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. A 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. Programs are also mounted at the Relativistic Heavy Ion Collider (RHIC), at the 88” cyclotron at Berkeley and at other forefront facilities. The major thrusts of the program are: a) deepening and generalizing our understanding of nuclear structure to allow a reliable description of all bound nuclear systems, b) studying the reactions which are important in the cataclysmic events in the cosmos which lead to the synthesis of the chemical elements, 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 studies of transfermium nuclei ($Z > 100$) with a goal of studying the very heaviest nuclei, the study of the shapes, and stability of nuclei along the proton dripline, the effects of deformation on proton radioactivity, the production and acceleration of short-lived nuclei and their use in measurements of reactions which are important in astrophysics, and the high-precision measurement of nuclear masses. In addition, there are complimentary efforts in the use of Accelerator Mass Spectrometry (AMS) for environmental research; in the investigation of nuclear matter at relativistic energies; and in the dynamics of cooled ions confined in storage rings or traps. 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 Fragment Mass Analyzer (FMA), a large solid-angle silicon array, “Ludwig”, the Canadian Penning Trap (CPT) which is operating at ATLAS, and the large array of BaF_2 detectors developed by the ORNL/MSU/Texas A&M collaboration which is presently mounted at the FMA target position. We continue to be strongly involved in all aspects of the Gammasphere project, including coordinating its move back to Berkeley for an operating cycle, continually rejuvenating its detectors, and performing research. Participation in all aspects of the PHOBOS experiment at RHIC, from detector construction to paper writing, forms the core of the relativistic heavy-ion program.

Some of the specific goals of the program can be summarized as follows:

- Develop and utilize beams of short-lived nuclei, ^{17,18}F, ^{21}Na, ^{25}Al, ^{44}Ti, ^{56}Ni and others, in order to improve the understanding of reactions of astrophysical importance. Particular emphasis has recently been focused on "in-flight" production of short-lived ion-species using kinematically inverse reactions on gaseous targets.

- Study the structure, stability, and modes of excitation and decay of the heaviest elements and study of the reaction mechanisms through which they can be synthesized. This research has many facets, including exploring the opportunities for producing the very heaviest nuclei ($Z > 106$), studies of isomeric decays, studies of "fine-structure" in the alpha decay of heavy elements, and "inbeam" spectroscopy and calorimetry.

- Study the shapes, stability and decay modes of nuclei along the proton dripline in order to improve understanding of partially bound nuclei. Studying proton tunneling through deformed barriers, in order to increase the spectroscopic information obtained through proton radioactive decay rates.

- 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. Improve the efficiency for production, separation, cooling, transportation, and trap loading of ions to increase sensitivity.

- Study the timescales and evolution of nuclear reactions through the measurement of very high energy (> 10 MeV) gamma-rays using a large array of BaF_2 scintillators operated in coincidence with the FMA and a Bismuth Germanate (BGO) calorimeter studying the changes in nuclear shell structure with excitation energy.

- 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.

- Perform R&D studies for the Rare Isotope Accelerator (RIA) and participate in efforts to develop the required accelerator and instrumentation infrastructure.

A. REACTIONS OF ASTROPHYSICAL IMPORTANCE USING STABLE AND EXOTIC BEAMS

In the last few years a variety of radioactive species have been accelerated at ATLAS. Studying reactions using these exotic nuclei helped clarify and quantify some reaction processes like the "breakout" from the hot CNO cycle and the beginning of the more explosive rp-process. Their production was through the "two-accelerator" method (for longer lived species like ^{18}F ($t_{1/2}$ = 110 m), ^{56}Ni ($t_{1/2}$ = 61 d) and ^{44}Ti ($t_{1/2}$ = 60 y)) or using "in-flight" production through reactions with highly inverse kinematics (for example, ^{17}F ($t_{1/2}$ = 65 s), ^{21}Na ($t_{1/2}$ = 22.5 s), ^{25}Al ($t_{1/2}$ = 7.2 s), and ^{8}B ($t_{1/2}$ = 770 ms)). The "in-flight" method seems particularly promising and offers considerable opportunity for expansion in scope. During the last year the "in-flight" production beam line was considerably redesigned and a new large-field solenoid procured in order to increase the quantity and quality of the secondary beams. In addition to exotic beam studies, stable beams were used for more indirect experiments that were used to gain access to states that have importance in astrophysically important reactions. These include reactions with Gammasphere, Eurogam and the spectrometer at Yale. A glimpse of neutron-rich nuclei along the r-process path was obtained by detailed spectroscopy of fission fragments.

a.1. The Influence of the First Excited $1/2^+$ State in ^{17}F on the ^{14}O(α,p)^{17}F Reaction Rate (B. Harss,* C. L. Jiang, K. E. Rehm, J. P. Schiffer, J. Caggiano, P. Collon, J. P. Greene, D. Henderson, A. Heinz, R. V. F. Janssens, J. Nolen, R. C. Pardo, T. Pennington, R. H. Siemssen, I. Wiedenhöver, M. Paul,† F. Borasi,‡ R. E. Segel,‡ J. Blackmon,§ M. Smith,§ A. Chen,¶ and P. Parker¶)

Because of experimental difficulties, the astrophysically important reaction ^{14}O(α,p)^{17}F is presently best studied through its time-inverse i.e. using a ^{17}F beam and a CH_2 target. This measurement, however, can only provide values for the widths Γ_α and Γ_p connecting the ground states of ^{14}O and ^{17}F. In an astrophysical environment, the ^{14}O(α,p)^{17}F reaction can also populate the first excited $1/2^+$ state in ^{17}F at E_x = 0.495 MeV, so one has to determine the width $\Gamma_{p'}$ through a separate measurement of inelastic proton scattering on ^{17}F.

We measured excitation functions for elastic and inelastic scattering of p + ^{17}F at energies covering the excitation energy region E_x = 7-7.8 MeV in ^{18}Ne. Details of the experimental technique are discussed in the following sections. A Q-value spectrum measured for the system ^{17}F + p at a scattering angle of 70º in the center of mass system (θ_{lab} = 52.5-56.5°) is given in Fig. I-1. The satellite structure, next to the strong elastic peak which is not observed for the ^{16}O + p channel (open symbols in Fig. I-1), is attributed to inelastic excitation of the $1/2^+$ state at 0.595 MeV in ^{17}F.

The excitation function measured for inelastic excitation of the $1/2^+$ state in ^{17}F at θ_{cm} = 70°, together with the excitation function for the ^{17}F(p,α) reaction, is shown in Fig. I-2. While for the two excitation energy regions around E_x = 7.05 and 7.60 MeV only upper limits of about 5 mb/sr for the inelastic cross sections can be given, a resonant-like structure is observed at E_x = 7.72 MeV. This structure coincides with a 7.71-MeV state seen in the ^{12}C(^{12}C,^{6}He) reaction[1]. The constraint on the angular momentum $l \leq 2$ restricts the spin-parity choice for this structure to small spin values (0^+,$1^\pm$,$2^\pm$ and 3^+). The fact that no strong yield is observed for the (p,α) reaction in this energy range suggests unnatural parity for this state, i.e. 1^+, 2^- or 3^+. Because there is a 2^- state in the mirror nucleus ^{18}O at E_x = 7.771 MeV, the structure seen in inelastic scattering could correspond to that level. This assignment is consistent with the angular distribution measured for the 7.71 MeV state in the ^{12}C(^{12}C,^{6}He)^{18}Ne reaction which has a structure similar to the one measured for the known 2^- state at E_x = 5.45 MeV[1].

From the measured cross sections for (p,α), (p,p') and the total widths one can deduce values for Γ_α, $\Gamma_{p'}$ and $\Gamma_{p'}$. The upper limits of the inelastic yields measured for the states with natural parity in ^{18}Ne translate into small values for $\Gamma_{p'}$ (typically less than 5% of the elastic widths). From this experiment we can, therefore, conclude that inelastic scattering contributes less than 5% to the astrophysical $^{14}O(\alpha,p)^{17}F$ reaction rate going through natural parity states at E_x = 7-7.8 MeV.

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[1] K. I. Hahn *et al.*, Phys. Rev C **54**, 1999 (1996).

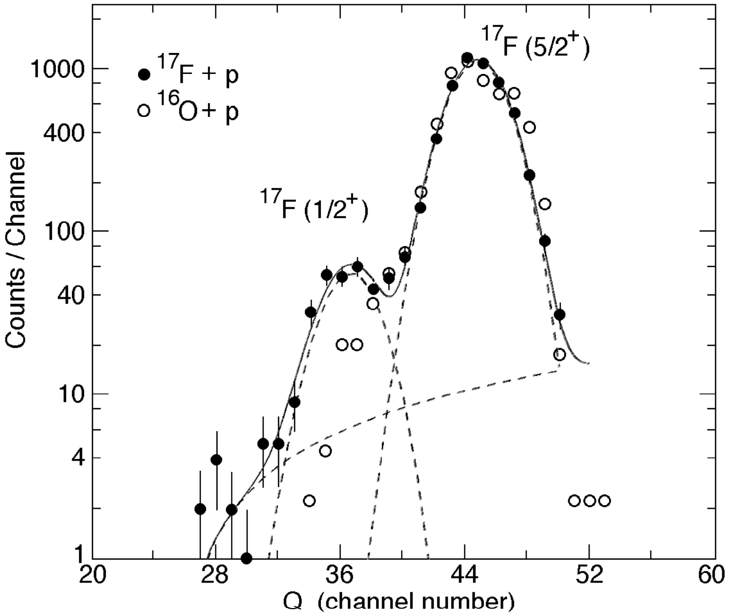

Fig. I-1. A Q-value spectrum measured for the system $^{17}F + p$ at a scattering angle of 70° in the center of mass system (θ_{lab} = 52.5-56.5°).

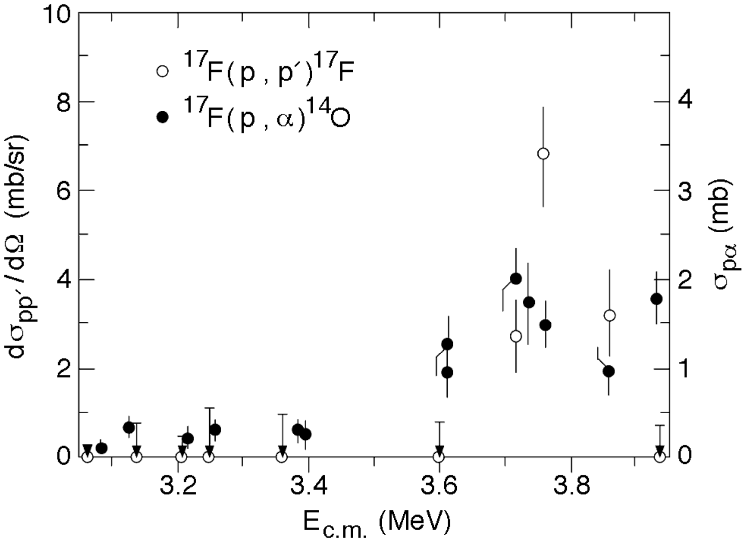

Fig. I-2. The excitation function measured for inelastic excitation of the 1/2+ state in ^{17}F at θ_{cm} = 72°, together with the excitation function for the $^{17}F(p,\alpha)$ reaction.

a.2. Spin Determination of Particle Unbound States in ^{18}Ne (B. Harss, C. L. Jiang, K. E. Rehm, J. P. Schiffer, J. Caggiano, P. Collon, J. P. Greene, D. Henderson, A. Heinz, R. V. F. Janssens, J. Nolen, R. C. Pardo, T. Pennington, R. H. Siemssen, I. Wiedenhöver, M. Paul,† F. Borasi,‡ R. E. Segel,‡ J. Blackmon,§ M. Smith,§ A. Chen,¶ and P. Parker¶)

The level structure of ^{18}Ne above the proton threshold at 3.92 MeV strongly influences a variety of astrophysical processes[1]. In the so-called breakout from the hot CNO cycle[2], the ^{14}O(α,p)^{17}F reaction, going through resonant states in ^{18}Ne, bypasses the waiting point at ^{14}O($T_{1/2}$ = 70.6 s). A direct measurement of an excitation function for this reaction is difficult because, in addition to a low-energy radioactive ^{14}O beam, it also requires a ^{4}He gas target. Using detailed balance, however, this reaction can also be studied via the time-inverse ^{17}F(p,α)^{14}O reaction.

In two earlier measurements[3,4] some information about excitation energies and spin values of states in ^{18}Ne above the proton threshold were obtained. Three states at E_x = 7.16 ± 0.15, 7.37 ± 0.06 and 7.62 ± 0.05 MeV were observed and suggestions for spin values were provided which, however, did not give unique assignments. In order to check the spin-parity assignments for states in this energy region, we measured an excitation function of elastic scattering in the system p + ^{17}F. The experiment was performed at the ATLAS accelerator with a ^{17}F beam produced with the in-flight technique. In order to separate elastic scattering in the system ^{17}F + p from elastic scattering of the beam contaminant ^{16}O + p, the two outgoing particles were detected in kinematic coincidence. The heavy particles (^{17}F and ^{16}O) were identified with respect to nuclear charge Z and energy in an annular gas detector consisting of a parallel plate avalanche counter followed by a Bragg-curve ionization chamber. This detector covered the angular range θ_{lab} = 1.5 - 6.5°. The coincident protons were measured with a solid-state detector array consisting of two double-sided, annular silicon strip detectors covering the angular region θ_{lab} = 7 - 24.5°. The annular Si detectors were segmented into 16 rings on the front face and 16 wedges on the back face. Six additional 5 × 5 cm^2 Si strip detectors with a strip width of 2 mm covered the angular range θ_{lab} = 32 - 56.5°.

The p(^{17}F,p)^{17}F scattering was measured at a number of incident energies, covering the range E_{lab} = 54.8-70.3 MeV which is equivalent to a proton energy range of about 3.1-4.1 MeV or the excitation energy range between 7-7.9 MeV in ^{18}Ne. CH_2 targets with thicknesses of ~ 100 μg/cm^2 were used.

The first measurement of the ^{17}F(p,α)^{14}O reaction[4] with a radioactive ^{17}F beam found that the main (p,α) strength populates a state at E_x = 7.60 ± 0.05 MeV with a resonance strength ωγ = 300 eV, while the strength for a state at 7.37 MeV is about a factor of 10 smaller. At 7.16 ± 0.15 MeV, another structure with a small resonance strength was identified. However, since this energy range was covered only with a thick target, the excitation energy and the resonance strength could only be determined with relatively large uncertainties. Based on these results and Coulomb shift arguments, the tentative spin assignments of 1^- (7.16 MeV) $1^-,4^+$ (7.37 MeV) and $1^-,2^+,3^-$ (7.62 MeV) were made for these states. These assignments were later questioned in Ref. 5, which argued that the 7.62 and 7.35 MeV levels in ^{18}Ne cannot have a $J^\pi = 4^+$ assignment nor could the 7.16 and 7.37 MeV levels be candidates for spin-parity of 1^-.

Results from the excitation function measurements of elastic scattering in the system ^{17}F + p are shown in Fig. I-3. At backward angles (θ_{cm} = 142°) an increase in cross section is observed at proton energies of 3.3 MeV, which corresponds to an excitation energy in ^{18}Ne of 7.05 MeV. At higher energies ($E_p \leq 3.9$ MeV) another rise in the cross section is observed. This region of excitation energy, however, is more complex and might include several overlapping states (see following contribution). The solid lines in Fig. I-3 are the result of R-matrix calculations assuming spin-parity values of 1^- or 4^+, for the state at E_x = 7.05 MeV. As can be seen, a 1^- value is unable to describe the data, pointing to a 4^+ (or possibly 2^+) assignment for this state. Because the mirror nucleus ^{18}O does not show a 2^+ state in this energy range within 1.15 MeV the 7.05 MeV level in ^{18}Ne has presumably a spin-parity assignment of $J^\pi = 4^+$.

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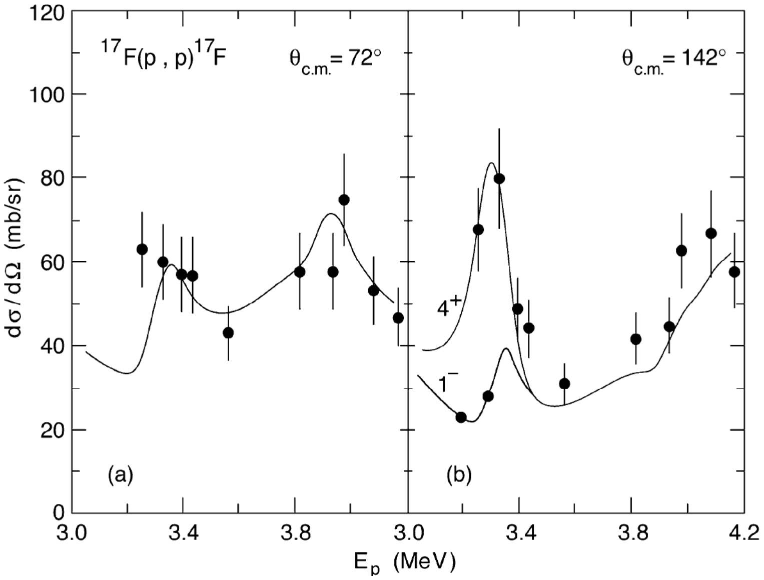

Fig. I-3. Results from the excitation function measurements of elastic scattering in the system $^{17}F + p$. The solid lines are the result of R-matrix calculations assuming spin-parity values of 1^- or 4^+, for the state at $E_X = 7.05$ MeV.

a.3. Study of the Branching Ratio of the 4.033 MeV $J^\pi = 3/2^+$ State in ^{19}Ne

(K. E. Rehm, J. Caggiano, P. Collon, A. Heinz, R. V. F. Janssens, C. L. Jiang, R. Pardo, M. Paul, J. P. Schiffer, R. H. Siemssen, A. H. Wuosmaa, L. Jisonna,* and R. E. Segel*)

The $J\pi = 3/2^+$ state in ^{19}Ne at 4.033 MeV excitation energy dominates the astrophysical reaction rate for the $^{15}O(\alpha,\gamma)$ reaction, which is one of the possible breakout paths from the hot CNO cycle into the rp-process. The α width of this channel was estimated to be about 10 μeV, which makes a direct measurement of this reaction very difficult. Many attempts were made to determine this width through indirect experiments with stable or radioactive beams, e.g. through a measurement of the branching ratio $\Gamma\alpha/\Gamma\gamma$. Because of its small α width we plan to use a high intensity, stable beam reaction populating the $3/2^+$ state via the $d(^{20}Ne,t)^{19}Ne^*(4.033\ MeV) \rightarrow (^{15}O + \alpha)$ reaction. Studying this reaction in inverse kinematics results in a forward focusing of the outgoing ^{15}O particles with magnetic rigidities that are different for the three particles of interest (t,^{15}O and ^{20}Ne, see top part of Fig. I-4). The tritons emitted at $\theta_{cm} = 0°$ are detected in the focal plane by a 5×5 cm^2 Si-strip detector which covers an excitation energy region in ^{19}Ne of about 700 keV. The ^{19}Ne and ^{15}O particles, which are in coincidence with the tritons, are detected in the gas-filled focal plane detector where they are identified with respect to mass and nuclear charge Z. Spectra obtained in a short test run with a CD_2 target and a 235 MeV low-intensity ^{20}Ne beam are shown in the lower part of Fig. I-4. The triton spectrum shows mainly states at 4.5 MeV excitation energy and very little yield in the vicinity in the 4.033 MeV region. This points to a small spectroscopic factor for this state when populated via the $^{20}Ne(d,t)^{21}Ne$ reaction, which can be compensated by a higher beam intensity of the ^{20}Ne beam. The good particle identification in the focal plane detector results in very clean coincidence spectra which are also shown in the figure. Increasing the beam intensity requires a rotating CD_2 target or a D_2 gas cell. This and other improvements in the count rate capability will be tested in upcoming runs.

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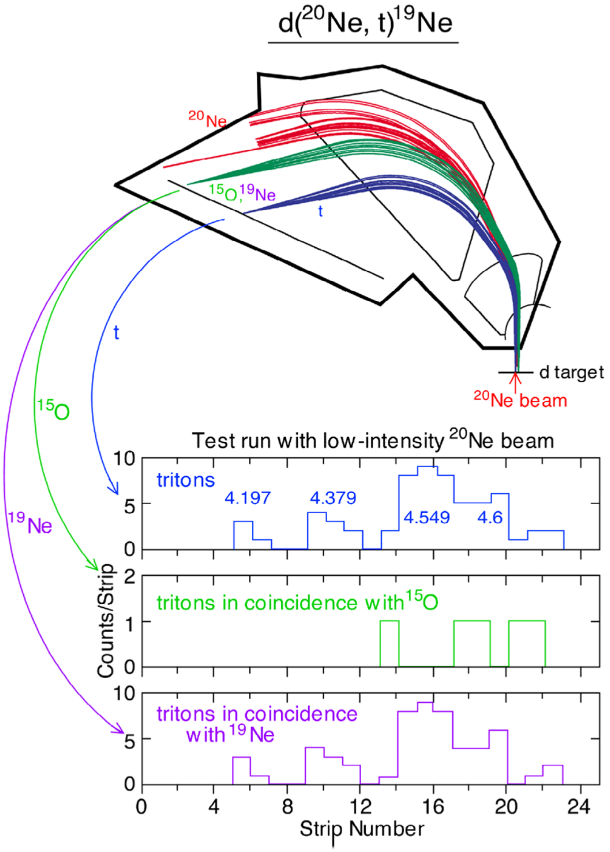

Fig. I-4. Identification of t,^{15}O and ^{20}Ne ions at the focal plane.

a.4. **Large Angle Alpha Scattering on ^{44}Ti** (K. E. Rehm, C. L. Jiang, I. Ahmad, J. Caggiano, P. Collon, J. P. Greene, D. Henderson, A. Heinz, R. V. F. Janssens, R. C. Pardo, T. Pennington, R. H. Siemssen, A. Wuosmaa, and M. Paul*)

Anomalous large angle scattering (ALAS) was extensively studied in the past with α particles on sd-shell nuclei including ^{40}Ca. In ALAS, enhanced cross sections for elastic scattering are observed at angles around 180°. It is believed that ALAS is a manifestation of weak absorption of the surface partial waves, but the origin of this surface transparency is not well understood. Because ALAS is especially pronounced for multiple-α nuclei (like ^{16}O, ^{28}Si, ^{32}S,. ^{40}Ca) is has been argued that α clustering might also play a role. Since ^{44}Ti(T$_{1/2}$ = 60y) is the first α-type nucleus beyond ^{40}Ca, we studied α scattering at backward angles for this system. For experimental reasons it was decided to study this reaction in inverse kinematics, i.e. by bombarding a ^{4}He target with a ^{44}Ti beam.

The ^{44}Ti material was produced via the ^{45}Sc(p,2n)^{44}Ti reaction using a 50 MeV, 20 μA proton beam from the linac injector of the Argonne Intense Pulsed Neutron Source. After chemical separation, the ^{44}TiO$_2$ compound was mixed with natural TiO$_2$ and placed inside a copper insert for a negative Cs sputter source. A beam of ^{44}TiO- was extracted from the ion source and accelerated in the ATLAS accelerator to an energy of 280 MeV. The average beam intensity measured on target was about 5 × 10^{5} ^{44}Ti/s with an equal amount of impurities from the stable isobar ^{44}Ca, which could not be separated by the beam transport system.

The ^{4}He target consisted of a 5-mm long gas cell with two 1.3 mg/cm^2 titanium windows, filled with 600 mbar of ^{4}He and cooled to LN$_2$ temperature. The areal density of the target was about 60 μg/cm^2. The α particles were detected by an array consisting of two

500-µm thick annular silicon strip detectors and a ΔE-E telescope at 0°. The annular detectors were segmented into 16 rings and 16 wedges allowing for θ and ϕ determination of the incident particles. They were placed in front of the target, covering the angular range from 8° to 30° in the laboratory system. To suppress the elastically scattered ^{44}Ti particles, wedge-shaped polyethylene absorbers were mounted in front of all Si detectors. Two Si detectors at ±6° served to monitor the beam intensity and purity.

The whole setup was tested with ^{28}Si and ^{40,44}Ca beams where angular distributions with α beams on ^{28}Si and ^{40,44}Ca targets were measured previously. In order to obtain the contribution of elastic scattering from ^{44}Ti in the mixed ^{44}Ti/^{44}Ca beam, measurements with a pure ^{44}Ca beam were performed under identical conditions. The results are shown in Fig. I-5a. The cross sections of elastic scattering of α particles on ^{44}Ti at backward angles are found to be at least an order of magnitude smaller than the ones observed for α on ^{40}Ca. The cross section integrated in the angle range θ = 140-180° is shown in Fig. I-5b and compared to several other nuclei in this mass range. The yield obtained for ^{44}Ti is comparable to the one measured for ^{44}Ca, indicating that the anomalous large alpha scattering effect seems to end with the α + ^{40}Ca system.

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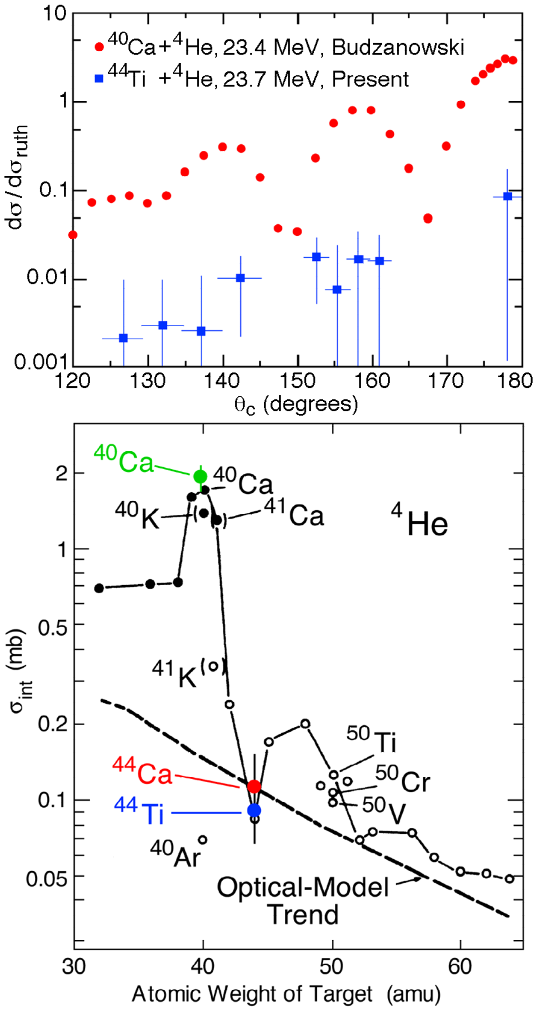

Fig. I-5. (top): Angular distributions for elastic α scattering on ^{40}Ca and ^{44}Ti. The ^{40}Ca data were taken from the literature. (bottom): Cross sections integrated over the angular range θ = 140° - 180° for elastic scattering of α particles on several nuclei. The trend predicted by optical model calculations is given by the dashed line.

a.5. **Measurement of ^{44}Ti Half-Life** (I. Ahmad, J. P. Greene, E. F. Moore, W. Kutschera,* and M. Paul†)

A measurement of the ^{44}Ti half-life, which has astrophysical significance, was started by our group in 1992. The half-life value determined from the decay for five years was published[1] in 1998. We continued this measurement in order to reduce the statistical uncertainty and to better understand the systematic errors. The last measurement of the spectra was made in December 2000. The measurements at Argonne and Jerusalem were partially analyzed and the new number agrees with our published value within the statistical error. One of the decay curves is shown in Fig. I-6 and the half-life obtained from the analysis of this data set is shown in the figure. The result will be published in Phys. Rev. C.

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[1] Ahmad *et al*., Phys. Rev. Lett. **80**, 2550 (1998).

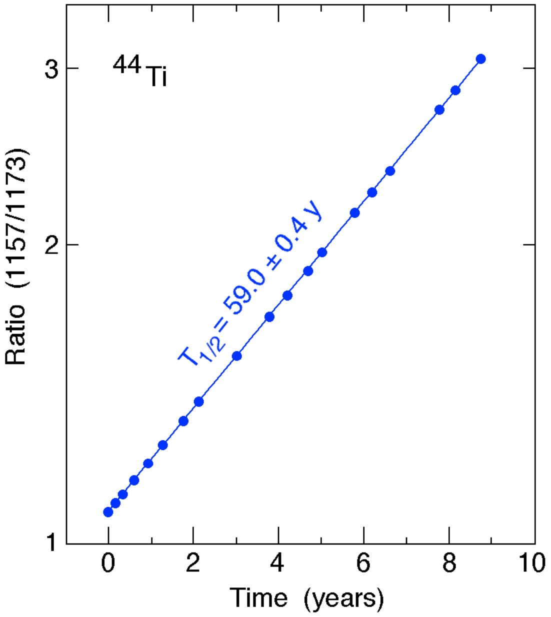

Fig. I-6. Semilogarithmic plot of the ratio of counts in the 1157-keV peak of ^{44}Ti to the counts in the 1173.2-keV peak of ^{60}Co measured at ANL against decay time.

a.6. **Measurement of ^{44}Ti Nucleosynthesis by γ and Atom Counting** (K. E. Rehm, I. Ahmad, J. Caggiano, P. Collon, J. Greene, D. Henderson, A. Heinz, R. V. F. Janssens, C. L. Jiang, R. C. Pardo, T. Pennington, , G. Savard, R. Vondrasek, I. Wiedenhöver, M. Paul,* D. Berkovits,† J. Goerres,‡ M. Hass,§ S. K. Hui,¶ and M. Wiescher‡)

The nuclide ^{44}Ti ($T_{1/2}$ = 59.2 yrs) recently became an important asset to nuclear astrophysics through the measurement of its cosmic radioactivity, yielding significant information on fresh ^{44}Ti nucleosynthesis in supernovae. Because of the value of its half-life (determined recently with precision $T_{1/2}$ = 59.2 ± 0.6 yr[1-3]), ^{44}Ti is a probe of the supernova activity of the Galaxy during the last few centuries. We started a measurement of the main reaction channel believed to be responsible for ^{44}Ti production in a supernova explosion, namely the ^{40}Ca(α,γ) nuclear reaction. The scheme of the measurement consists of an activation run in which a ^{40}Ca beam bombards a ^{4}He gas target and collection of ^{44}Ti recoil nuclei implanted in a catcher material. The catcher is then counted by γ spectroscopy and at a later stage chemically processed to extract (with a chemical carrier) produced ^{44}Ti atoms. Accelerator Mass Spectrometry (AMS) will then be used to count the ^{44}Ti atoms and a reaction cross section extracted.

An intense 68 MeV ^{40}Ca^{11+} beam from the ECR-2 ion source was transported to the target chamber of the Enge spectrograph in Area II, filled with high-purity He gas. A rotating-foil setup was installed at the entrance of the target chamber, equipped with a 1" diameter 1.4 mg/cm^2 Ni foil, dissipated the heat of the beam (Fig. I-7). Beam currents of up to 1.5 eμA could be accepted for periods of ten to twenty hours before foil changing; the total activation time was of about 24 hours, corresponding to 12 particle-mC irradiation. A high-purity water-cooled Cu plate (1/4" thick, 2" diameter) was used as catcher and beam stop. A small Bragg gas detector, mounted at 40º to the incident beam, monitored elastically scattered beam particles, discriminating ^{40}Ca from a ~10% ^{40}Ar component[4]; the ^{40}Ar incident particles cannot produce ^{44}Ti from the He target. Three activation runs were performed: (i) at a known resonance energy of the ^{40}Ca + ^{4}He system; (ii) at the same energy, using Ar gas as a target to estimate possible ^{44}Ti production from contaminants (e.g. foil window, beam stop); (iii) with He gas, at energy below resonance. Soon after the activation run, the catcher irradiated at the resonance energy was placed in front of a Ge detector. A ^{43}Sc γ line from the ^{40}Ca(α,p) reaction was observed. A longer γ measurement (~1 week) of the catcher, taken with a low-level Ge detector[5] did not show the 1157-keV line of ^{44}Ti decay above background, determining an upper limit of 1.6×10^7 ^{44}Ti atoms at the 95% confidence level. This limit is consistent with the estimate of the (α,γ) resonance strength. We are pursuing at present preparations towards the AMS measurement of the irradiated samples, in particular development of a chemical method for extraction of the ^{44}Ti implanted atoms and purification from Ca contaminants (to reduce the ^{44}Ca isobaric interference).

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Fig. I-7. Incandescent beam spot of the ^{4}He beam on the rotating window and fluorescence of the gas target. The beam (upper glow) comes from the right; the lower image and the beam spot is viewed in a mirror facing the foil window.

a.7. Study of Proton-Unbound States in Astrophysically-Interesting Nuclei

(J. A. Caggiano, A. Heinz, R. V. F. Janssens, C.-L. Jiang, K. E. Rehm, G. Savard, A. H. Wuosmaa, W. Bradfield-Smith,* R. Lewis,* P. D. Parker,* and D. W. Visser*)

In last year's Annual Report we described the initiation of a program to measure states in proton-rich nuclei not far above the proton threshold. The goal of this study was to identify missing unnatural parity states that can have significant impact on proton capture reaction rates in the rp process in novae. This report summarizes the progress made in this endeavor.

The experiments were all designed to measure the momentum spectrum of ^{6}He with a split-pole spectrograph following the ^{25}Mg,^{29}Si(^{3}He,^{6}He)^{22}Mg,^{26}Si transfer reactions with a beam of ^{3}He at 45-57 MeV. A series of experiments were performed at Yale University and one experiment was attempted at ATLAS. The experiments performed at Yale were successful, and several beam energies and target configurations were tried. Figure I-8 shows momentum spectra of ^{6}He nuclei following (^{3}He,^{6}He) reactions on several targets. The reactions of interest are not contaminated by reactions on C or O in the target as the Q-values are more negative. However, reactions on other isotopic impurities, e.g. ^{13}C(^{3}He,^{6}He) (1% in carbon backings), ^{26}Mg(^{3}He,^{6}He) (4% in the ^{25}Mg targets), and ^{30}Si(^{3}He,^{6}He) (3% in the ^{29}Si targets) may complicate the spectra, usually at a small, but non-trivial level. The Q-values for the (^{3}He,^{6}He) on ^{24}Mg and ^{28}Si target nuclei are also too negative to be seen with the spectrograph.

Studies at higher beam energy (51 MeV vs 45 MeV) prove advantageous for two reasons. First, the cross section for states above the proton threshold is higher. Second, alpha particles are generated very prolifically and dominate the count rate in the detector. At higher energy, more of these alphas are kinematically focused away from the detector, enabling higher beam currents. Angular distributions prove inconclusive for rigorous spin assignments, but sometimes they have distinct shapes which may limit the number of possible configurations. This work will continue with two more experiments in 2001.

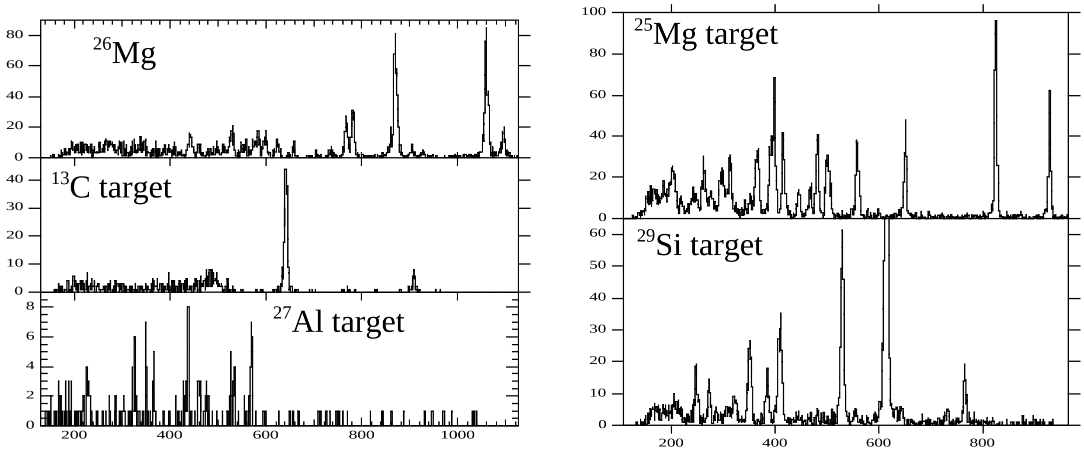

Fig. I-8. The ^{6}He momentum spectra from the (^{3}He,^{6}He) reaction on several targets at 51 MeV.

a.8. Reaction Rates of the ^{22}Na(p,γ) and ^{22}Ne(p,γ) Breakout Reactions

(D. Jenkins, C. J. Lister, K. E. Rehm, A. H. Wuosmaa, and M. P. Carpenter)

High-Lying states in ^{23}Na and ^{23}Mg, just above the proton separation energy, play an important role in breakout reactions that lead to the synthesis of intermediate mass nuclei. The exact location of these states and their spins, parities and decay properties determine the rate of synthesis of A = 23 nuclei and destruction of A = 22 nuclei through proton capture reactions. Heroic efforts were made to directly measure the states involved, and the reaction rates 1,2. However, due to extreme experimental difficulty, the location of many critical states and their properties were not categorized, and thus there is considerable uncertainty over the reaction rates.

In a novel approach to this problem, we used the ^{12}C(^{12}C,p) and ^{12}C(^{12}C,n) reaction at a beam energy of 22 MeV to populate high lying states in A = 23 nuclei. Gammasphere was used to study the subsequent gamma-decay of states. The excellent sensitivity of the device allowed proton unbound states with small radiative widths to be observed and studied. Angular correlations and gamma-gamma coincidences permitted several new rigorous spin/parity assignments. The short lifetimes of the states (10's fs) could be measured by a Differential Doppler method. These new data were then included in reaction rate calculations resulting in an enhancement of the calculated rate and a considerable improvement in precision. An example for the ^{22}Na (p,γ) reaction is shown in Fig. I-9. Final analysis is in progress and a paper is being written.

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[1] J. Gorres, C Rolfs *et al*, Nucl. Phys. **A385**, 57 (1982).
[2] J Gorres *et al*., Nucl. Phys **A408**, 372 (1983).

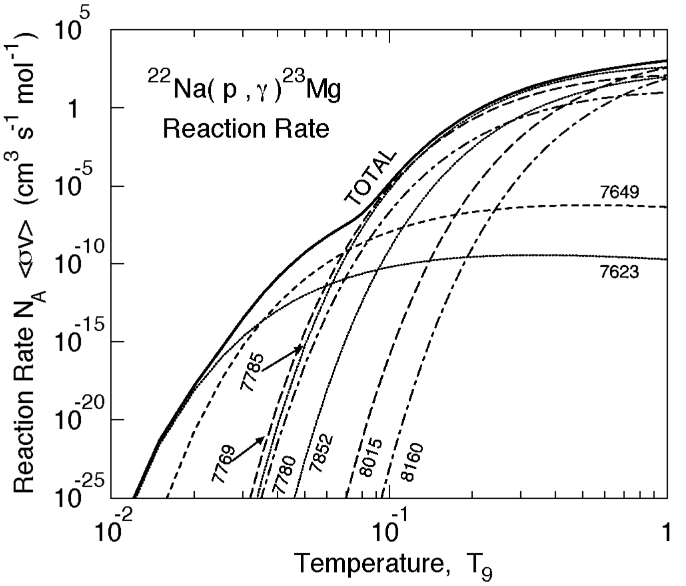

Fig. I-9. Reaction rates for the ^{22}Na(p,γ)^{23}Mg reaction, recalculated with the new information on states in ^{23}Mg near the reaction threshold, shown as a function of temperature in billions of degrees, T_9.

a.9. **Excited States in ^{139}Te and the Properties of the r-Process Nuclei with Z ~ 50 and N > 86** (I. Ahmad, W. Urban,* W. R. Phillips,† N. Schulz,‡ B. J. P. Gall,‡ M. Bentaleb,‡ J. L. Durell,† M. A. Jones,† M. J. Leddy,† E. Lubkiewicz,‡ L. R. Morss,§ A. G. Smith,† and B. J. Varley†)

The knowledge of the structure of the very neutron-rich (N > 86) nuclei around the doubly magic ^{132}Sn is crucial for understanding the flow of the astrophysical r-process. One of the important experimental data required for the calculation of the r-process path is the location of the single-particle states in these nuclei. To provide the relevant data, we studied the structure of very neutron-rich tellurium isotopes. The levels in ^{137}Te and ^{138}Te were deduced last year and were published. This year we studied the structure of ^{139}Te, which is the most neutron-rich nucleus near the Z = 50 closed shell, for which experimental data are available.

Levels in ^{139}Te were populated in the spontaneous fission of ^{248}Cm and the γ rays in the fission fragments were measured in multifold coincidence with the EUROGAM2 array of Compton-suppressed Ge detectors. Gamma rays in ^{139}Te were obtained by gating on transitions in the light ruthenium isotopes. Since nothing was known about ^{139}Te, a mass correlation technique was used to assign γ rays to

^{139}Te. A cascade of γ rays with energy 271.0, 356.5, 436.4, 534.8 and 611.8 keV was observed in prompt coincidence with transitions in $^{106\text{-}108}$Ru. The weighted mass of the Ru in coincidence with transitions in each Te isotope is plotted against Te mass in Fig. I-10a. Figure I-10b shows the relative yields of Te isotopes in ^{248}Cm fission. The smooth variation of the weighted Ru mass and the independent Te yields confirm the mass assignment. The level scheme is displayed in Fig. I-11. The level scheme of ^{139}Te is found remarkably similar to level schemes of heavier N = 87 isotones. The results of this investigation were published.[1]

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[1] Phys. Rev. C **62**, 044315 (2000).

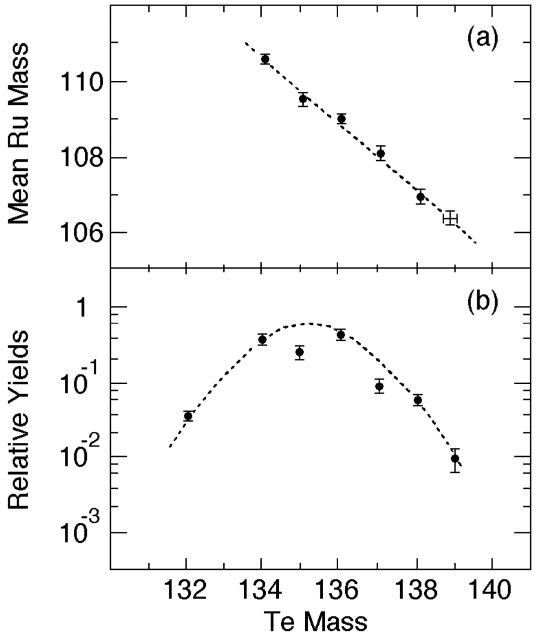

Fig. I-10. (a)Correlation between masses of Te isotopes and the mean mass of the complementary Ru isotopes. (b). Independent yield of Te isotopes in the spontaneous fission of ^{248}*Cm.*

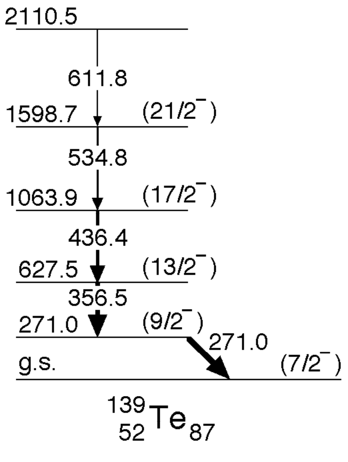

Fig.I-11. The partial level scheme of ^{139}*Te deduced in the present work. Nothing was known about* ^{139}*Te levels before this work.*