I. HEAVY-ION NUCLEAR PHYSICS RESEARCH

OVERVIEW

This research involves investigating the structure, stability, reactions and decays of nuclei. This information is crucial for understanding the evolution of the universe, the workings of stars and the abundances of the elements that form the world around us. The forefront area of research is investigating the properties of nuclei which lie very far from stability, and which are critical in understanding nucleosynthesis. Most of our research is based at the Argonne Tandem-Linac Accelerator (ATLAS), a national heavy-ion user facility. During this year programs were also mounted at the Relativistic Heavy Ion Collider (RHIC), at Michigan State University, at Yale University, and at other forefront facilities. The major thrusts of the program are: a) studying the reactions that are important in the cataclysmic events in the cosmos which lead to the synthesis of the chemical elements, b) deepening and generalizing our understanding of nuclear structure to allow a reliable description of all bound nuclear systems, and c) testing the limits of the Standard Model, the fundamental theory that currently best represents our understanding of the laws and fundamental symmetries of nature.

The specific research topics we are pursuing include the measurements of reactions that are important in astrophysics. Many approaches are used, including the production and acceleration of short-lived nuclei in order to measure key reaction rates, and the use of Gammasphere to investigate the properties of states in the "Gamow window". Our program of nuclear physics measurements on trapped atoms and ions has become very productive. An "online" atom trap now complements the existing CPT Penning ion trap and there is rapid development of a new "open-geometry" trap for weak interaction studies. Gammasphere operating on two beamlines offers world-unique opportunities for gamma-spectroscopy and a wide range of experiments are being carried out on both neutron-rich and neutron poor nuclei. The key thrust of spectroscopic studies is to investigate the modification of residual interactions in nuclei far from stability. In addition, there are complimentary efforts in the use of Accelerator Mass Spectrometry (AMS) for environmental research and in the investigation of nuclear matter at relativistic energies. The ATLAS-based research exploits the unique capabilities of the accelerator, both in the stable beam program, and in production of accelerated beams of short-lived isotopes. The experiments employ state-of-the-art research equipment, including the national gamma ray facility, Gammasphere, the Fragment Mass Analyzer (FMA), a large solid angle silicon array, "Ludwig", and the Canadian Penning Trap, (CPT) all of which are operating at ATLAS. Several new detector initiatives are being pursued including refining the "in-flight" radioactive beam facility and its detector systems, constructing the Advanced Penning Trap (APT), and refinement of the online atom trap (ATTA). Effort continues in developing the next generation gamma ray detectors in the GRETINA project, and development of a compact and efficient array for decay studies (the X-Array). Participation in the PHOBOS experiment at Brookhaven has continued. Some of the specific goals of the program can be summarized as follows:

- Develop and utilize beams of short-lived nuclei, ^{6}He ^{8}Li, ^{8}B, ^{11}C, ^{14}O, ^{16}N, ^{17,18}F, ^{20,21}Na, ^{25}Al, ^{37}K, ^{44}Ti, ^{56}Ni, and others, to improve the understanding of reactions of astrophysical importance. Emphasis focused on "in-flight" production of short-lived ion-species using kinematically inverse reactions on light gaseous targets. Considerable scope still remains for further improving the intensity and quality of these beams in the future, and the beamline is being continually upgraded.

- Make high-precision measurements of nuclear masses with the CPT, particularly the masses of N = Z nuclei which are of astrophysical interest and are important for testing CVC theory, and measuring the masses of neutron fission fragments that lie close to the anticipated r-process path. Improve the efficiency for production, separation, cooling, transportation, and trap loading of ions to increase sensitivity. Develop the open geometry "Advanced Penning Trap", the APT.

- Study the structure of neutron-rich nuclei in order to understand the modification of shell gaps and the apparent changes in spin-orbit splitting. Study transfer reactions on spherical tin isotopes, the decay and Coulomb excitation of exotic nuclei produced in fragmentation, and the most neutron rich nuclei that can be reached by multi-nucleon transfer and heavy-ion fusion.

- Investigate the collisions and deconfinement of nucleons in nuclear matter at very high temperatures and densities that are achieved in relativistic heavy-ion collisions of gold nuclei at 200 GeV/u. Our participation is using the PHOBOS detector at the RHIC accelerator at Brookhaven National Laboratory.

- Studying the properties of very heavy nuclei through "in-beam", "isomer", and "decay" spectroscopy. The measurements reveal information on the single particle sequence, shell gaps, pairing strength, and fission barriers of very heavy systems. These properties govern the mass limits of nuclear existence.

- Study the shapes, stability and decay modes of nuclei along the proton dripline in order to improve understanding of partially bound nuclei. Study proton tunneling through deformed barriers, in order to increase the spectroscopic information obtained through proton radioactive decay rates. Study the influence of vibrations and coupling to other nucleons in odd-odd systems to generalize the understanding of proton radioactivity. Study excited states in these nuclei using the RDT technique to trigger Gammasphere.

- Perform detailed R&D studies for the Rare Isotope Accelerator (RIA) and participate in all efforts to refine the designs for the accelerators, target stations, post accelerator, and experimental equipment. Intense effort is being directed to development of the "gas catcher" technology for cooling primary beams.

- Developing position-sensitive germanium detectors, for "tracking" gamma rays in order to allow the imaging of the source of radiation. The ANL focus is on developing planar germanium wafer technologies, in parallel with involvement in the GRETINA project to construct a 1π germanium tracking detector.

A. REACTIONS OF ASTROPHYSICAL IMPORTANCE

Research into nuclear reactions that are relevant to astrophysical processes is at the core of our science, and is part of our strategic plan. A wide variety of techniques are currently used, exploiting almost all of our equipment, including experiments with radioactive beams, studies with Gammasphere, measurements with the Canadian Penning Trap (CPT), and the use of Accelerator Mass Spectrometry (AMS) for trace element analysis.

a.1. Measurement of the E1 Component of the Low-Energy $^{12}C(\alpha,\gamma)^{16}O$ Cross Section

(X. D. Tang, K. E. Rehm, I. Ahmad, J. Greene, A. Hecht, D. Henderson, R. V. F. Janssens, C. L. Jiang, E. F. Moore, M. Notani, R. C. Pardo, G. Savard, J. P. Schiffer, S. Sinha, M. Paul,* L. Jisonna,† R. E. Segel,† A. Champagne,‡ and A. Wuosmaa§)

The radiative capture of α particles on ^{12}C, *i.e.* $^{12}C(\alpha,\gamma)^{16}O$, is an important reaction in stellar nucleosynthesis. It not only influences the ratio of the important elements carbon and oxygen, but it also determines the evolution of massive stars. Since there is no resonant level in ^{16}O located in the Gamow window, the astrophysical reaction rate is determined by the contributions from several neighboring states, with the most important ones coming from two sub-threshold states with $J^{\pi} = 1^-$ and 2^+. Because of the small cross sections (~10^{-18} b) at stellar temperatures, a direct measurement of the reaction rate at temperatures typical of red giant stars is not possible and one has to rely on indirect methods. Two multipolarities (E1 and E2) contribute to the transition and, thus, several different measurements are required to determine the total reaction rate. To determine these parameters, measurements of the beta-delayed alpha decay of ^{16}N, angular distributions of E1 and E2 alpha capture and of elastic alpha scattering on ^{12}C are needed. In several measurements of the beta-delayed alpha decay of ^{16}N the low-energy alpha particles from the decay of alpha-unstable levels in ^{16}O were detected in thin Si-surface barrier detectors.[1-4] The small alpha/beta branching ratio in this decay (~10^{-5}) results in a very high beta-background that can influence the low-energy part of the alpha spectrum from which the E1 reaction rate, S(E1), is obtained.

In the present experiment we have used a somewhat different approach to measure the ^{16}N decay. To produce the ^{16}N activity we used the in-flight method, which eliminates the $^{17,18}N$ contamination of one of the earlier measurements. To reduce the sensitivity to beta particles we have developed an array of high-acceptance ionization chambers of minimal thickness, to be used for the detection of ^{12}C and alpha particles in coincidence, but which are rather insensitive to β-decays.

A schematic of the experimental setup is shown in Fig. I-1. A ~ 60 MeV ^{16}N ($T_{1/2}$ = 7.1 sec) beam is slowed down in a gas-filled attenuator cell and stopped in a 10 μg/cm^2 thick carbon foil (foil I) mounted on a rotating wheel which is located in the main part of the detection chamber. The attenuator cell and the main chamber are filled with P10 counting gas at a typical pressure of 150 Torr. After an irradiation period of 15 sec, the foil is rotated (in 60 ms) to be between a pair of twin ionization chambers (pair I) for the coincident detection of ^{12}C – α pairs. The carbon foil is counted in this pair of ionization chambers for 15 sec. During this time a second foil (II), mounted 120^o from the first, is irradiated. At the end of the irradiation period foil II is rotated to be between a second pair of ionization chambers (pair II) and counted, while foil I is again irradiated with ^{16}N. Detector pair I is meanwhile counting a non-irradiated foil giving the background in the entire setup. The same foil is also used for measuring the background in detector pair II. A description of the setup and the results of first test measurements have been presented in a previous annual report. In this reporting period several improvements to the setup have been incorporated. They include:

- Installation of a mechanical brake to reduce the electronic noise from the stepping motor,
- Modification of the foil holder,
- Development of a detector simulation program,
- Optimization of the energy attenuator cell,
- Incorporation of the ionization chamber grid signal, which provides information about the emission angles of the particles,
- Measurement of the alpha background,

- Study of the detector response to beta particles.

The results of the different improvements are described in the equipment development chapter (sections h.19.-h.23.). The results from a first "shake-down" run are presented in the following section (a.2.).

*Hebrew University, Jerusalem, Israel, †Northwestern University, ‡University of North Carolina, §Western Michigan University.
[1]L. Buchmann *et al*., Phys. Rev. Lett. **70**, 726 (1993).
[2]R. E. Azuma *et al*., Phys. Rev. C **50**, 1194 (1994).
[3]Z. Zhao *et al*., Phys. Rev. Lett. **70**, 2066 (1993).
[4]R. H. France III *et al*., Nucl. Phys. **A621**, 165c (1997).

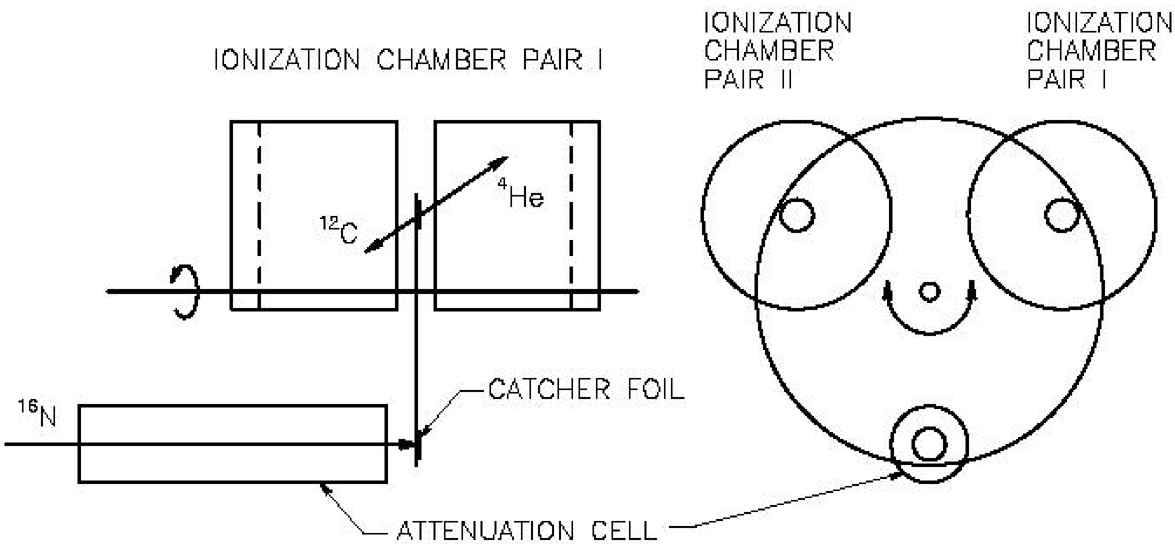

Fig. I-1. Schematic of the experimental setup used to study the beta-delayed alpha decay of ^{16}N.

a.2. Results from the First ^{16}N Decay Experiment (X. D. Tang, K. E. Rehm, I. Ahmad, J. P. Greene, A. Hecht, D. Henderson, R. V. F. Janssens, C. L. Jiang, E. F. Moore, M. Notani, R. C. Pardo, G. Savard, J. P. Schiffer, S. Sinha, M. Paul,* L. Jisonna,† R. E. Segel,† A. Champagne,‡ and A. Wuosmaa§)

The entire setup for ^{16}N decay studies was tested in a first "shake-down run" at the end of 2004. The statistics that were achieved were determined by a variety of factors. With a beam current of 3×10^6 ^{16}N/sec, from the d(^{15}N,^{16}N)p reaction (see section h.20.), a stopping efficiency of the slowed down particles in the 10 μg/cm^2 carbon foil of 5%, a counting-efficiency of 0.38 originating from the various delay times during irradiation, α-counting and rotation cycle, and an alpha/beta branching ratio of 1×10^{-5}, we obtain a $\alpha - {}^{12}C$ coincidence rate of the whole array of about 30 counts/minute or 4.5×10^4/day. Allowing for the time needed for ^{10}B(n,α)^{7}Li calibration measurements, about 1.6×10^5 coincidences were accumulated in a four day run.

A two-dimensional ^{12}C-α coincidence spectrum of one detector pair is shown in the left part of Fig. I-2. The right part of Fig. I-2 gives the corresponding background spectrum, obtained from a non-irradiated foil. Because of the asymmetry in the foil holder, which influences alpha particles emitted into detector 1 close to the foil, only events emitted at angles larger than ~80^o with respect to the foil are accepted. The two main peaks correspond to the ^{12}C-α coincidences emitted into the two different detectors, respectively. The background in between the

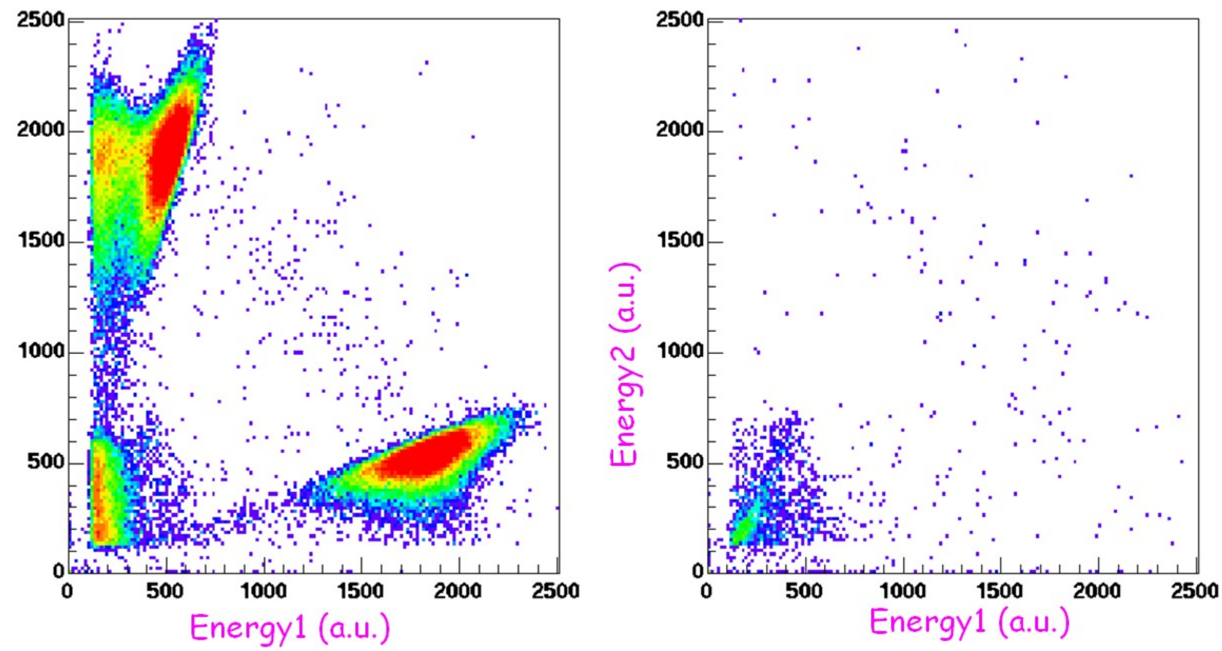

Fig. I-2. Left: ^{12}C-alpha coincidences measured in one detector pair using a 10 microg/cm^2 thick carbon foil which was bombarded by ^{16}N particles. Right: coincidence spectrum measured in the same detector pair with a non-irradiated carbon foil.

two peaks originates from gaseous ^{16}N diffusing into the detector volume and producing a signal in both detectors whose sum corresponds to the alpha decay energy of ^{16}N. The fact that due to momentum conservation the ^{16}N ^{12}C - α decay events have to show a energy ratio of 3:1 provides an additional restriction to the data.[1] Since pulse height defects in gas counters are smaller than for Si detectors, the pulse height ratio is, on average, about 3.4:1, quite close to the theoretical value of 3.

Selecting events with a pulse height ratio above 3 results in a ^{16}N alpha spectrum from all four detectors, which is shown in the upper part of Fig. I-3 by the open circles. Because of the low detection efficiency for betas, the spectra shown in Figs. I-2a and I-2b extend down to energies of 450 keV. This spectrum has not yet been unfolded for the experimental resolution. Comparisons with earlier results and R-matrix calculations are in progress.

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*Hebrew University, Jerusalem, Israel, †Northwestern University, ‡University of North Carolina, §Western Michigan University.

[1]R. E. Azuma *et al*., Phys. Rev. C **50**, 1194 (1994).

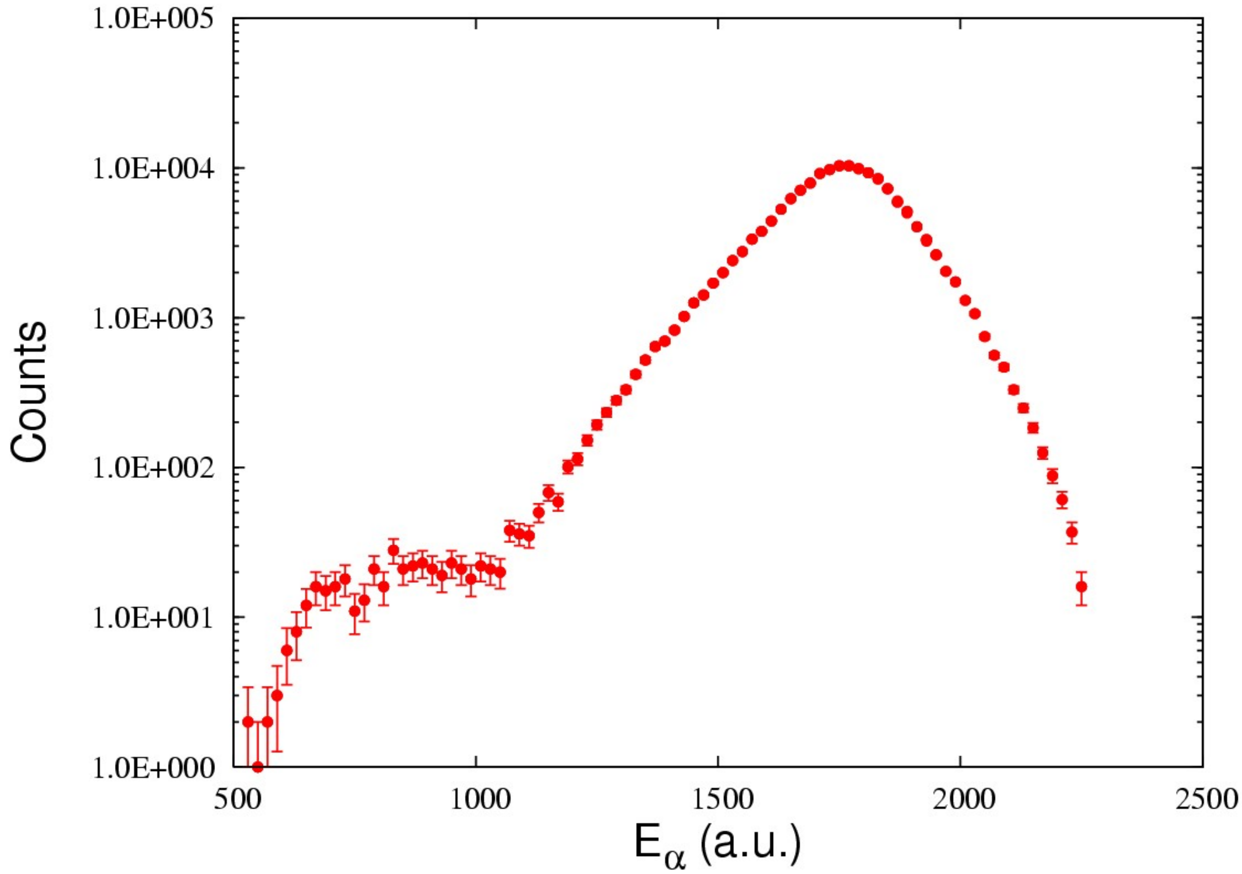

Fig. I-3. Preliminary beta-delayed alpha spectrum from ^{16}N obtained in a first experiment. This spectrum, taken at a pressure of 150 Torr has not been unfolded for the detector response.

a.3. ^{18}Ne(α,p)^{21}Na, a Possible Breakout Reaction from the Hot CNO Cycle to the rp Process (S. Sinha, J. P. Greene, D. Henderson, R. V. F. Janssens, C. L. Jiang, E. F. Moore, R. C. Pardo, K. E. Rehm, J. P. Schiffer, X. D. Tang, A. Chen,* R. E. Segel,† L. Jisonna,† R. H. Siemssen,‡ and A. H. Wuosmaa§)

At temperatures of 1-2 GK and densities of 10^3-10^6 g/cm^3, which are typical X-ray bursts conditions, the main route connecting the CNO cycle and the rapid proton capture (rp) process passes through the ^{18}Ne(α,p)^{21}Na reaction. Earlier direct measurements of this reaction covered an excitation energy range above ~10 MeV in the compound nucleus ^{22}Mg, which corresponds from the Gamow window to temperatures above 2 GK. For temperatures of 1-2 GK one has to study the yields at c.m. energies of 1.2-1.8 MeV where, so far, only theoretical cross section estimates exist. Direct measurements of the ^{18}Ne(α,p)^{21}Na reaction with an active He target are extremely challenging, as shown by the fact that the two earlier measurements[1,2] differ in their cross sections by up to an order of magnitude.

In an earlier ATLAS experiment we have repeated the cross section measurement of Ref. 2 populating a state in ^{22}Mg at E_x = 2.51 MeV with the time-inverse reaction ^{21}Na(p,α)^{18}Ne. The experiment was done with a ^{21}Na beam produced with the "in-flight" technique via the p(^{21}Ne,^{21}Na)n reaction, using a ^{21}Ne beam on a cryogenic hydrogen-filled gas cell. Details of the experiment were given in last year's annual report.[3] The cross section at this energy was found to be about a factor of 50 smaller than the one given in Ref. 2. The possible reasons for this disagreement are presently being discussed with the Edinburgh group.

In this reporting period we have extended the measurements to the astrophysically important region of E_x(^{22}Mg) = 9.3-10 MeV. The experiment was again done via the ^{21}Na(p,α)^{18}Ne reaction with a ^{21}Na beam bombarding a 370 mg/cm^2 thick CH_2 target. The heavy ions (^{21}Na, ^{18}Ne) were identified in an annular ionization chamber covering the angles 1 - 4.5^o, while the outgoing light particles (protons and alphas) were detected in coincidence, in an array of three annular double-sided Si strip detectors, covering the angular region of 5 - 20^o (alphas) and 40 - 60^o (protons). The whole setup was tested with the ^{21}Ne(p,α)^{18}F reaction which has a similar kinematics. Figure I-4 shows the excitation function of the ^{21}Na(p,α)^{18}Ne reaction, converted to the ^{18}Ne(α,p)^{21}Na system and plotted as function of the excitation energy in ^{22}Mg. Since the inverse ^{21}Na(p,α)^{18}Ne reaction only connects the ground states of ^{21}Na and ^{18}Ne, the cross sections shown in Fig. I-4 represent a lower limit of the total ^{18}Ne(α,p) yields. A preliminary analysis of the ^{21}Na(p,p') data, obtained in the same experiment, indicates, however, that in this excitation energy region the contributions from excited states in ^{21}Na are, at most, of the same order of magnitude as the ground state, resulting in no more than a factor of 2 increase for the total yields. Calculations of the astrophysical reaction rates are in progress.

*Queen's University, Kingston, Ontario, †Northwestern University, ‡University of Groningen, The Netherlands, §Western Michigan University.

[1]W. Bradfield-Smith *et al*., Phys. Rev. C **59**, 3402 (1999).

[2]D. Groombridge *et al*., Phys. Rev. C **66**, 055802 (2002).

[3]S. Sinha *et al.*, ANL Physics Division Annual Report 04/22, Section a.3.

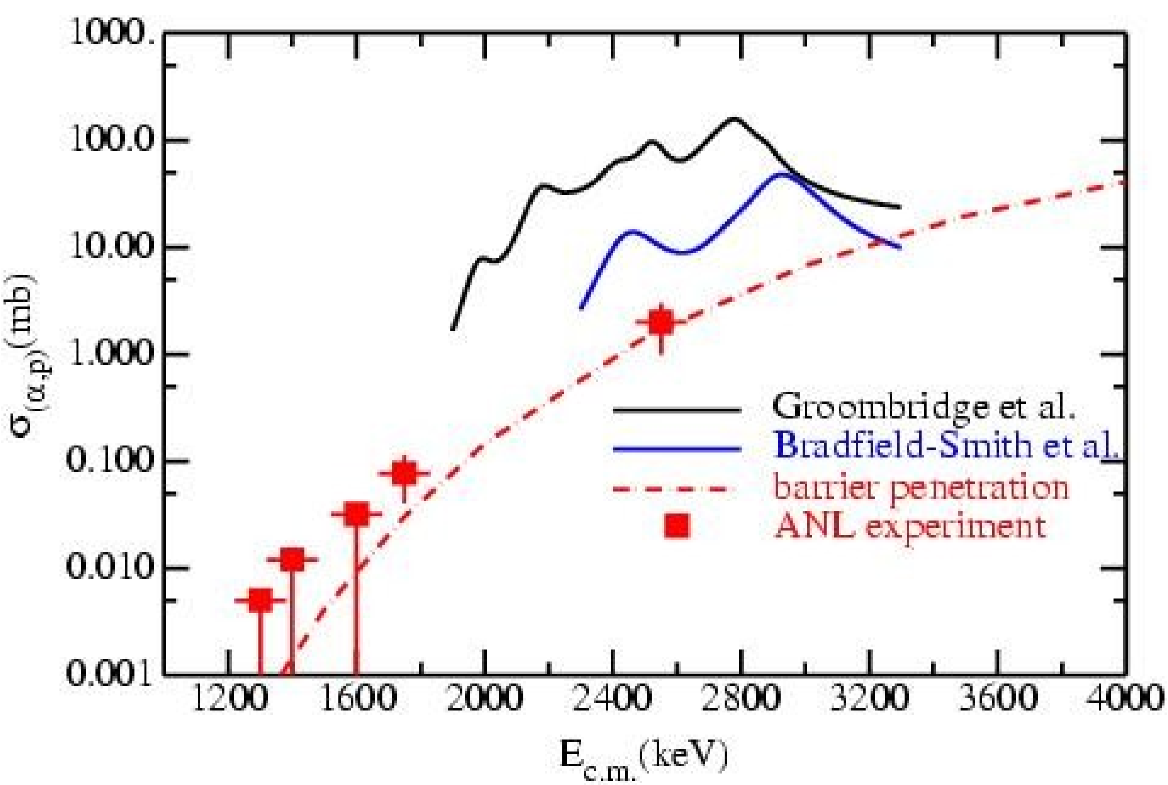

Fig. I-4. Excitation function of ^{18}Ne(α,p)^{21}Na obtained from a study of the inverse ^{21}Na(p,α) reaction. The solid lines represent the cross sections obtained in Refs. 1 and 2, respectively. The dot-dashed curve is the result of a barrier penetration calculation, normalized to the point at the highest energy.

a.4. Level Structure and Mass of ^{22}Mg (D. Seweryniak, M. P. Carpenter, R. V. F. Janssens, T. Lauritsen, C. J. Lister, S. Sinha, P. J. Woods,* T. Davinson,* D. G. Jenkins,† C. Ruiz,‡ J. Shergur,§ and A. Woehr¶)

The nucleus ^{22}Mg has provoked considerable interest in recent time, both in the astrophysical and weak-interaction communities. A precise and comprehensive knowledge of the states in the region of the proton threshold is essential for determining the ^{21}Na(p,γ)^{22}Mg reaction rate in Oxygen-Neon (ONe) Novae outbursts. This is particularly important since the 1275 keV γ ray associated with the beta decay to ^{22}Na was suggested as an astronomical observable in novae, and its signature has been sought by the COMPTEL satellite mission. The high isotopic abundance of ^{22}Ne in pre-solar grains is indicative of the earlier presence of ^{22}Na material that may have been associated with individual novae outbursts. As a T_z = -1 nucleus with a superallowed $0^+ \rightarrow 0^+$ beta decay, a precise knowledge of the mass of ^{22}Mg is required to improve the precision of tests of the conserved vector current (CVC) hypothesis in the Standard Model.

The level structure of ^{22}Mg has been studied with high-sensitivity γ-ray spectroscopy techniques. A complete level scheme was derived incorporating all sub-threshold states, and all levels in the energy region relevant for novae burning. The excitation energy of the most important astrophysical resonance is measured with improved accuracy and found to differ from previous values. Combining the present result with a recent resonance energy measurement of this state leads to a derived ^{22}Mg mass excess of -400.5(13) keV. The results were published as a Physical Review Letter.[1]

*University of Edinburgh, United Kingdom, †University of York, Heslington, United Kingdom, ‡Simon Fraser University, Burnaby, British Columbia, §Argonne National Laboratory and University of Maryland, ¶University of Notre Dame.

[1]D. Seweryniak, P. J. Woods *et al*., Phys. Rev. Lett. **94**, 032501 (2005).

a.5. In-Beam Spectroscopy Above the Proton Threshold in ^{27}Si and the Production of ^{26}Al in Novae (D. Seweryniak, M. P. Carpenter, R. V. F. Janssens, C. J. Lister, S. Zhu, P. J. Woods,* and D. Jenkins†)

The ^{26}Al nucleus is a key astrophysical isotope since its radioactive decay has been observed in space by the detection of a characteristic γ-ray line at 1.809 keV, and its stable daughter ^{26}Mg has been identified in meteorites. An important issue affecting nova outburst production yields for ^{26}Al is the ^{26}Al^g(p,γ)^{27}Si reaction rate.[1] At nova temperatures ~10^8 K the reaction rate on a single resonance at ~188 keV increases the reaction rate by two orders of magnitude.[2] Consequently this resonance reaction can strongly deplete ^{26}Al in novae explosions.[1] The state was first identified by Vogelaar *et al*.[2] using the ^{26}Al(^{3}He,d)^{27}Si reaction and assigned to be a high spin state since the ground state of ^{26}Al is 5^+. However, ambiguities in the deuteron angular distributions meant that the proton angular momentum transfer and exact spin could not be determined.

In order to resolve this ambiguity, assign spins and parities to other states above the proton threshold, and search for new resonances in ^{27}Si, excited states in ^{27}Si were populated using the ^{12}C(^{16}O,n) fusion-evaporation reaction. Prompt γ-ray transitions were detected using Gammasphere. The observed γ-ray spectrum was dominated by lines associated with ^{27}Al and ^{24}Mg. The spectrum of γ rays in coincidence with the 2164 keV transition connecting the well know $7/2^+$ state and the $5/2^+$ ground state in ^{27}Si is shown in Fig. I-5. Several transitions visible in Fig. I-5 deexcite known states above the proton threshold in ^{27}Si, including the transition originating from the important resonance at 188 keV. The detailed data analysis of the angular distribution of these transitions and the precise excitation energies of the resonances is in progress.

*University of Edinburgh, United Kingdom, †University of York, Heslington, United Kingdom.

[1]R. B. Vogelaar *et al*., Phys. Rev. C **53**, 1945 (1996).
[2]J. Jose *et al*., Astrophys. J. **520**, 347 (1999).
[3]P. M. Endt, Nucl. Phys. **A521**, 1 (1990).

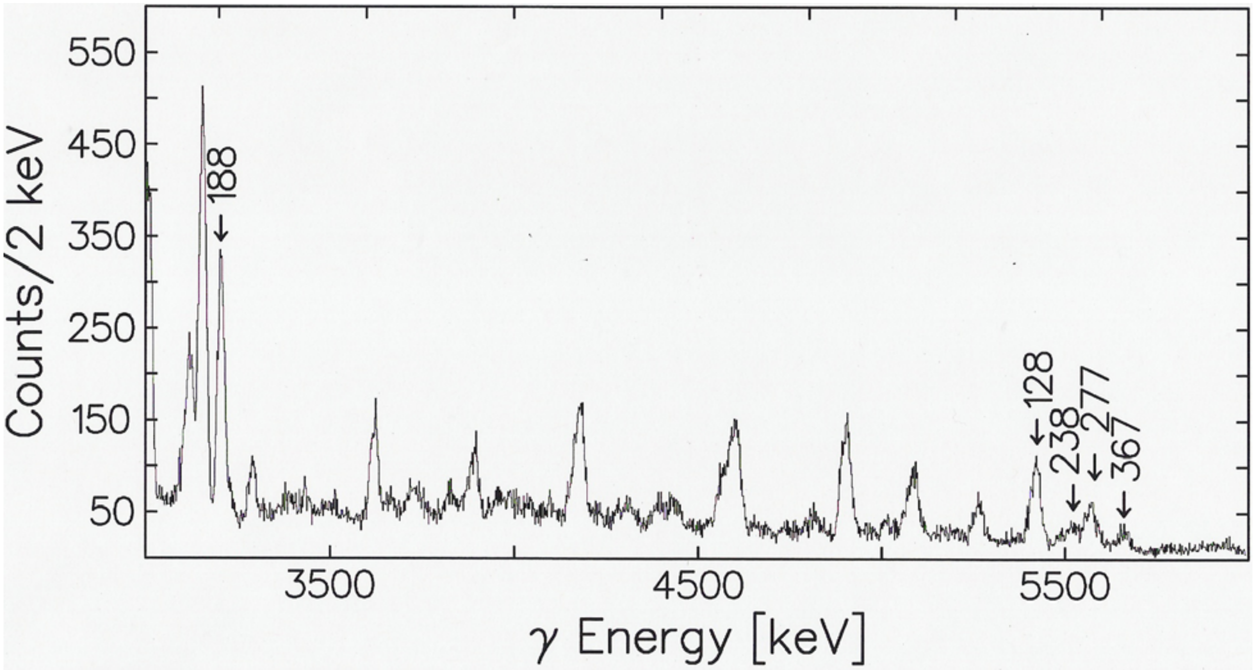

Fig. I-5. Gamma rays in coincidence with the 2164 keV $7/2^+ \rightarrow 5/2^+$(gs) transition in ^{27}Si. Transitions deexciting states above the proton threshold are labeled with the resonance energies taken from Ref. 3.

a.6. Re-Evaluation of the ^{30}P(p,γ)^{31}S Astrophysical Reaction Rate in Novae

(C. J. Lister, M. P. Carpenter, N. J. Hammond, R. V. F. Janssens, T. L. Khoo, T. Lauritsen, D. Seweryniak, E. Rehm, D. G. Jenkins,* A. Medowcroft,* P. Chowdhury,† T. Davinson,‡ P. Woods,‡ A. Jokinen,§ H. Penttila,§ G. Martinez-Pinedo,¶ and J. Jose¶)

The ^{30}P(p,γ)^{31}S reaction rate is believed to be the key determining factor in establishing the end point of the rp-process in Novae. The actual reaction rate is, to date, unmeasured and has been estimated using Hauser-Feshbach methods. We have populated states in the Gamow window of ^{31}S and will use this information to evaluate the true reaction rate.

^{31}S was produced in the ^{12}C(^{20}Ne,n)^{31}S reaction at 32 MeV. The entry region was preferentially selected by exploiting the properties of the 2-body kinematics and selecting ^{31}S residues of the appropriate velocity at zero-degrees in the FMA. The properties of γ-ray emitting states were deduced by detecting photons in Gammasphere, in coincidence with identified ^{31}S ions at the focal plane.

Online analysis showed this method to be successful, and new states in the appropriate energy range were observed. Some lifetimes (and hence gamma-widths) could be inferred from differential Doppler shift analysis. Angular correlations and branching ratios usually allow determination of the angular momentum of the states. These data have been used to calculate the reaction rate, as a function of temperature. These analyses are in progress and a first draft of a paper is being prepared. It is clear that there are substantial Mirror Energy Differences (MED).

The spectroscopy of the A = 31 mirror pair of nuclei, ^{31}S and ^{31}P has been investigated and has led to a separate publication (see section d.2.1.).

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a.7. Measurement of ^{44}Ti Half-Life (I. Ahmad, J. P. Greene, E. F. Moore, W. Kutschera,* and M. Paul†)

The half-life measurement of ^{44}Ti, which was started in March 1992, has been continued at Argonne and Jerusalem with the aim of reducing statistical and systematic uncertainties. The half-life determined from 5 years decay was published[1] in 1998. The half-life is being determined by measuring spectra of a mixed source of ^{44}Ti and ^{60}Co with a 25% Ge detector at regular intervals. We have data for 12 years decay and have stopped counting. The data have been analyzed and a paper is under preparation for publication in Phys. Rev. C.

*University of Vienna, Austria, †Hebrew University, Jerusalem, Israel.
[1]I. Ahmad *et al.*, Phys. Rev. Lett. **80**, 2550 (1998).

a.8. The ^{40}Ca(α,γ)^{44}Ti Reaction at Astrophysical Energies (I. Ahmad, J. P. Greene, D. Henderson, R. V. F. Janssens, C. L. Jiang, R. C. Pardo, T. Pennington, K. E. Rehm, G. Savard, R. Scott, R. Vondrasek, H. Nassar,* M. Paul,* S. Ghelberg,* N. Trubnikov,* M. Hass,† and B. S. Nara Singh†)

The radioactive ^{44}Ti nuclide has long been considered an important signature of the conjectured α-rich freezeout regime during the expansion phase of a core-collapse supernova. ^{44}Ti radioactive decay has since been observed[1] from the Cassiopaea A supernova remnant by γ-ray astronomy. Together with the determination of its half-life (59.2 ± 0.6 yr)[2] and the knowledge of the date and distance of the supernova, this observation makes ^{44}Ti one of the very few cases where the absolute total yield of a specific nuclide in a stellar nucleosynthesis event can be quantitatively measured. The relation of this quantity with astrophysical models requires knowledge of nuclear cross sections in the relevant path. We have studied the major reaction for production of ^{44}Ti, namely ^{40}Ca(α,γ)^{44}Ti, in the range of energies corresponding to stellar temperatures $T_9 = 0.8 - 3.0$ (where T_9 denotes the temperature in units of 10^9 K), relevant to supernova nucleosynthesis. Preliminary results of our experiment are presented here, showing a significantly stronger yield than observed in previous measurements[3] which spanned the range $T_9 = 1.5 - 3.0$.

The experimental method consisted of the bombardment of a He (99.999%) gas target by a ^{40}Ca beam from the Pelletron Tandem accelerator at the Weizmann Institute and implantation of recoil products in a forward-positioned Cu catcher. ^{44}Ti atoms are chemically extracted together with a ^{nat}Ti carrier by etching the catcher and separated by ion-exchange methods. The ^{44}Ti/Ti ratio (r_{Ti}) of the order of 10^{-12} is then measured by accelerator mass spectrometry and the yield of ^{44}Ti nuclei produced in the activation is obtained from the relation $Y_{44} = r_{Ti}n_{Ti}$ where n_{Ti} denotes the number of atoms of ^{nat}Ti carrier used. The thickness of the ^{4}He gas target was selected to integrate the reaction yield from E_{cm} = 4.2 MeV down to E_{cm} = 1.7 MeV, representing the relevant energy range. The derived ^{44}Ti yield (5.1×10^7 atoms) corresponds to an overall resonance strength of 40 to 60 eV (depending on the energies of contributing resonances), much stronger than that measured by prompt-γ measurements ($\Sigma\omega\gamma$ = 10 eV). Figure I-6a compares the average cross section measured in this work with recent Hauser-Feshbach calculations. The stronger astrophysical rate (Fig. I-6b) for ^{44}Ti production relative to that currently assumed in stellar calculations, has important consequences regarding the comparison with ^{44}Ti activity of supernova remnants measured by γ-ray astronomy.[4]

†Hebrew University, Jerusalem, Israel, ‡Weizmann Institute, Rehovot, Israel.
[1]R. Diehl *et al.*, Astron. Astrophys. **298**, 445 (1995).
[2]I. Ahmad *et al.*, Phys. Rev. Lett. **80**, 2550 (1998); and to be published.
[3]E. L. Cooperman, M. H. Shapiro, and H. Winkler, Nucl. Phys. **A284**, 163 (1977).
[4]R. Diehl, N. Prantzos, and P. von Ballmoos, Nucl. Phys. A, in press.

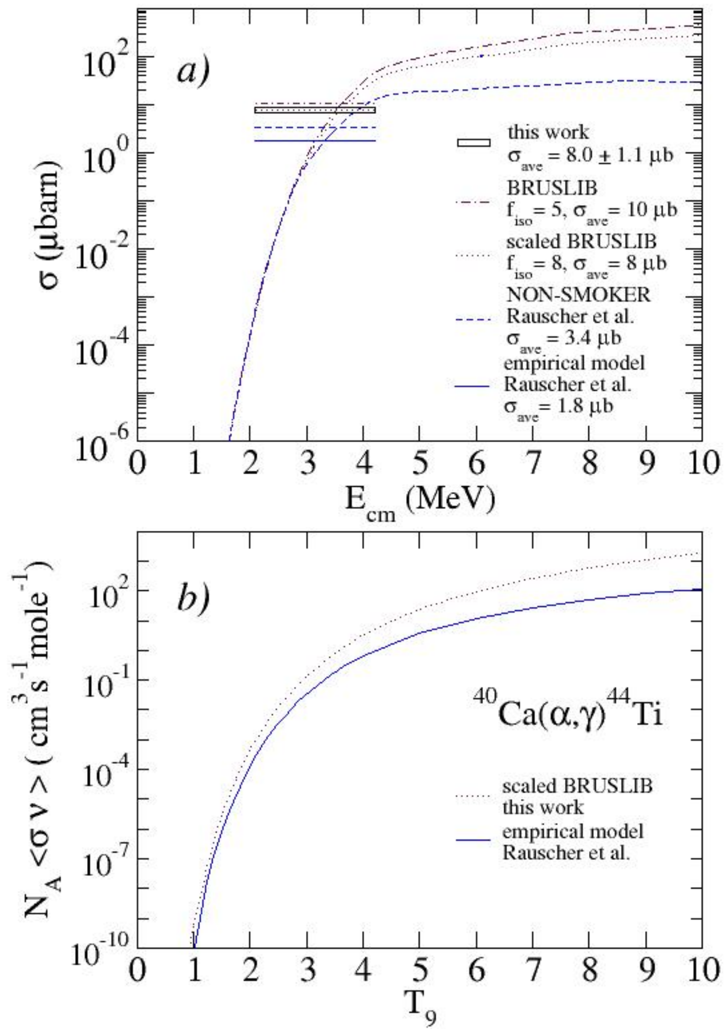

Fig. I-6. a) Comparison of the present experimental average cross section in the range E_{cm} = 1.8 – 5 MeV with recent theoretical estimates and Hauser-Feshbach calculations; b) Astrophysical rate derived from a), showing a strong enhancement of ^{44}Ti production, compared to previous estimates.

a.9. New Half-Life Measurement of ^{182}Hf: An Improved Chronometer for the Early Solar System (I. Ahmad, C. Vockenhuber,* F. Oberli,† M. Bichler,‡ G. Quité,† M. Meier,† A. N. Halliday,† D.-C. Lee,§ W. Kutschera,* P. Steier,* R. J. Gehrke,¶ and R. G. Helmer¶)

The decay of ^{182}Hf, now extinct, into stable ^{182}W has developed into an important chronometer for studying early solar system processes, such as the accretion and differentiation of planetesimals and the formation of Earth and Moon. The only ^{182}Hf half-life measurements were performed 40 years ago and resulted in a rather imprecise value of $(9 \pm 2) \times 10^6$ yr.[1] Because of the importance of the ^{182}Hf-^{182}W system as a geo-chronometer, we have remeasured the half-life of ^{182}Hf with the goal of obtaining a more precise value.

Some 35 years ago, a larger quantity of ^{182}Hf was produced by Helmer *et al.*[2] at Idaho Falls to investigate ^{182}Ta levels populated in decay. We obtained this material and measured the absolute intensities of ^{182}Hf γ rays at Argonne[3] and the half-life at Vienna/Zurich. The decay rate of a known mass of the Hf sample was measured by counting the 270.0-keV γ ray with a Ge detector. The number of ^{182}Hf atoms in the sample was determined by two different methods. In one case, neutron activation technique was applied and in the second case isotopic dilution method was used. The isotopic compositions of the Hf samples were measured at the Department of Earth Sciences, ETH-Zentrum, Zurich/Switzerland using Nu 1700, a new high-resolution multiple-collector inductively coupled mass spectrometer (MC-ICPMS). The neutron activation-plus-activity measurement method gave a half-life value of 9.034 ± 0.251 yr and the isotope dilution-plus-activity measurement gave a value of 8.896 ± 0.089 yr. The weighted mean of the two values gave a half-life of 8.904 ± 0.088 yr, a twenty times more precise half-life as compared with the original value.[1] The results of this study were published.[4]

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