ion. By adjusting the beam power, we can melt the target, but for longer life of the target, we generally work just below the melting point. We have observed the melting with a CCD camera, since the emissivity of the liquid is about 5% higher than that of the solid. There is a corresponding large increase in the Fr beam because of the enhanced diffusion in the liquid.

The ions are transported at 5 keV in the all-electrostatic beam line. The transport is mass independent, so that we can tune everything with a Rb+ beam generated by spraying Rb atoms onto the hot Au target, or from the inevitable impurity alkali atoms present in even the highest purity Au.

Seth Aubin has led the effort to test the new trapping system by measuring lifetimes and hyperfine structure in the 9s state [5]. These measurements test the ability of the ab-initio atomic calculations to predict matrix elements similar to the ones that are needed for interpreting PNC measurements. Figure 3 shows the energy levels relevant to the measurement. We used a sequence of laser pulses at different wavelengths to move a large fraction of the population of the atoms in the trap into the 9s state. With all of the lasers switched off, we then detected the decay of the state with a photomultiplier and an 851nm interference filter. The measured lifetime is compared with theory in Figure 4. The agreement with the ab-initio theories is remarkable, well within the uncertainty of the theory.

The hyperfine interaction constant is also an important testing ground for ab-initio atomic calculations of Fr. While the nuclear g-factor has been previously measured with a precision of 2%, a more precise measurement is necessary for testing the atomic wave functions that are used for weak interaction measurements in Fr. We propose to measure the nuclear g-factor with Fr+ ions, in which the much larger electron magnetic moment is removed. We are developing an apparatus, similar in concept to the TRIUMF polarized Li beam: We start with a Fr+ beam, neutralize it, polarize it by optical pumping, and then re-ionize the atoms to form a polarized Fr+ beam. We will then slow, cool, and confine the ions in an ion trap. We will measure the nuclear magnetic moment to high precision by resonantly destroying the spatial...
anisotropy of the alpha-particle decay distribution.

The g-factor measurement apparatus is presently under construction. The neutralization step has been successfully accomplished with Rb vapor as a neutralizer. We simultaneously injected both a Rb\(^+\) beam and a much weaker Fr\(^+\) beam through a Rb vapor and determined the Rb ion/atom ratio by measuring the Rb\(^+\) ion current in Faraday cups before and after the vapor region. The Fr ion/atom ratio was determined by stopping the Fr beam in front of an alpha-particle detector and deflecting the Fr\(^+\) ions after the vapor region with a transverse electric field. With this system, we have established that the charge exchange cross section for Fr\(^+\) + Rb is larger than the corresponding cross section for Rb\(^+\) + Rb, and 90% of Fr\(^+\) are neutralized with 4cm of Rb vapor at T≈115ºC with atom density of 1.5 x 10\(^{13}\)/cm\(^3\).

Acknowledgments

E. Gomez is supported by CONACYT, Mexico. This work has been supported by NSF. L. A. Orozco has recently moved to the University of Maryland but will continue the Fr research program at Stony Brook.

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Selected Isotope Applications in Cosmochemistry and Geochemistry

Abstract

Today, isotope techniques are a firmly established tool in both geochemistry and cosmochemistry. A plethora of dating techniques is now routinely used, chosen to suit the timescale of the process being investigated, existing instrumentation, and availability of appropriate samples [1]. Nevertheless, the age provides only the timeframe for other isotopic information such as material origin and process(es) recorded by the various isotope systems. We illustrate this here with some topical examples from interstellar grain cosmochemistry and studies of early Earth geochemistry.

Introduction

Geochemistry has its roots entangled both in the economic need to identify ore minerals and the quest to understand the origin of the world we live in. The latter has had arguably the greatest impact on our understanding of geological processes, with resulting huge economic benefits provided almost as a sideshow. Our fascination with the Earth and its geology encompasses the more obvious earthquakes, volcanoes and dinosaurs, as well as the more esoteric, such as the structure and evolution of the core, silicate mantle, continental crust, and ocean/atmosphere system. Indeed, with much current emphasis on environmental issues, the impact and control of the geological system on our immediate surroundings has established geochemistry as an interface science with atmospheric chemistry, climatology, oceanography, hydrology, and many other related disciplines.

Isotope cosmochemistry provides another interface, providing an insight into the basic element building processes in stars and how this material is captured, accreted, and processed to form the planets that we see or stand on today. A quick inventory of even the most well-known sample resources reveals huge variety and scale, e.g., solar wind; micron-sized interstellar grains; interplanetary dust particles; Martian, lunar, and asteroid meteorites; and lunar sample return, and also illustrates how nuclear physics, astrophysics, and cosmochemistry are strongly intertwined. To cover all facets of isotope geochemistry and cosmochemistry would require several textbooks. We present below just a few areas in isotope geochemistry and cosmochemistry that exemplify the application of isotopes in the study of widely different areas and available sample resources.

Interstellar Grains

It is well known that astronomers study photons from the whole range of the electromagnetic spectrum to try and understand violent astrophysical and nucleosynthetic events ranging from star formation to the death of galaxies. What is perhaps not quite so well known is that over the last two decades, meteoriticists have discovered interstellar grains from these extreme environments existing almost unaltered in meteorites and have developed ways of isolating them for study [2–4]. Astronomical observations of extreme phenomena such as supernovae are crucial to help improve our understanding of nuclear and astrophysical theory, but how advantageous to also have solid condensates from those events available for study in the laboratory! Grains from supernovae, novae, Wolf-Rayet, and giant stars have been isolated and identified and the study of their isotopic patterns for a whole range of elements now drives astrophysical and nuclear theory in these extreme conditions [5]. The study of interstellar grains can be used to infer information in areas of stellar dynamics that cannot be probed by any other means, for example, obtaining many nuclear cross-sections, precise isotopic compositions within stars, the number of stellar sources contributing to the formation of the solar system, and implications for galactic chemical evolution and the age of the galaxy. It can also complement astronomical spectral observations of stars by providing an additional source of information for the isotopic composition within stars and information on the physical and chemical conditions within stellar atmospheres. Interstellar grain studies also have the potential to constrain conditions during the formation of the solar system and the environment and method of capture within their parent meteorite bodies.

The grains of silicon carbide, graphite, and corundum themselves though are typically micron sized, and measuring accurate isotope ratios of a range of elements in such tiny samples challenges the capabilities of modern analytical instruments. Nevertheless, the scientific potential is huge as the
discovery of actual condensates from a time early in galactic history and from objects as extreme as supernovae gives us a new window on the universe, if only we can see through micron-sized panes. The key to understanding their history lies in the analysis of their isotope ratios.

Isotopic analysis, however, requires mass spectrometry and therefore the destruction, or certainly damage, of the sample. Much of the development of instruments such as noble gas mass spectrometers, as well as high-spatial-resolution electron, laser, and ion probes, has therefore been driven by the need to analyze the absolute minimum quantity of material possible. An interstellar grain 1 micron in diameter contains only about \(10^{11}\) atoms in total with abundances of rarer elements and isotopes running right down to “a few atoms.” The spatial resolution and sensitivity required to work within these constraints are now being met by secondary ion mass spectrometers, which focus ion beams down to 50 nm, producing secondary ions for analysis or using lasers to ionize the sputtered atoms [6–8]. Achievements in this field are now the construction of 50 nm resolution isotope maps of micron-sized grains with very high sensitivity (Figure 1). The spin-offs of these developments are widely applicable to many other areas where samples are small and isotope ratios are required.

**Nuclear Astrophysics**

With rare exceptions, the isotope ratios of any element vary comparatively little on the Earth, usually within a few percent or so at the most. However, in interstellar grains the isotope ratios in common elements such as carbon, nitrogen, and oxygen can vary by up to four orders of magnitude and silicon by one order of magnitude (indeed, this is the primary evidence to identify them as interstellar). \(^{12}\)C, \(^{14}\)N, and \(^{16}\)O participate in CNO nucleosynthesis in massive stars, with only minor reactions producing the other stable isotopes of these elements: \(^{13}\)C, \(^{15}\)N, and \(^{17,18}\)O. Thus within a massive star, the major/minor isotope ratio can vary enormously depending upon depth and temperature. In the heavier elements, the pattern of “s” process nucleosynthesis has been clearly seen and isotope abundances generally agree with theoretical predictions. Expected patterns of “r” process nucleosynthesis have not been seen in interstellar grains, however, and this is a major puzzle [4].

Big bang nucleosynthesis produced H, He, and some \(^{7}\)Li. All other elements have been synthesized since that time in massive stars and ejected into the interstellar medium to seed new star formation with heavier elements. Thus, over the lifetime of the universe, the chemical composition of average stellar material has become progressively enriched in heavier elements. (Only massive stars have contributed to this galactic chemical evolution since they are short-lived [<10⁶ years] and so can eject substantial material back into the interstellar medium, unlike stars such as the sun.) Exothermic fusion reactions synthesize lighter element isotopes, and this combined with models of neutron capture in supernovae may be able to account quite accurately for the observed abundances of elements up to the iron group elements. Above that mass, isotopes are synthesized by neutron capture. If the neutron flux is sufficiently high that successive captures occur on a timescale that is
short compared to the $\beta$ decay lifetime of the capturing isotope, then increasingly neutron-rich isotopes will form. If the neutron capture rate is low compared to the $\beta$ decay lifetime of the capturing isotope, then production of the same mass isotope of the element of 1 larger atomic number will result. Photon-induced reactions can produce neutron-poor isotopes of many elements. The general theory of "r," "s," and "p" process nucleosynthesis, as these are known, respectively, has been worked out in some detail over the last 50 years [9], but the nucleosynthetic sites are still not known [9,10]. There are many excellent reviews of this area, such as [9], that deal with this topic far more rigorously than space allows here, but the details are still sufficiently challenging that a recent report from the National Academy of Sciences included "How are the elements from iron to uranium synthesized?" as one of 11 major unanswered questions facing modern astrophysics for the new century, ranked alongside such questions as "What is dark matter?" and "What is the nature of dark energy?" [11].

The Oldest Rocks, Early Oceans, and Life

The impact of instrument development on terrestrial studies is equally great, but very much focused on obtaining age information and precisely resolving the much smaller isotopic differences that provide information about material origin or processes that have operated in the past. Identifying the conditions existing on the very early Earth is difficult because almost nothing is left in the geological record. Much evidence is inferred from isotopic changes that can only have been caused by these early conditions. For example, while the oldest preserved microfossils are 3.5 Ga, carbon isotopic compositions that can only be caused by biological process are preserved in samples as old as 3.8 Ga [12]. More recently, high-resolution ion probes with a spot size of 20–25 $\mu$m diameter have recently enabled zircon fragments to be dated at 4.404±0.008 Ga—the oldest terrestrial samples yet found [13]—and close to the age the Earth formed (4.55 Ga). Importantly, the oxygen isotopic composition of these samples can only have come from an environment containing liquid water [13,14]. These latest results suggest that the conditions for development of life on Earth may have existed as much as 600 Ma before the earliest isotopic record of life.

A clue to why life took so long to gain a foothold is found in the cratering record of the moon that shows a late (3.8–4.0 Ga) heavy meteorite bombardment. Evidence for this also affecting the Earth is found by examining the tungsten isotope composition of some of the earliest metamorphosed sediments found in Greenland (3.7–3.8 Ga). These record a $^{187}$W anomaly, the decay product of $^{182}$Hf ($\tau_{1/2} = 9$ Ma), only found in meteorites, and show that these sediments have incorporated a significant raw meteorite component [15].

The Structure of the Earth and Its Chemical Evolution

Perhaps one of the most important changes in our understanding of the way the Earth continued to evolve has occurred only over the previous 6–7 years. For the last 25 years geochemists have argued successfully that the Earth’s silicate mantle is chemically layered and that only 30–50% by mass of the mantle has played any role in continental crust and atmosphere formation. This separation has been attributed to the endothermic phase change that occurs in the mantle at 670 km depth, retarding or even preventing mass transfer across this boundary. New high-resolution seismic images of density contrasts in the mantle clearly show cold dense oceanic crust being subducted under the continents and sinking through the 670 km boundary, possibly to the core mantle boundary [16]. Combined with recent advances in numerical models of convection (Figure 2) that have incorporated the isotopic evolution of volatile tracers in the mantle ($^{3}$He/$^{4}$He), these results suggest that the mantle should in fact be well mixed and not layered [17,18]. Why do geochemical and geophysical approaches predict such apparently irreconcilable differences in their models for the Earth’s internal structure and therefore its chemical evolution?

Samples from the mantle come from two different sources. Mid-ocean ridges extend some 65,000 km around the globe and form the source for new oceanic crust and provide material from the uppermost mantle. Ocean islands “hotspots” or “plumes,” such as Hawaii and Iceland, probably sample much deeper portions of the mantle system. Compositional and isotopic differences exist between these different sample types that require the existence of different and long-lived geochemical reservoirs in the mantle. The mid-ocean ridge material is derived from a source that has been degassed and depleted in its crust-forming elements. Oceanic islands in contrast tap a reservoir that in part looks like oceanic crust that has been subducted and isotopically evolved (e.g., $^{147}$Sm→$^{143}$Nd, $^{87}$Rb→$^{87}$Sr, $^{235,238}$U→$^{207,208}$Pb) in the mantle for 1–2 Ga [19]. Another component of the ocean island material has never been involved in surface process. This is shown by its high accretionary volatile content inferred from $^{3}$He/$^{4}$He ratio
determinations (see [18]). This tracer can be used confidently because there is no significant production of $^3$He in the mantle, while U and Th decay dominate the $^4$He inventory. $^3$He/$^4$He is therefore a good proxy for the accretionary volatile to solid ratio. It is worth noting that predicted accretionary values of $^3$He/$^{22}$Ne are found in the Earth’s mantle—occasional advocates of nuclear processes producing mantle $^3$He such as natural critical mass reactors or cold fusion must also account for this relationship.

While recent modeling approaches have increased the number of degrees of freedom by introducing additional but seismically invisible density contrasts into the model mantle system, the reconciliation of geophysical observation and fluid dynamical models with geochemical observations has yet to be achieved [20]. The role of the geochemist must be to find evidence for early earth processes and conditions that would support or refute such concepts. One promising way to address this puzzle is to try to understand the conditions that would enable the high accretionary volatile concentrations recorded by the $^3$He/$^4$He in the deep mantle samples to be trapped in the Earth’s interior. This is effectively an attempt to understand what happened in that missing 100 Ma before the first surface water on Earth was present.

**Noble Gases, CO$_2$-Rich Natural Gas, and the Origin of Volatiles in the Earth**

Noble gas isotopes such as $^3$He/$^4$He (but also Ne, Ar, and Xe isotopes) are a very powerful tool used across cosmochemistry and geochemistry [21]. Their particular advantage lies not only in their chemical inertness, greatly simplifying interpretation, but also in their very low abundance in most natural samples. The latter property means that small isotopic additions from background nuclear processes are simple to identify and quantify. Although a lot of noble gas work has focused on samples from mid-ocean ridges or hot spots, CO$_2$-rich natural gases derived from the mantle occur in many continental regions [22]. In particular, a CO$_2$ natural gas sample from New Mexico recorded the first observed terrestrial excess $^{129}$Xe/$^{132}$Xe [23], clearly showing that a geochemical reservoir within the Earth has preserved a separate record of early $^{129}$I activity ($t_{1/2} = 17$ Ma). This and subsequent results provide important evidence that this part of the mantle lost much of its volatile inventory to the atmosphere while $^{129}$I was still active, in the first 80 Ma of the Earth’s history.
But how were the volatiles incorporated into the mantle in the first place? Two currently competing models respectively advocate (i) equilibration between the molten accreting planet and a massive early atmosphere, not too dissimilar to what we see surrounding gas giants today; and (ii) volatiles trapped within accreting material being carried into the Earth’s deep interior. Neon isotopes may provide the answer [24] (Figure 3). A massive early atmosphere would have a Solar Ne isotopic composition \( ^{20}\text{Ne}/^{22}\text{Ne}=13.8 \) while accreting material that has been irradiated by solar wind preserves a distinct composite mix, often called Ne-B \( ^{20}\text{Ne}/^{22}\text{Ne}=12.5 \). To date, the upper \( ^{20}\text{Ne}/^{22}\text{Ne} \) limit recorded in ocean island samples (deep mantle) and at mid-ocean ridges (upper mantle) is compromised by ubiquitous air/seawater contamination of samples on eruption. Both sample sets have \( ^{21}\text{Ne} \) in excess of solar Ne values due to \( ^{16}\text{O}(a,n)^{19}\text{Ne} \) production in the mantle. The volatile, rich, deep mantle is less deflected by this production than the more degassed upper mantle.

Although natural CO\(_2\)-rich gases are also subject to air contamination, in a few fields this is very small. Indeed, recently samples from the same gas field that showed the first \(^{129}\text{Xe}/^{132}\text{Xe} \) anomaly have been used to identify a solar-like \(^{124-128}\text{Xe}/^{132}\text{Xe} \) component [26] and is the first indication that the convecting mantle may have evolved by equilibration between a solar-like early massive atmosphere rather than a trapped composition. Detailed investigations of the Ne isotopes from this sample resource are currently underway in Manchester and will provide an important piece in the early Earth jigsaw.

**References**


CHRIS J. BALLENTINE
IAN LYON
University of Manchester

The Highly Specialized Seminar on “Symmetries in Nuclear Structure” was held at the Ettore Majorana Centre in Erice, Italy, March 23–30, 2003. The meeting was intended to celebrate, on the occasion of his 60th birthday, the career and the remarkable achievements of Francesco Iachello. Since the development of the Interacting Boson Model in the early 1970s, the ideas of Francesco Iachello have provided a variety of frameworks for understanding collective behaviour in nuclear structure, founded in the concepts of dynamical symmetries and spectrum generating algebras. The original ideas, which were developed for the description of atomic nuclei, have now been successfully extended to cover spectroscopic behaviour in other fields, such as molecular or hadronic spectra. More recently, the suggestion by Iachello of critical point symmetries to treat nuclei in shape/phase transitional regions has opened an exciting new front for both theoreticians and experimentalists.

The meeting gathered more than 80 people from 20 countries. With a few exceptions that were due to a large extent to the sudden worsening of the international situation in the Middle East, all the individuals who have contributed to the field were present for the reunion, showing their scientific and personal gratitude to Francesco Iachello for the important role played by his seminal work in the whole field of nuclear research.

The talks presented at the meeting covered many of the most active forefront areas of nuclear structure as well as other fields where ideas of symmetries are being explored. Topics in nuclear structure included extensive discussions of dynamical symmetries, critical point symmetries, phase transitions, statistical properties of nuclei, supersymmetry, mixed symmetry states, shears bands, pairing and clustering in nuclei, shape coexistence, exotic nuclei, dipole modes, and astrophysics, among others. An important session focused on talks by European Laboratory Directors (or their representatives) outlining future prospects for nuclear structure, while other sessions were devoted to the application of symmetry ideas to molecular phenomena and to hadron spectroscopy. Finally, special lectures by Nobel Laureate Alex Mueller, on s and d wave symmetry in superconductors, and by Antonino Zichichi, on supersymmetry in particle physics, presented unique insights into allied fields.

Erice and the Ettore Majorana Centre provided an ideal venue for the meeting. The location fit perfectly with the spirit of the reunion, since precisely in this place so many of the early successes of the interacting boson model were announced in the late 1970s to early 1980s.

Andrea Vitturi
Universita’ di Padova, Italy
International Symposium on Physics of Unstable Nuclei

The symposium program covered a wide range of topics on the physics of unstable nuclei, which are grouped in the three following areas:

1. *Structure of unstable nuclei* presented the latest experimental results on exotic nuclei, nuclear clusters and molecules, superheavy nuclei, as well as the application of the shell model, relativistic mean field theory, quasi-particle random-phase approximation and other structure models to study unstable nuclei.

2. *Nuclear reactions induced by exotic beams* included the excitation and breakup of exotic nuclei, elastic and inelastic scattering, transfer and charge exchange reactions, fusion and fission, and isospin distillation in heavy-ion collisions.

3. *Nuclear astrophysics* discussed low-energy nuclear reactions with exotic beams, nucleosynthesis, asymmetric nuclear matter and supernova neutrinos.

During the six days of the symposium we had many excellent presentations of new results in the physics of unstable nuclei as well as lively discussions about the open questions and challenges, and the symposium has been very beneficial to many participants, in particular to the young researchers and students from universities and institutions in Vietnam, many of whom were attending an international meeting in nuclear physics for the first time. ISPUN02 has been rated by many colleagues as a very successful attempt to promote basic science in Southeast Asia.

Last but not least, this symposium was also a good opportunity for the nuclear physicists of the international community, especially those visiting Vietnam for the first time, to discover not only the beauty of the country’s landscape but also the hospitality of the Vietnamese people.

DAO TIEN KHOA
Vo VAN THUAN
INST Hanoi

NGUYEN DINH DANG
RIKEN and INST Hanoi

SHIGERU KUBONO
CNS Tokyo

NGUYEN VAN GIAI
IPN Orsay
David B. Fossan

David B. Fossan, a world leader in studies of nuclear structure and properties of exotic states of nuclei, died July 27, 2003 following a heart attack that occurred while swimming at Long Island’s south shore. He was on the annual beach outing he organized for his research group. Dave was a professor of physics at the State University of New York at Stony Brook, where he had been on the faculty since 1965.

Fossan was born in Faribault, Minnesota in 1934. He received his B.A. from St. Olaf College in Minnesota in 1956 and his Ph.D. from the University of Wisconsin in 1960 under the direction of Prof. Heinz Barschall. Before joining the Stony Brook faculty, he held a postdoctoral appointment at the Niels Bohr Institute at the University of Copenhagen (1961–1962) and Lockheed Corporation (1963–1964).

On joining the young department at Stony Brook in 1965, David was a charter member of the new Nuclear Structure Laboratory. His research has been the cornerstone of the Laboratory’s program until today. His research program was remarkable both for its breadth of focus and its productivity, with over 260 publications. He returned many times to several themes for exploring nuclei in extreme conditions as new techniques and theories opened new avenues. Fossan was a Fellow of the American Physical Society, held a Humboldt U.S. Senior Scientist Award in 1989, and in 2002 received the State University of New York Chancellor’s Award for Excellence in Research in the first year of the award’s existence.

Fossan was a leading player in establishing the gammasphere detector and served on its steering committee from inception of the project until 1996. Fossan’s earlier studies of nuclear shapes matured in the last few years with the discovery of chiral doublet structures in odd-odd nuclei, in which right- and left-handed triaxial nuclei were shown to have a nearly degenerate set of energy levels. The presence of such mirror nuclei had been hitherto unknown, and their observation opens new avenues of study of the role of symmetries in nuclear structure.

In the national arena, Fossan played a variety of important roles. In addition to his leadership in the gammasphere project, he served on advisory committees at Brookhaven National Laboratory, the Indiana Cyclotron Facility, Lawrence Berkeley National Laboratory, Oak Ridge National Laboratory, and Argonne National Laboratory. He held guest appointments at Brookhaven Lab, the University of Munich, Lawrence Berkeley Lab, and Chalk River Nuclear Laboratory. He served as a member of the Editorial Board for Physical Review C, and as chair of the 1987 Gordon Conference on Nuclear Chemistry.

Fossan was an exceptional mentor for young scientists. He supervised the thesis research of over 20 Ph.D. students and 16 postdocs who have gone on to outstanding careers in physics, medical physics, and other areas. Although he set rigorous standards, David’s energy, enthusiasm, and dedication helped him provide an unparalleled learning environment for students. He gave students real responsibility and demanded that they produce, but offered advice at each step along the way. He was enormously generous with his time, going far out of his way to work with students in the laboratory and in the classroom.

David’s affability and good nature masked a deep competitive drive. Some of this came out through the demands he placed upon himself to extend the understanding of physics, but an even more apparent manifestation was his athletic drive. His early love for basketball transformed in later days to frequent rounds of tennis, during which he would put away the opposition with a smile on his face.

We will remember David Fossan for his many contributions to our understanding of the complex processes at work in large and exotic nuclei. His experimental skills, coupled with his deep understanding of the quantum basis for multiparticle systems, distinguished his research career. Even more, we will remember him for his outstanding personal contributions to generations of physicists, his fierce honesty, his remarkable cheerfulness, and his deep commitment to bringing out the best in others.

ROBERT L. McGRATH AND GENE D. SPROUSE
State University of New York

Call for Nominations for the Lise Meitner Prize for Nuclear Science

The Nuclear Physics Board of the EPS invites nominations for the year 2004 for the “Lise Meitner Prize.” The award will be made to one or several individuals for outstanding work in the fields of experimental, theoretical, or applied nuclear science. The Board would welcome proposals that represent the breadth and strength of European nuclear sciences.

Nominations should be accompanied by a completed nomination form, a brief curriculum vitae of the nominee(s), and a list of major publications. Letters of support from authorities in the field which outline the importance of the work would also be helpful.

Nominations will be treated in confidence, and although they will be acknowledged, there will be no further communication. Nominations should be sent to:

Selection Committee LM Prize
Chairman Prof. Ronald C. Johnson
Department of Physics
School of Physics and Chemistry
University of Surrey
Guildford, Surrey,
GU2 7XH, United Kingdom

Phone: +44 (0)1483 879375
Fax: +44 (0)1483 876781
E-mail: R.Johnson@surrey.ac.uk

To download a nomination form and for more detailed information, see the website of the Nuclear Physics Division, http://www.kvi.nl/~eps_np and the website of EPS, www.eps.org (EPS Prizes, Lise Meitner Prize)

The deadline for the submission of the proposals is January 10, 2004.

Call for Nominations for the IBA-Europhysics Prize 2004 for Applied Nuclear Science and Nuclear Methods in Medicine

The Nuclear Physics Board of the EPS invites nominations for the year 2004 for the IBA-Europhysics prize. The award will be made to one or several individuals for outstanding contributions to applied nuclear science and especially to nuclear methods and nuclear research in medicine.

The Board welcomes proposals that represent the breadth and strength of applied nuclear science and nuclear methods medicine in Europe.

Nominations should be accompanied by a completed nomination form, a brief curriculum vitae of the nominee(s), and a list of major publications. Letters of support from authorities in the field which outline the importance of the work would also be helpful.

Nominations will be treated in confidence and although they will be acknowledged, there will be no further communication. Nominations should be sent to:

Selection Committee IBA Prize
Chairman Prof. Ch. Leclercq-Willain
Department of Theoretical Nuclear Physics–PNTPM–CP 229

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To download a nomination form and for more detailed information, see the website of the Nuclear Physics Division, http://www.kvi.nl/~eps_np and the website of EPS, www.eps.org (EPS Prizes, IBA-Europhysics Prize)

The deadline for the submission of the proposals is January 10, 2004.
calendar

2004

January 11–17
Hirschegg, Kleinwalstertal, Austria. Electromagnetic Interactions in Nuclei and the Nucleon. International Workshop XXXII on Gross Properties of Nuclei and Nuclear Excitations. Contact: G. Kluckner, Tel.: +49-6151-16-3073. Fax: +49-6151-16-6076. E-mail: hirschegg@crunch.ikp.physik.tudarmstadt.de

January 11–17
Oakland, CA, USA. Quark Matter 2004. Contact: Anna Smith, Tel.: (510) 486-7493. E-mail: qm2004@lbl.gov
Web: http://qm2004.lbl.gov/

January 25–February 1
Bormio, Italy. XLII International Winter Meeting on Nuclear Physics. Contact: I. Iori or A. Moroni, Bormio@mi.infn.it or Iori@mi.infn.it
Web: http://www.mi.infn.it/bormio

March 2–12
ECT*, Trento, Italy. Spectroscopic Factors. Contact: Angela Bonaccorso, bonaccorso@pi.infn.it
Web: http://www.df.unipi.it/~angela/Trento04.html

March 24–27
Grenoble, France. INSTAR2004: Workshop on the Physics of Excited Baryons. Contact: nstar04@lpsc.in2p3.fr

April 19–22
Hacienda Cocoyoc, Morelos, Mexico. Nuclear Physics, Large and Small: Microscopic Studies of Collective Phenomena. Contact: Dr. Roelof Bijker, bijker@nuclecu.unam.mx
Web: http://www.nuclecu.unam.mx/~bijker/StuFiesta.html

May 23–27
Paestum, Italy. 8th International Spring Seminar on Nuclear Physics: Key Topics in Nuclear Structure.
Web: http://www.na.infn.it/paestum2004

May 23–28
Indiana University, Bloomington, IN, USA. QNP2004 Conference.
Web: http://www.qnp2004.org

May 24–28
ECT*, Trento, Italy. Workshop on “Advances and Challenges in Nuclear Astrophysics.” Contact: Carmen Angulo, Coordinator (CRC Louvain-la-Neuve): angulo@cyce.ucl.be

June 8–11
Grenoble, France. From Parity Violation to Hadronic Structure and More . . . Part II. Contact: Serge Kox, kox@in2p3.fr

June 20–25
University of Surrey, Guildford, UK. Modern Trends in Activation Analysis. Contact: Prof. N. Spyrou, MTA11@surrey.ac.uk
Web: http://www.mtaa11.com

June 27–July 2
Web: http://www.fy.chalmers.se/INPC2004

July 5–12
Peterhof, Russia. International Symposium on Exotic Nuclei (EXON-2004). Contact: exon2004@jinr.ru
Web: http://www.jinr.ru/exon2004/

July 19–23
Vancouver, BC, Canada. The 8th International Symposium on Nuclei in the Cosmos, NIC VIII. Contact: nic8@triumf.ca
Web: http://www.triumf.ca/nic8

July 26–30
Argonne National Laboratory, Argonne, IL, USA. Conference on “Nuclei at the Limits.” Contact: Jeannie Glover, limits04@anl.gov
Web: http://www.phy.anl.gov/limits04

September 12–16
Callaway Gardens Resort, Pine Mountain, GA, USA. The Fourth International Conference on Exotic Nuclei and Atomic Masses (ENAM’04). Contact: enam04@phy.ornl.gov
Web: http://www.phy.ornl.gov/enam04/

December 15–16
Université Libre de Bruxelles, Brussels, Belgium. 20th Brussels meeting between astrophysicists and nuclear physicists. Contact: pdesc@ulb.ac.be or sgoriely@astro.ulb.ac.be

2005

January 5–8
University of Surrey, Guildford, UK. The International Conference on Nuclear Structure, Astrophysics and Reactions (NUSTAR’05). Contact: Paddy Regan, Chair, p.regan@surrey.ac.uk