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Basic research with low-energy accelerator systems

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ABSTRACT. The major important tasks of basic research are to push back the frontiers of scientific knowledge, and to train students. It will be shown that small accelerator facilities are still capable of producing interesting and exciting results that are on the leading edge of scientific inquiry. In addition, I will argue that, although these facilities often cannot afford to train students in the use of the most modern research equipment, there is an important compensating benefit in that they instruct them in the art of posing challenging problems that cannot or have not been addressed at larger facilities. This "liberal" education, as opposed to "technical" instruction in the use of the most modern research equipment, may well be of more value to society in the long run.

RESUMEN. Las tareas más importantes de la investigación básica son extender las fronteras del conocimiento científico y entrenar estudiantes. Se demuestra que los pequeños aceleradores son aún capaces de producir resultados interesantes y excitantes que están en la punta de la búsqueda de información científica. Además se argüirá que, aunque las instalaciones respectivas no pueden en general ofrecer entrenamiento a estudiantes para el uso del equipo de investigación más moderno, hay en compensación un importante beneficio en el hecho de que los instruyen en el arte de descubrir y atacar problemas desafiantes que no pueden o no han sido estudiados en instalaciones más grandes. Esta educación "liberal", en contraposición a la instrucción "técnica" en el uso del equipo de investigación más moderno, bien puede ser de más valor a la sociedad a largo plazo.

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1. INTRODUCTION

Basic research in nuclear physics has been carried out at least since the beginning of this century, and for the past fifty years at the University of Notre Dame. During that time, a vast amount of information has been obtained on the inner structure of the atomic nucleus, and on its interactions with other nuclei induced by the use of powerful accelerator systems. For the past few years, there has been an increasing emphasis on sub-nucleonic (*i.e.*, "quark") degrees of freedom as they might be expressed in the nucleus. The oft-stated hope is that quantum chromodynamics will at last provide a proper understanding of the force that binds nucleons together within the nucleus, and thus in principle solve all of the remaining problems of basic nuclear physics. Even if such a program were to succeed, however, there is a great deal of difference between principle and practice. The nucleus is a complicated many-body system; only a small percentage of particle-stable nuclei, have ever been studied in any detail. (By "particle-stable" is meant those with meanlives greater than about 10^{-20} s or so). Even in these few cases, the exploration has largely been confined to structure near the ground state, and to reactions under relatively normal conditions. Under even modest stress, such as higher angular momentum leading to "superdeformed" states, the nucleus continues to surprise.

This report will touch on only a very few of the ways in which basic research into the nucleus as a laboratory for many-body effects can be interesting, rewarding, and important; it will highlight a few of the research programs being carried out at the University of Notre Dame that are producing fundamental new insights into the structure and properties of atomic nuclei. These programs, which actually represent only a fraction of the work being carried out at Notre Dame, are (a) a pioneering study of reactions induced by secondary beams of short-lived radioactive nuclei, (b) a continuing program to investigate sub-Coulomb-barrier interactions in nuclear systems, (c) a study of nuclear reactions important as neutron sources in stellar environments, and (d) a search for multi-phonon excitations in non-spherical nuclei.

2. Radioactive nuclear beams

Many of the problems of contemporary nuclear astrophysics involve the determination of reaction rates for light radioactive nuclei such as ^{6}He, ^{7}Be, ^{8}Li, ^{13}N, etc. Such nuclei, which have meanlives ranging from seconds to days, are stable on the time scale of stellar explosions and may also play a role in primordial nucleosynthesis. In particular, considerable attention has recently been paid to the possibility that the early universe might have been rather inhomogeneous, consisting of high-density, proton-rich regions coupled with low-density, neutron-rich regions [1]. Malaney and Fowler [2] have identified a set of key reactions involving ^{8}Li which could be important for the process of nucleosynthesis in nonstandard big bangs including strong baryonic fluctuations. The ^{8}Li nucleus is also quite neutron rich and therefore of interest in more conventional nuclear spectroscopy. One might expect reactions with a light $T_z = 1$ projectile to provide some unique tests of nuclear models. For these reasons, the main research effort with the UND/UM radioactive nuclear beam (RNB) facility has been directed toward the utilization of the ^{8}Li beam, though some exploratory studies have been done with ^{6}He, ^{7}Be, and isomeric ^{18}F^m beams [3,4].

2.1. Experimental apparatus

The optimal study of nuclear reactions induced by a radioactive nucleus requires a device which can produce a high-intensity energy-and angle-resolved beam, focussed to a well-defined beam spot and free of contamination by other species. Devices which utilize conventional magnetic dipoles and quadrupoles as secondary beam collectors usually suffer from low efficiency, due to restricted solid angle and/or background from unwanted beams. Quadrupoles in particular are not double-focussing by themselves and therefore need to be used in doublet and triplet combinations, resulting in a poor aspect ratio (bore/focal length). Also, the ions orbits inside quadrupoles are not particularly simple, which can lead to complications in the design of beam-blocking apertures. As a result, devices of this type tend to be large and expensive, with many optical elements.

A device which circumvents many of these problems, and which is well-suited to the collection and focussing of low-energy RNB, is a superconducting air-core solenoid. In its

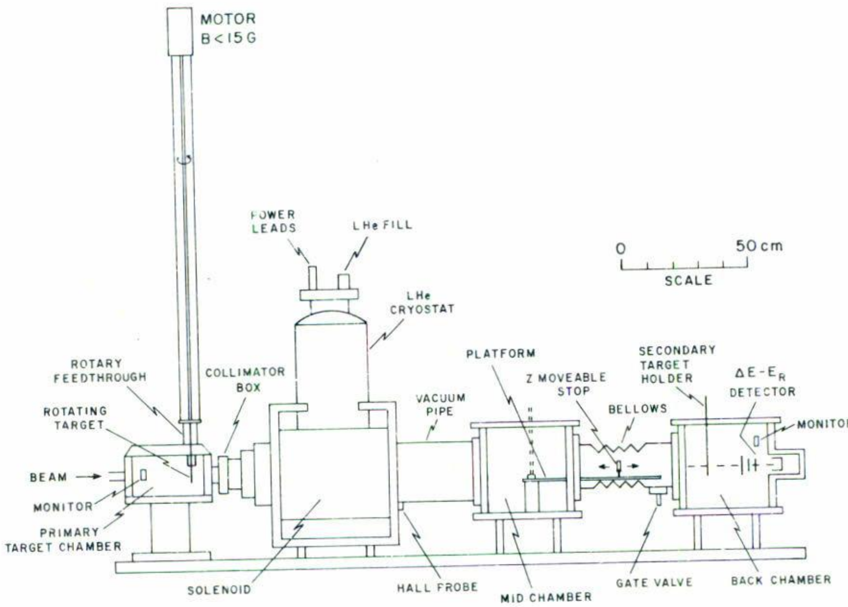

FIGURE 1. Schematic diagram of the RNB beamline. Note in particular the rotating target mechanism, with its motor placed well outside the fringe field of the solenoid, and the z-moveable stop used to remove inelastically scattered primary beam particles from the secondary beam.

present configuration, the UND/UM RNB facility utilizes a 3.5 T, 20 cm bore, 40 cm long solenoid to collect and focus nuclear reaction products (Fig. 1). It exists on a dedicated beam line on the FN tandem Van de Graaff accelerator at the University of Notre Dame, and has been operational for three years. The solenoid acts as a thick lens and is operated in an asymmetric mode ($d_{\text{obj}} = 0.5$ m, $d_{\text{image}} = 1.5$ m) to maximize the available solid angle at the expense of energy range ($E_{\text{max}}/A = 3$ MeV per nucleon). The resultant transverse magnification is $M_T = 3$, and the angular magnification is therefore $M_\theta = 1/3$. With an incident primary beam spot size that is typically less than 2 mm dia., and a solenoid aperture that spans the range from 3°–11° ($\Delta\Omega = 120$ msr), the image at the secondary target has been measured to be 5 mm dia. with a maximum angular divergence of 4°. These parameters are quite suitable for nuclear physics experiments.

The majority of the work carried out with this RNB facility has been with beams of ^{8}Li produced via the ^{9}Be(^{7}Li, ^{8}Li)^{8}Be reaction at an incident energy of 10–20 MeV. In this case, the ^{8}Li ions are more rigid than the inelastically-scattered ^{7}Li beam, so it is a simple matter to introduce a blocking aperture at the focal point of the latter, located in a mid-stream chamber (Fig. 1). To maximize the purity of the secondary beam, it is essential that this beam block can be moved along the axis of the device (z-axis). The beam consists of about 70% ^{8}Li ions, together with ^{4,6}He ions that have the same magnetic rigidity, and a very small amount (typically less than 1%) of $Z > 3$ contaminants. Only a trace amount of ^{7}Li ions that multiple-scatter within the solenoid (and so avoid the beam block) is present. Fortunately, the reaction Q-values for most ^{8}Li-induced reactions are very positive, so that identification of secondary reactions involving this nucleus is generally unambiguous. The most difficult experiment to date has proven to be the study of inelastic scattering of ^{8}Li, in which case it is essential to completely remove from the beam all of the ^{8}Li ions that were initially produced in an excited state at the primary target.

The ^{7}Li beam current delivered to the production target is limited to 2 $e\mu$A (3^+ charge state) by beam-heating and radiation-damage effects. (The ion source for the accelerator has produced up to 10 $e\mu$A of negative ^{7}Li beam, and the transmission through the system is approximately 50% at the low energies used for these experiments). The primary target, a 2.3 mg/cm^2 ^{9}Be foil, is rotated at up to 100 rpm in order to alleviate beam-heating problems, but deterioration is rapid at currents above 2 $e\mu$A. Nonetheless, the observed maximum secondary beam yield is 2×10^6 particle per second (pps), with an energy resolution that is typically better than 500 keV FWHM.

2.2. The experiments

Several interesting and important experiments have been carried out with RNB from this facility over the last three years. For example, in one of the initial studies of ^{8}Li reaction rates [5], it was found that the ^{2}H(^{8}Li, ^{7}Li) ^{3}H cross section is quite large. This reaction is of astrophysical interest since it is one of the main routes for destruction of ^{8}Li formed in nonstandard big bangs. It had been left out of early model calculations since it was incorrectly assumed that its cross section was small compared with other reactions. At present, the total cross section for this reaction is being carefully measured over the c.m. energy range from 1.5–4 MeV, together with that of the ^{2}H(^{8}Li, ^{9}Be$_{gs}$)n reaction, which is one of the ways to synthesize $Z > 3$ nuclei. Note, however, that population of excited states of ^{9}Be in this reaction will lead to destruction of ^{8}Li without the formation of heavy elements, since the excited states of ^{9}Be are unbound to neutron decay. Evidence for the importance of this process has recently been obtained from a study of the ^{2}H(^{8}Li, ^{8}Be$_{gs}$) reaction, which shows a large yield of ^{8}Be presumably coming from neutron decay of excited states of ^{9}Be. Studies of this process are continuing, together with attempts to observe ^{8}Be in its broad first excited state, which can also be formed in the neutron decay of some excited states of ^{9}Be. The challenge in the latter case is to efficiently detect the α-particles resulting from the breakup of ^{8}Be, which are spread over a wide angular range due to the large reaction Q-value.

The ^{1}H(^{8}Li, ^{8}Be$_{gs}$)n charge-exchange reaction has also been observed to have a large cross section. Here again the reaction is of astrophysical interest due to its effect on the destruction of ^{8}Li produced in nonstandard big bangs. However, the intrinsic (p, n) process is also important, both from a reaction-mechanism point of view and as a calibration for the (^{8}Li, ^{8}Be) charge-exchange reaction. This latter process is of special interest because it has a large positive Q-value in most cases. The corresponding reactions with other projectiles typically have large negative Q-values and thus tend to populate much different final states.

Finally, the most interesting nuclear-structure result to date came from studies of ^{8}Li inelastic scattering. The first of these experiments [6], with a ^{12}C target (Fig. 2), led to the conclusion that the transition quadrupole moment to the first excited state of ^{8}Li is extraordinarily large (35 ± 15 e^2fm^4). This is about four times larger than the transition strength of the corresponding transition in ^{7}Li, but comparable to that observed for other

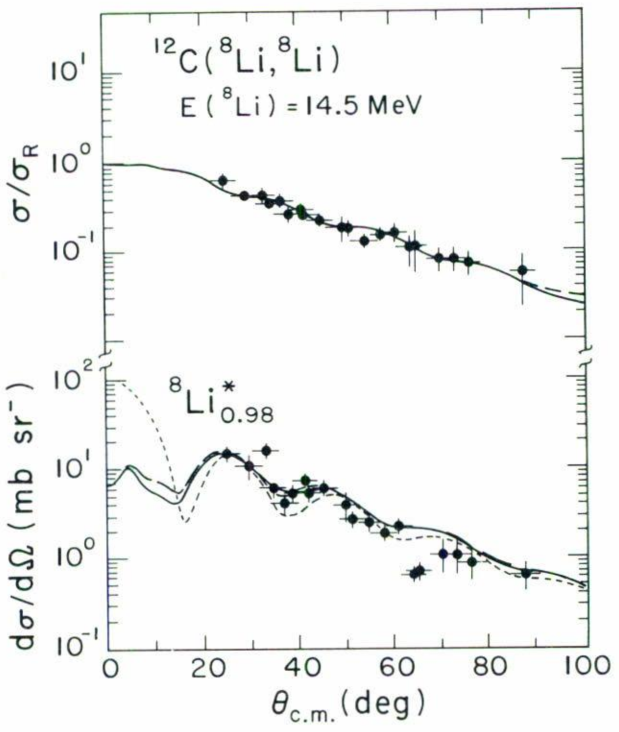

FIGURE 2. Elastic and inelastic scattering angular distribution for ^8Li+C, compared with coupled-channels calculations.

$T = 1$ p-shell nuclei. However, this result was based on the assumption of a collective model, since the transition is dominated by the nuclear force if one uses a ^{12}C target. Also, contributions from $L = 0$ spin-flip excitations could not be ruled out. More recently, the experiment has been repeated [7] with a Ni target at energies both below and slightly above the Coulomb barrier (Fig. 3). The Coulex experiments are not subject to the uncertainties discussed above, and the measured $B(E2 \Uparrow) = 45 \pm 10$ $e^2\text{fm}^4$ is consistent with that determined from the ^{12}C experiment. Apparently, then, the transition quadrupole moment for the ground-state to first-excited-state transition in ^8Li is extraordinarily large, and much bigger than that predicted by "standard" shell-model calculations. No explanation for this result, which was only recently obtained, yet exists. However, one may speculate that it is related in some way to the "neutron halo", and the corresponding soft dipole resonance, that have been observed [8] in ^{11}Li.

The UND/UM RNB facility was developed as a collaboration between groups at the University of Notre Dame and the University of Michigan. More recently, researchers from Ohio State University, Florida State University, Oberlin College, and Western Kentucky University have joined the collaboration. Plans for the immediate future emphasize the continuing use of the ^8Li beam, with a gradual increase in the utilization of other light radioactive beams such as ^6He.

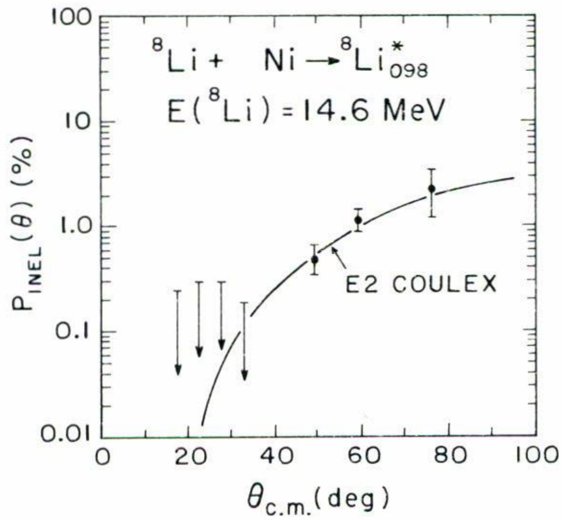

FIGURE 3. Probability for Coulomb excitation of the first excited state of ^{8}Li.

3. SUB-BARRIER INTERACTIONS

In recent years, there has been considerable interest in heavy-ion reactions at energies near to and well below the Coulomb barrier. Observations of enhanced low energy heavy ion fusion rates, as a compared with the predictions of conventional barrier penetration models, have accelerated the exploration of how nuclear structure influences the fusion process. At the opposite end of the reaction spectrum, optical model analyses of heavy ion elastic scattering data are found to require strongly energy-dependent complex potentials in the region of the barrier. In particular, the magnitude of the imaginary part of the optical-model potential has been found to decrease, and the magnitude of the attractive real potential to increase, as the bombarding energy is lowered. It is natural to expect that increased low energy fusion rates should be correlated with increased attraction in the optical model potential since both phenomena reflect the dynamic polarizability of the colliding nuclei.

The interpretation of these recent developments relies upon having a consistent body of data for both fusion and elastic scattering cross sections. The measurements of the S + Ni systems by the Legnaro group [8-10] have played a prominent role in discussions of the physical basis behind the observed phenomena. There are, however, some unusual features of these data which must be clarified before one attempts to draw conclusions from them. In particular, the elastic scattering angular distributions for ^{32}S$+^{58,64}$Ni, near to and below the Coulomb barrier, are characterized by strong deviations from Rutherford scattering at angles that are well forward of the expected "grazing" angle. As emphasized by Udagawa, *et al.* [11], this seems to imply that an anomalously large, unknown direct reaction process is occurring in these systems. With regard to the fusion channel, we note that the barrier parameters extracted in Ref. 1 demonstrate a strong isotope effect that has been interpreted as possible evidence for neck formation in the more neutron-rich systems according to the model of Stelson [12].

In order to gain a better insight into the behavior of the S + Ni systems, we have made new measurements of the elastic scattering and fusion channels near the barrier which unfortunately show none of these unusual features. These new data have been analyzed in the context of a coupled-channels barrier penetration model, and excellent agreement with the data is achieved without the need to introduce an explicitly energy-dependent optical-model potential.

3.1. Elastic scattering

As mentioned above, the low-energy elastic scattering results for the S + Ni systems could possibly be interpreted [12] by invoking a significant flux-loss to unmeasured reaction channels. We therefore decided to use a kinematic coincidence technique to study the elastic scattering. This should also be a sensitive way to search for strong inelastic and/or transfer channels which might be responsible for the observed anomalies. Two sets of two silicon surface-barrier position sensitive detectors (PSDs) each were placed on either side of the beam. The entire relevant center-of-mass (c.m.) angular range (40° to 160°) can be covered with only four settings of the detector arrays. The results are shown in Fig. 4. As mentioned, they show none of the pathological effects noted in Refs. [8-10]. Consistent with this, no evidence was found for the existence of an anomalously strong direct reaction process in the S + Ni systems.

3.2. Fusion

The evaporation residues (ER) from fusion, emitted in a narrow cone within a few degrees around the beam axis, were deflected out of the direct beam by means of an electrostatic deflector. The separated residues were then identified in a time-of-flight (TOF) and energy spectrometer, which consisted of a microchannel plate and a silicon surface barrier detector (SSB) which together defined a 1 m flight path. Great care was taken in determining the relative and absolute normalization of the fusion cross section. The results, shown in Fig. 5, again do not display the anomalies noted in Ref. [8].

3.3. Coupled-channels calculations

The scope and methodology of the coupled-channels calculations have been described by Esbensen, *et al.* [13]. The model consists of a real, energy-independent ion-ion potential and explicit couplings to inelastic excitation and single-nucleon transfer reaction channels. The fusion process is simulated by imposing ingoing-wave boundary conditions in all channels at a separation distance inside the Coulomb barrier. In this way, the main reaction processes are accounted for without introducing phenomenological imaginary potentials. The results of these calculations are shown by the various curves in Figs. 4 and 5. Of particular interest for the elastic scattering (Fig. 4) is the fact that coupling to inelastic channels alone (dotted curves) is inadequate to explain the experimental data. On the other hand, inclusion of particle-transfer channels (solid curves) produces

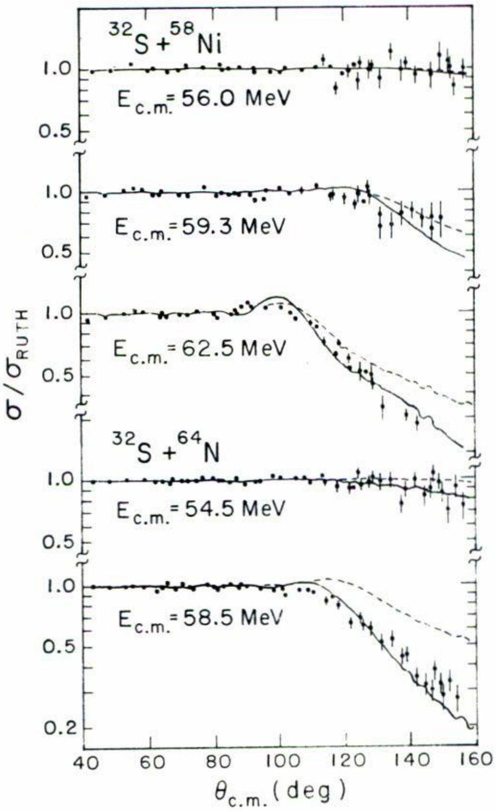

FIGURE 4. Comparison of the coupled-channels calculations with the elastic-scattering angular distributions of the present experiment. The dashed curves correspond to the calculations in which only coupling to inelastic channels is allowed, while the solid curves include transfer couplings.

excellent agreement. A similar effect shows up in the fusion data (Fig. 5), where again very good agreement is obtained when particle-transfer channels are included. The overall agreement with all the fusion excitation functions is very satisfying, particularly as it is obtained simultaneously with good fits to the elastic scattering data as shown in Fig. 4. This good agreement gives us confidence that the theoretical model is fundamentally sound. Dynamical couplings are clearly required to explain the low-energy fusion rates, and the predicted increase in the single-nucleon transfer strength in going from $^{32}S + ^{58}Ni$ to $^{32}S + ^{64}Ni$ accounts for a significant part of the difference in the corresponding elastic-scattering angular distributions.

4. Reactions important as stellar neutron sources

Neutron burning processes, such as the slow neutron capture (s) and rapid neutron capture (r) processes, are essential in explaining the production and abundances of the elements beyond Fe in our universe. The reaction sequences leading to nucleosynthesis of such heavy

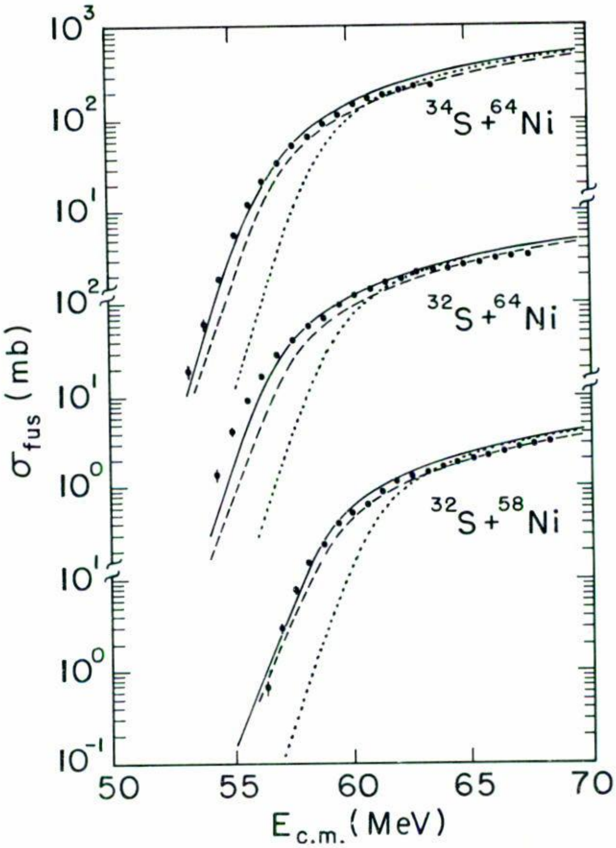

FIGURE 5. Comparison of the calculated $^{32}S + ^{58,64}Ni$ and $^{34}S + ^{64}Ni$ fusion cross sections with the results of the present experiment. The dotted curve is the no-coupling result, the dashed curve includes coupling to the inelastic channels, and the solid curve is the full calculation including transfer couplings.

elements require a certain neutron flux in the stellar burning zones. These neutrons can only be produced by charged particle reaction, barring the very extreme environmental conditions that occur near a collapsing iron core that triggers a supernova explosion. Therefore, the neutron production rate most usually depends exponentially on the temperature and linearly on the density in the burning zones. Since (α, n) reactions on light nuclei are the most likely sources of neutron production, the expected neutron flux will also depend on the abundances of light elements, which implies that the entire history of the nuclear burning stages, as well as the hydrodynamical conditions in the burning zones, must be known.

Observation of enhanced abundances of s-process nuclei in the stellar atmospheres of red-giant stars provides strong evidence for s-process nucleosynthesis in the He-burning cores of such stars, requiring a neutron flux on the order of 10^8–10^9 s^{-1}. In the currently-favored scenario, the core material of a massive star is enriched in ^{14}N during the previous

CNO-burning cycle. A sequence of α-capture reactions,

$$^{14}\mathrm{N}(\alpha,\gamma)\,^{18}\mathrm{F}(\beta+\nu)\,^{18}\mathrm{O}(\alpha,\gamma)\,^{22}\mathrm{Ne},$$

may then lead to neutron production via the final ^{22}Ne(α, n) reaction. The neutron production rate depends not only on the cross section for the (α, n) reaction, but also on the rate of the feeding reaction ^{18}O(α,γ) ^{22}Ne. To remove all uncertainties, at least in the nuclear physics arena, it is necessary to know every cross section in the neutron-producing reaction sequence. Several approaches were undertaken to determine these cross sections.

The ^{18}O(α,γ) reaction has previously been measured [14] in the energy range from 0.6 to 2.3 MeV, corresponding to a stellar temperature range from $T = (0.3 - 4.3) \times 10^9$ K. However, studies of the ^{19}F(α, pγ) ^{22}Ne and ^{20}Ne(t, p) ^{20}Ne reaction [15,16] indicated the existence of threshold states in ^{22}Ne which have not been observed in the ^{18}O(α,γ) channel and yet may significantly influence the reaction rate at the temperature of stellar He burning. No information about the spins and parities of these states was available from previous work. Note that only natural-parity states can be populated in the (α,γ) reaction. These states were therefore studied via the ^{18}O(^{6}Li, d) ^{22}Ne and ^{18}O(^{6}Li, t) ^{22}Ne reactions which are subject to the same selection rules.

The experiments were performed with the Notre Dame tandem Van de Graaff accelerator, using Li beam currents of intensity 0.3–0.6 μA, at beam energies of 16 MeV (^{7}Li) and 32 MeV (^{6}Li), incident on targets of 150 μg/cm^2 of $W_2\,^{18}O_5$ evaporated onto a 280 μg/cm^2 Au backing. The reaction products were momentum analyzed in a broad-range spectrograph, and the data confirmed the expected states and revealed two previously unreported levels at energies closer to the α-emission threshold. Fig. 6 shows spectra for the two reactions; the state at 10.04 and 10.13 MeV are new. The angular distributions are still being analyzed. In a followup experiment, performed at the University of Toronto, a 200 μA beam of α-particles in the energy range from 0.6–0.8 MeV was used to bombard a thick $Ta_2\,^{18}O_5$ target in an attempt to search for these new levels in the direct α-capture reaction and determine their resonance widths. A Ge detector was used to measure they γ-decay of states in ^{22}Ne populated in this reaction. So far, only upper limits have been obtained.

A recent investigation [17] of the ^{22}Ne(α,γ) and (α, n) reactions, the latter of which is perhaps the neutron source for the s-process in He-burning stars, indicates that the stellar reaction rate will be dominated by a strong resonance at 0.83 MeV. The (α,γ) resonance strength is known, but only an upper limit for the (α, n) channel has been obtained and there was some evidence from the ^{25}Mg(n, γ) that the resonance strength in this channel might be small enough to rule out the ^{22}Ne(α, n) reaction as a possible s-process neutron source. Thus, the ^{22}Ne(α, n) reaction has been studied, again at the University of Toronto. A ^{22}Ne implanted target was bombarded with the 200 μA α-particle beam, and neutrons were detected in an array of ^{3}He gas counters. the data are shown in Fig. 7; the inset in this figure shows the neutron decay of the 0.83-MeV resonance, after the subtraction of various background components. The resonance strength is presently being evaluated. Finally, the ^{22}Ne(^{6}Li, d) reaction has recently been studied at Notre Dame to search for threshold states that might affect the stellar reaction rates. Two new α-unbound

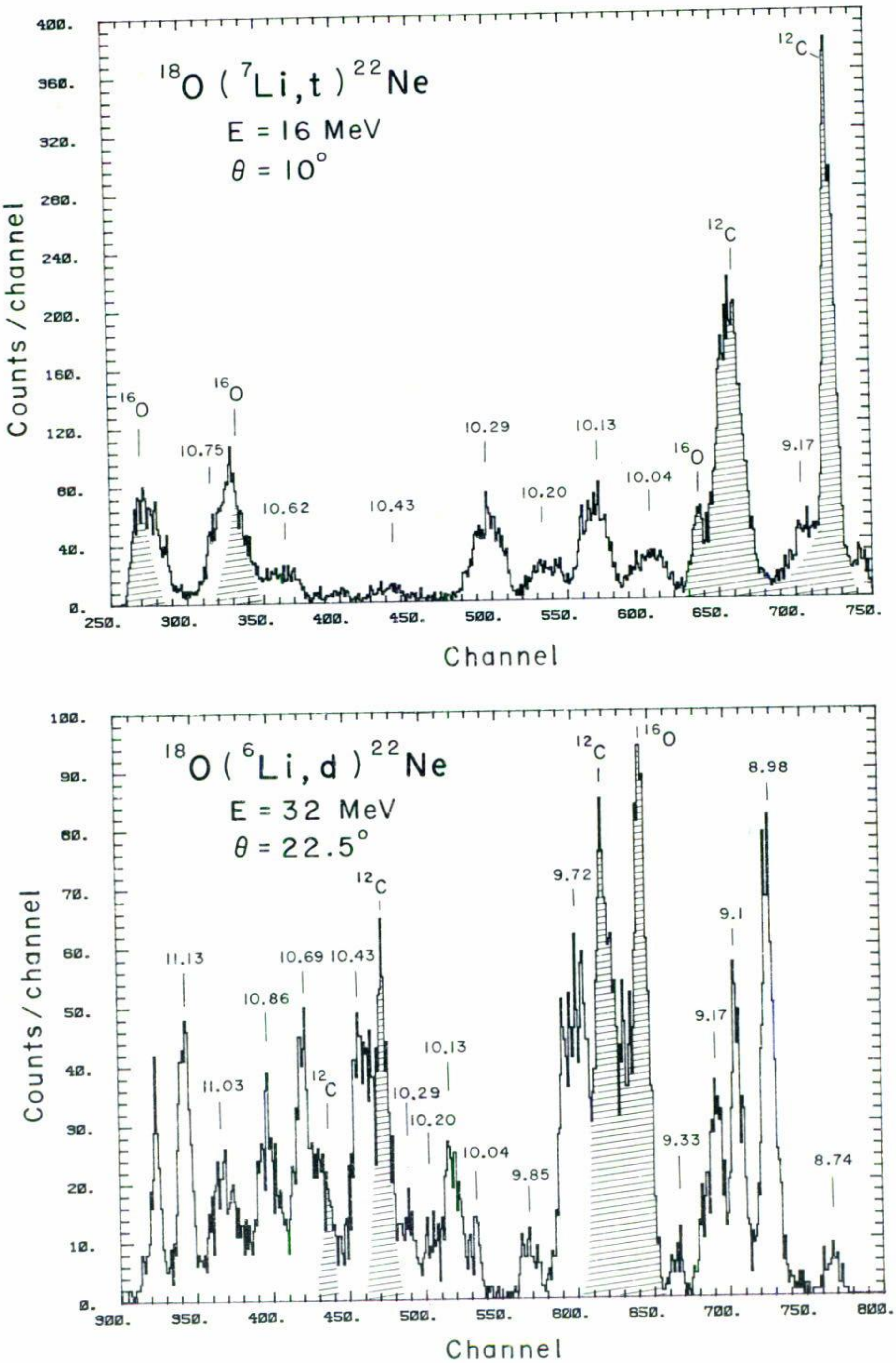

FIGURE 6. Spectrum of states in ^{22}Ne populated in the (^{7}Li, t) and (^{6}Li, d) reaction, near the neutron emission threshold.

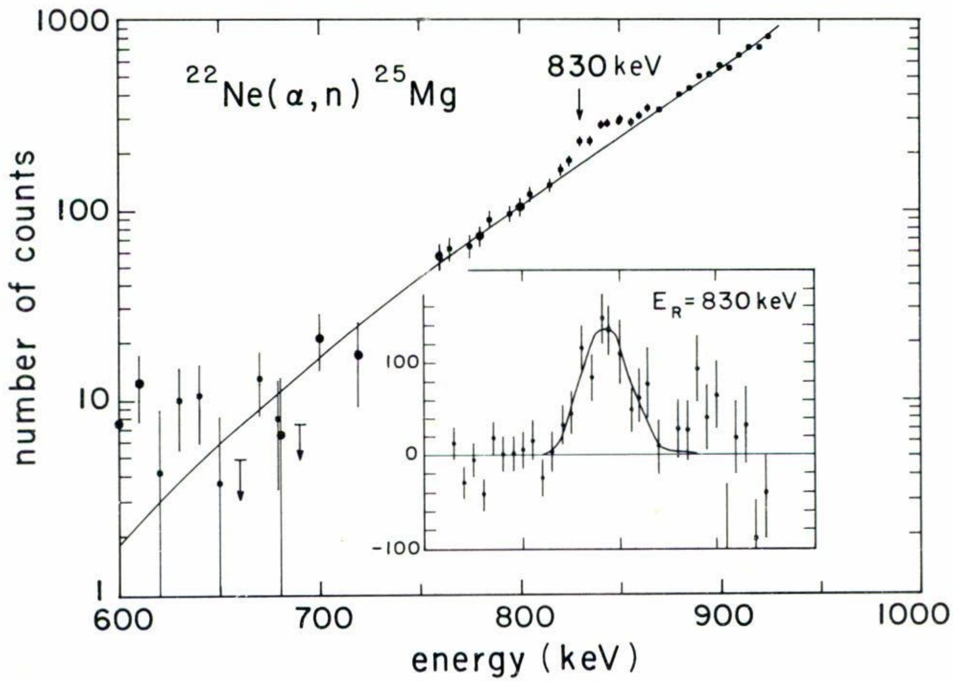

FIGURE 7. Neutron decay of the 830-keV resonance in the interaction of α-particle with ^{22}Ne.

levels were found at energies below the neutron threshold, which could contribute to the competing (α, γ) channel.

5. Search for multiphonon states in deformed nuclei

The excitation-energy spectrum of spherical nuclei often shows the distinctive pattern expected from collective harmonic vibration. the first excited state, at excitation energy E_1, has spin/parity $J^\pi = 2^+$ and its transition strength to the ground state tends to be large, *i.e.*, several tens of "single particle units". The second excited "state", at $E \approx 2E_1$, is actually a $(0^+, 2^+, 4^+)$ multiple which displays strong transitions to the first excited state. This "two-phonon" multiplet is the lowest of the multi-phonon states formed by successively more energetic vibrational excitation of the nucleus.

The predominant collective excitation of deformed nuclei, on the other hand, is the usual rotational pattern. Collective vibrational excitations often do occur, however. Two forms of motion can be characterized (Fig. 8), depending upon whether the vibration occurs along the symmetry axis (β-vibration) or transverse to it (γ-vibration). Remarkably enough, although β- and γ-vibrations are common in deformed nuclei, multiphonon excitations have never been found. The nuclear-structure group at Notre Dame is presently engaged in a search for the double-γ mode, and have identified at least one good candidate for this two-phonon excitation. Interestingly enough, the excitation-energy spectrum in this case appears to indicate that the vibration is significantly anharmonic.

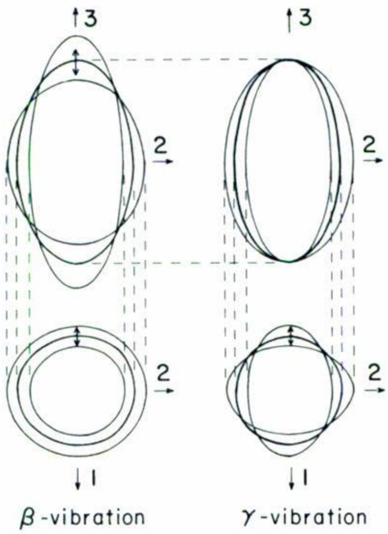

FIGURE 8. Vibrational excitations of deformed nuclei.

They key to the identification of this structure in the complicated spectrum of collective rotational excitations is the use of a multi-detector array. Generally, these arrays have been used to sort out high-angular-momentum states in the search for "superdeformed" states. One such array, constructed as a collaboration between Notre Dame and Argonne National Laboratory, led to the exciting discovery of superdeformation in Hg isotopes, among other important results. A less common but potentially equally interesting use of these instruments is in the search for unusual low-spin structures such as multiphonon excitations. This type of experiment, which does not require very heavy ions or very high energies, is especially suited for a small accelerator facility such as the one at Notre Dame.

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