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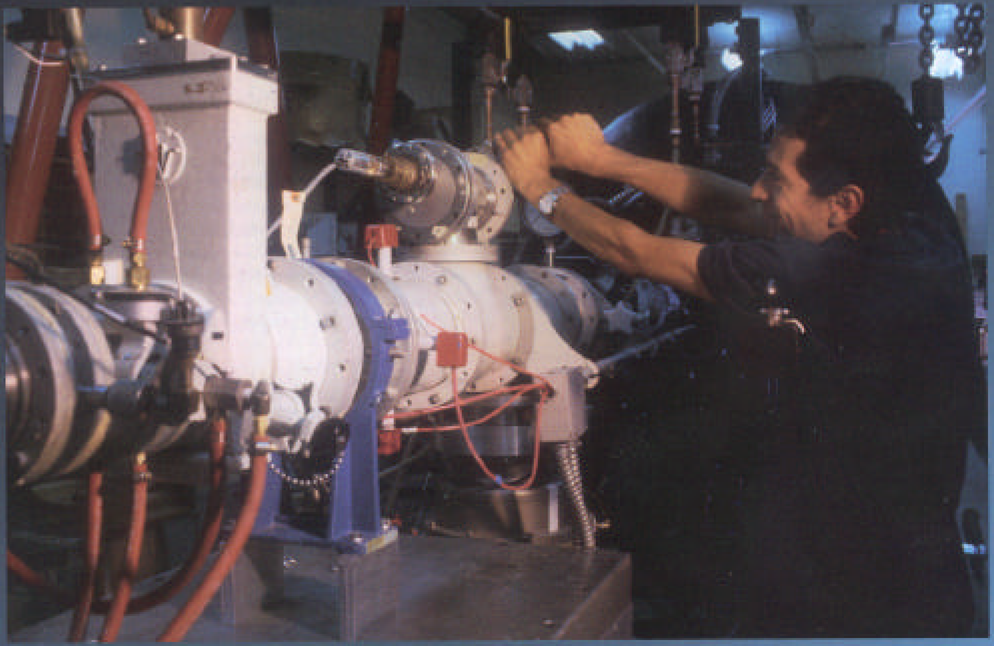
FEATURING:
Lab Portrait Notre Dame • Exotic Clustering in Nuclei • Density Functional Theory



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Nuclear Physics at Notre Dame

Introduction

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

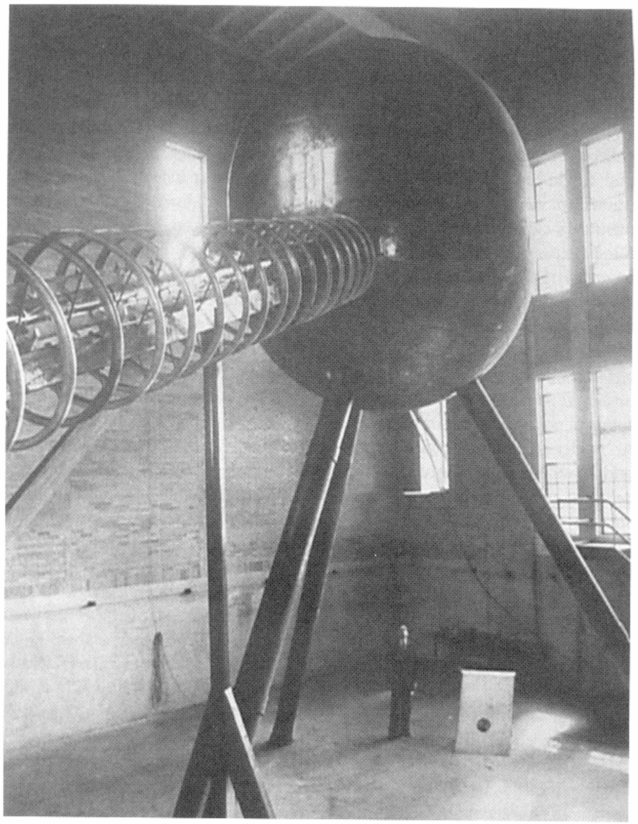
The compressional mode resonances, particularly the isoscalar giant dipole resonance, allow a direct measurement of the nuclear incompressibility coefficient. Low-lying vibrational modes give a precise analysis of the contributions of collective excitations, quasi-particles, and single-particle excited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

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

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

The Laboratory Then . . .

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



The first accelerator at Notre Dame.

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

The Laboratory Now . . .

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

Weak Interactions and Fundamental Symmetries

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

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

Nuclear Structure

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

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

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

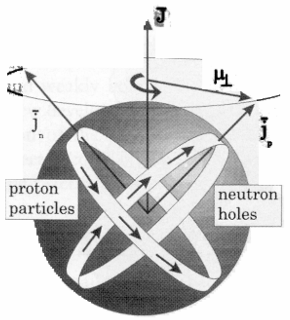


Figure 1. *Magnetic rotation of a near-spherical nucleus. Proton particles and neutron holes on the circular orbits generate a long magnetic dipole, which rotates about the angular momentum vector $\vec{J}$.*

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

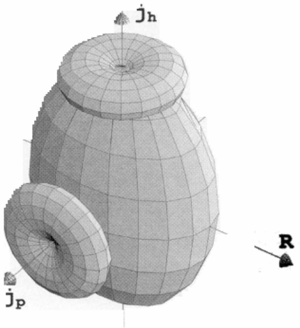


Figure 2. *Chiral composition of angular momentum in a triaxial nucleus. The orientation of the proton particles (jp) and neutron holes (jh) corresponds, respectively, to maximal attraction and repulsion of the triaxial core, which carries angular momentum (R) along the intermediate axis. The three components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

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

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

From Nuclear Matter . . .

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

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

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

. . . to Nuclear Vibrations

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

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

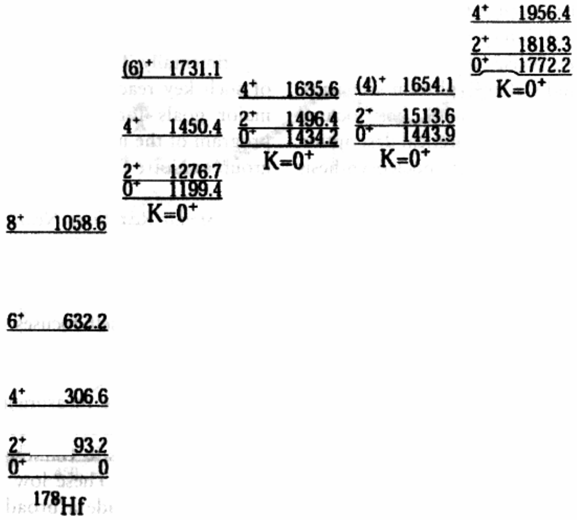


Figure 3. *A partial-level scheme of ^{8}Hf showing all the known $K^{\pi} = 0^{+}$ bands.*

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

Reactions with RIBs

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

From Sub-Coulomb Breakup . . .

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

. . . to Sub-Barrier Fusion

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

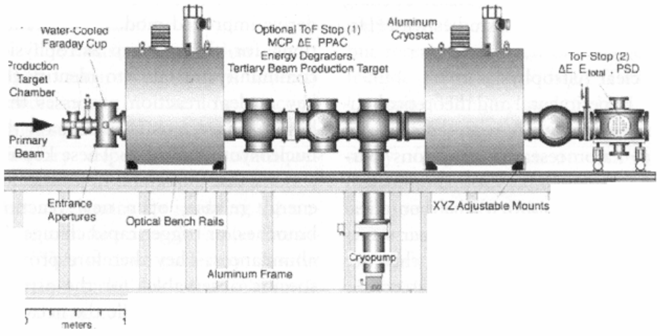


Figure 4. *A schematic of TwinSol at the Nuclear Structure Laboratory.*

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

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

... to γ-Ray Spectroscopy with RIBs

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

Nuclear Astrophysics

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

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

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

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

Studies of processes in stellar hydrogen burning presently focus on reactions in the CNO cycle and the NeNa cycle which are important for the understanding of hydrogen shell burning during late stellar evolution and explosive hydrogen burning in novae. These measurements take advantage of newly developed detection techniques coupling an array of eight BaF$_2$ detectors with a high-efficiency Ge detector to uniquely identify reaction events and reject beam induced background with high efficiency. Figure 5 shows the detailed study of the excitation range between 450 and 850 keV in search of a broad resonance in ^{19}F(p,γ) around 500 keV despite the high background rate from the competing ^{19}F(p,$\alpha - \gamma$) reaction.

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

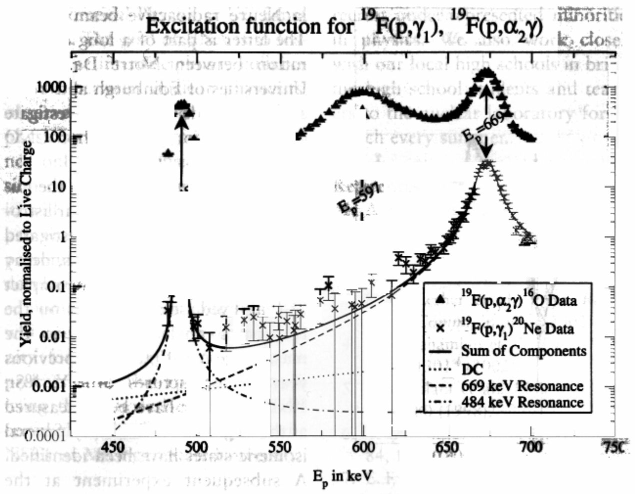


Figure 5. *Excitation curves for $^{19}F(p,\gamma)$ and $^{19}F(p,\alpha - \gamma)$ measured for the beam energy range between 0.45 and 0.7 MeV. The resonant and direct capture contribution to the $^{19}F(p,\gamma)^{20}Ne$ reaction channel have been calculated and are shown in comparison with the experimental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

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

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

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

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

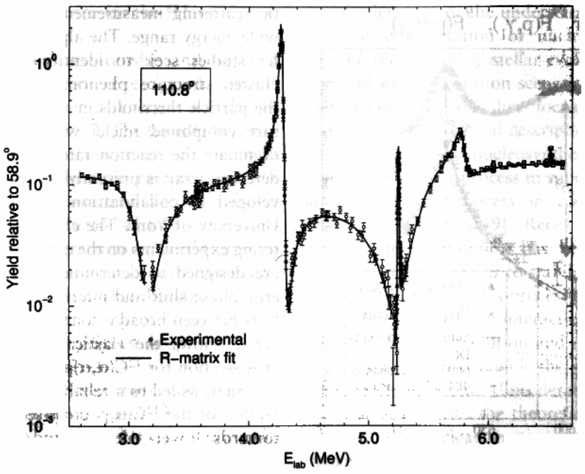


Figure 6. *Excitation curve for $^{12}C(\alpha,\alpha)$ for the energy range between 2.8 and 6.5 MeV at an angle of 110°. The data were fit with a single channel R-matrix code to determine resonant and direct capture parameters for the $^{12}C(\alpha,\gamma)$ reaction channel.*

. . . towards the Particle Drip-Lines

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

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

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

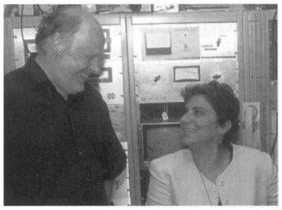
The nuclear astrophysics group at Notre Dame has recently been approved as lead institution for the NSF Physics Frontier Center JINA, the Joint Institute for Nuclear Astrophysics. JINA includes nuclear and astrophysics groups at the University of Chicago, Michigan State University, and associated institutions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

Conclusion

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

References

1. A. Garcia et al., *Hyp. Int.* 129, 237 (2000).
2. C. E. Ortiz et al., *Phys. Rev. Lett.* 85, 2909 (2000).
3. S. R. Lesher et al., *Phys. Rev. C Rapid Comm.*, in press (2002).
4. A. Aprahamian et al., *Phys. Rev C* 65, 031301® (2002).
5. J. J. Kolata et al., *Phys. Rev. Lett.* 81, 4580 (1998).
6. V. Guimaraes et al., *Phys. Rev. Lett.* 84, 1862 (2000).
7. E. F. Aguilera et al., *Phys. Rev. C* 63, 061603® (2001).
8. S. Vincent et al., *NIM A* 41726 (2002).
9. H. Schatz et al., *Phys. Rep.* 294, 167, (1998).
10. J. Fisker et al., *ADNDT,* 79, 241 (2001).
11. J. Goerres et al., *Phys. Rev. C* 62, 055801 (2000).
12. P. Tischhauser et al., *Phys. Rev. Lett.* 88, 072501 (2002).
13. C. Brune et al., *Nucl. Phys. A* 688, 263 (2001).
14. M. Wiescher, J. Goerres, H. Schatz, *J. Phys. G* 25, R133 (1999).
15. Ressler et al., *Phys. Rev. Lett.* 84, 2104 (2000).



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