# A. REACTIONS OF ASTROPHYSICAL IMPORTANCE USING STABLE AND RADIOACTIVE BEAMS

In the last few years a variety of radioactive species were accelerated at ATLAS. Studying reactions involving these exotic nuclei has 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), $^{8}$B ($t_{1/2}$ = 770 ms), and $^{14}$O ($t_{1/2}$ = 70.6 s)]. The reconfigured radioactive ion production beam line, which now includes a large-bore solenoid, was tested and successfully used in experiments. In addition to the ATLAS projects with accelerated radioactive beams, several more conventional heavy-ion reaction studies produced data on nuclei critical to the rp-nucleosynthesis path. A significant opportunity lies in studying compound nuclear states near the (p,γ) reaction threshold, populated with near-barrier fusion of heavy ions, and spectroscopically investigated using Gammasphere. This technique seems to have many possibilities, as it is excellent for precisely determining the excitation energy of levels and their angular momentum properties

## a.1. Measurement of the $^{8}$B Neutrino Spectrum with a New Technique

(K. E. Rehm, C. L. Jiang, I. Ahmad, J. Greene, A. Heinz, D. Henderson, R. V. F. Janssens, E. F. Moore, G. Mukherjee, R. C. Pardo, T. Pennington, G. Savard, J. P. Schiffer, D. Seweryniak, G. Zinkann, M. Paul,* W. Winter,† and S. J. Freedman†)

The neutrino spectrum from $^{8}$B decay is a crucial ingredient in interpreting the data from solar neutrinos obtained in recent experiments by the SNO and Superkamiokande collaborations. Because of its high end point energy a direct measurement of the beta decay spectrum has so far been only performed once.[1] Since the beta decay populates a broad $2^+$ state in $^{8}$Be which subsequently decays into two α particles the shape of the neutrino spectrum can be more easily inferred from a measurement of the alpha-particle spectrum following the decay. Several measurements of the α–decay spectrum have been performed in the past.[2] These experiments disagree, however, in the critical low-energy region that influences the highest energy neutrinos.

A new technique has been developed at the ATLAS accelerator to accurately measure this spectrum. A beam of 28-MeV $^{8}$B nuclei ($T_{1/2}$ = 0.77 s) was produced by bombarding a $^{3}$He filled gas cell with an intense $^{6}$Li beam. $^{8}$B nuclei with this energy were separated from the primary beam with a bending magnet and transported to the focal plane of the Enge split pole magnetic spectrograph where they were implanted into a 91-μm-thick Si detector cooled to -5°C. A measurement cycle consisted of a 1.5 s period of $^{8}$B implantation, followed by 1.5 s of decay counting during which the $^{6}$Li beam was stopped near the accelerator.

The advantage of the implantation method, in comparison to the earlier experiments,[2,3] is that both alpha particles are detected in the same detector and systematic effects due to energy loss in catcher foils and in dead layers of the detector are eliminated. Since the α decay of the $2^+$ state in $^{8}$Be is preceded by a $\beta^+$ decay from $^{8}$B, the energy spectrum is shifted towards higher energies because of β-α summing in the Si detector. To minimize this effect a thin plastic scintillator was mounted directly behind the Si detector. A coincidence measurement restricted the β's to be emitted within a ~40° cone which limits the energy shift to less than ~20 keV.

To calibrate the detector, α particles from the decay of $^{20}$Na, produced and implanted with the same technique, were used. In this case about 1/5 of the decay energy is carried by the $^{16}$O recoil, so a correction for the pulse height defect of oxygen (relative to α particles) had to be applied. This correction is believed to be accurate to ≤10 keV. Details of the production method of the $^{20}$Na beam are described in section a.5. In addition, external

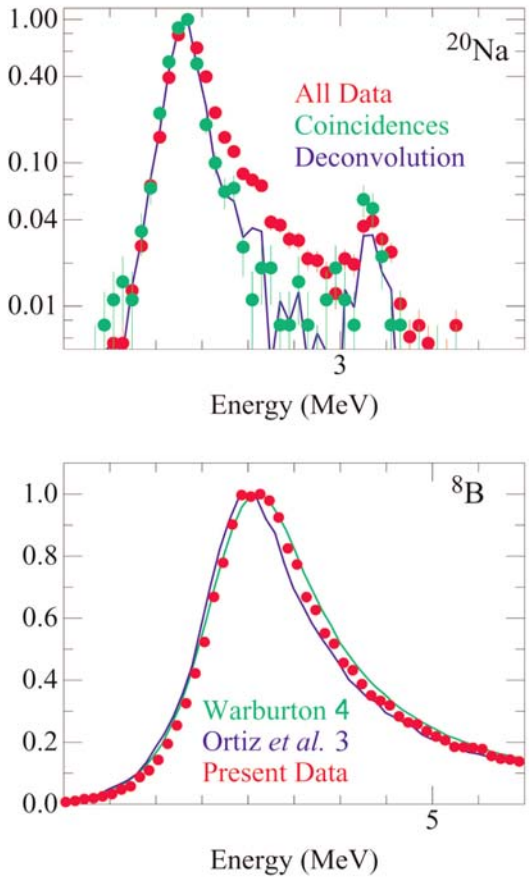


*Fig. I-1. (a) Alpha calibration spectrum from the decay of $^{20}$Na nuclei, implanted into a 91 μm thick Si detector. The solid line corresponds to the deconvolution of the singles data. (b) Alpha spectrum measured from the decay of implanted $^{8}$B nuclei, compared to previous measurements (3,4).*

α-particle sources ($^{228}$Th, $^{148}$Gd) were also used. For this part of the calibration the energy loss of the α particles in the source material and the dead layer of the detector was measured.

Figure I-1(a) shows part of the energy spectrum from $^{20}$Na particles implanted into the Si detector, measured in singles (red) and in silicon-scintillator coincidences (green). The high energy tail which is much reduced in the coincidence spectrum is the result of the α - $\beta^{+}$ summing mentioned above. The blue line, which is the result of a deconvolution of the singles data using the electron energy deposition from a simulation of the added pulse-height spectrum from electrons, is in excellent agreement with the experimental coincidence spectrum.

The α spectrum from the decay of $^{8}$B, deconvoluted with the detector response is presented in Fig. I-1(b). It is found to be in reasonable agreement with the results obtained by Warburton[4] (see green line) though somewhat narrower, but is shifted towards higher energies with respect to the spectrum by Ortiz *et al.*[3] (blue line).

*Hebrew University, Jerusalem, Israel, †Lawrence Berkeley National Laboratory

[1]J. Napolitano, S. J. Freedman and J. Camp, Phys. Rev. **C36**, 298 (1987).
[2]J. N. Bahcall, E. Lisi, D. E. Alburger, L. DeBraekeleer, S. J. Freedman and J. Napolitano, Phys. Rev. **C54**, 411 (1996).
[3]C. E. Ortiz, A. Garcia, R. A. Waltz, M. Bhattacharya and A. K. Komives, Phys. Rev. Lett. **85**, 2909 (2000).
[4]E. K. Warburton, Phys. Rev. **C33**, 303(1986).

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

(K. E. Rehm, A. Wuosmaa, C. L. Jiang, J. Greene, A. Heinz, D. Henderson, R. V. F. Janssens, G. Mukherjee, R. C. Pardo, T. Pennington, J. P. Schiffer, R. H. Siemssen, M. Paul,* L. Jisonna,† and R. E. Segel†)

In the CNO cycle, which occurs in stars somewhat heavier than the sun, the rate of energy production is limited by the slow β-decays of $^{14,15}$O ($T_{1/2}$ = 70.6 and 123 s, respectively). These waiting points can be bypassed at higher temperatures by proton and α induced reactions on these nuclei, which results in a strong increase of the energy production as well as in a breakout from the hot CNO cycle into the rapid proton capture (*rp*) process -- a sequence of (p,γ) reactions and β decays producing nuclei above mass 20. The reaction Q-values in this mass region are such that once nuclei heavier than $^{19}$Ne have been formed no reaction sequence can recycle the nuclei back into CNO material. Among the three possible breakout paths: $^{15}$O(α,γ)$^{19}$Ne, $^{18}$F(p,γ)$^{19}$Ne and $^{18}$Ne(α,p)$^{21}$Na, the first reaction is thought to be the most important.

A direct measurement of the $^{15}$O(α,γ)$^{19}$Ne reaction which has an estimated cross section of ~100 pb is presently not possible because it requires a very intense $^{15}$O beam. For this reason, only indirect measurements have been performed so far. The first levels in $^{19}$Ne above the (α,γ) threshold at 3.534 MeV is a $3/2^+$ state at 4.033 MeV followed by $9/2^-$ and $7/2^-$ levels at 4.140 and 4.197 MeV, respectively. Because of the low angular momentum transfer (Δl = 1) and the low excitation energy, the $3/2^+$ level has the largest influence on the (α,γ) reaction at typical nova temperatures.

In indirect measurements of the $3/2^+$ state in $^{19}$Ne the level is populated in a transfer reaction and the branching ratio of the subsequent decay of $^{19}$Ne into an α–particle and $^{15}$O is determined by detecting the decay products. While earlier attempts[1] used reactions in normal kinematics, e.g. bombarding a $^{19}$F target with a $^3$He beam, a large increase in detection efficiency can be achieved by using inverse kinematics i.e. bombarding a deuterium or $^3$He target with a F or Ne beam. Under these conditions the high energy $^{19}$Ne nuclei produced in the reaction are focused into a small forward cone which simplifies their detection and identification.

Because $CD_2$ is a readily available solid deuterium target we have studied the use of the d($^{20}$Ne,t)$^{19}$Ne reaction to populate the 4.033-MeV state in $^{19}$Ne. However, it was found that the spectroscopic factor for this state is small resulting in cross sections at forward angles of only ~ 20 - 30 μb/sr. We have therefore investigated the use of other transfer reactions. The most promising among them is the $^3$He($^{20}$Ne,α)$^{19}$Ne reaction.

In a first test experiment we have used a 100-MeV $^{20}$Ne beam from ATLAS to populate the 4.033-MeV state in $^{19}$Ne. For this reaction, the α-particles associated with small center-of-mass angles have very low energies in the laboratory system (typically ≤1 MeV). Consequently, we have used α-particles from backward angles in the center-of-mass, which are emitted in the angular range $\theta_{lab}$ = 6 - 15° with energies of about 50 MeV. The coincident $^{19}$Ne reaction products have an energy of about 50 MeV and are emitted into the laboratory angular range $\theta_{lab}$ = 2.5 - 7°.

The $^3$He target consisted of a 1.5-mm long gas cell with two 1.3-mg/cm$^2$ titanium windows, filled with 750 mbar of $^3$He and cooled to $LN_2$ temperatures resulting in an areal density of about 50 μg/cm$^2$.

The α-particles from the ($^3$He,α) reaction were detected in a 500 μ thick annular Si strip detector. The detector was segmented in the front into 16 1.5 mm wide rings covering the angle range $\theta_{lab}$ = 10 - 20° and 16 wedges, each with an opening angle of 22.5° in the back.

The coincident $^{19}$Ne and $^{15}$O particles were separated from the incident $^{20}$Ne beam with the Enge Split Pole magnetic spectrograph and identified in the focal plane in a hybrid position sensitive parallel-plate-avalanche-counter (PPAC) ionization chamber (IC) detector system. Two charge states of the outgoing particles (q = 8,9 for $^{19}$Ne and q = 7,8 for $^{15}$O) were detected simultaneously in the focal plane detector. With this setup very clean particle identification was achieved even for processes with very small cross sections.

The upper part of Fig. I-2 presents Q-value spectra measured in the Si detector for α particles which are in coincidence with $^{19}$Ne (open circles) and $^{15}$O particles (solid points) identified with respect to mass and Z in the split-pole spectrograph. The lower part of Fig. I-2 gives the ratio of the cross sections (corrected for detection efficiencies) which corresponds to the branching ratio $\Gamma_\alpha/\Gamma_\gamma$.

In this first test run the Q-value resolution was limited by the beam spot and the strip size of the Si detector to about 600 keV. With a higher granularity Si detector and improved geometry we should be able to improve the resolution to less than 200 keV. This will allow us to measure branching ratios below $10^{-3}$. The technique will also be useful for measurements of other branching ratios which are of interest to nuclear astrophysics.

*Hebrew University, Jerusalem, Israel, †Northwestern University

[1]P. V. Magnus, M. S. Smith, A. J. Howard, P. D. Parker and A. E. Champagne, Nucl. Phys. **A506**, 332 (1990).

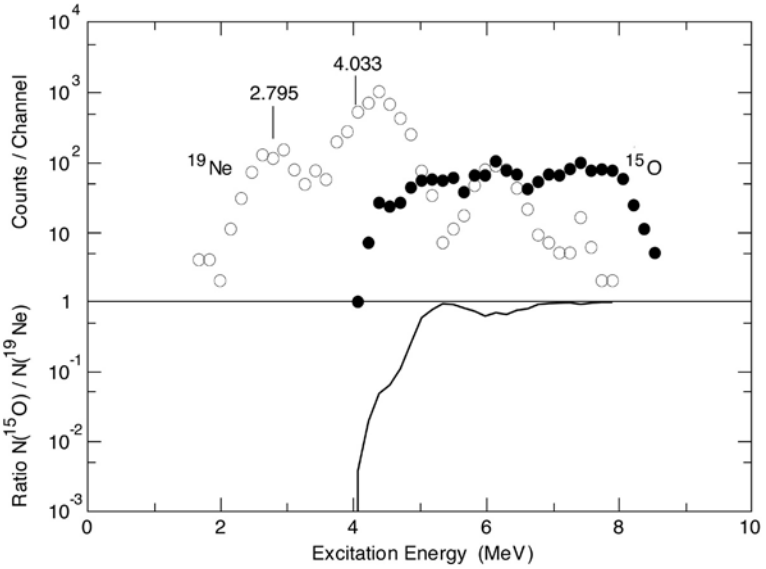


*Fig. I-2. Top: Q-value spectra for α particles in coincidence with $^{19}$Ne or $^{15}$O identified with respect to mass and Z in the split-pole spectrograph. Bottom: Branching ratio $\Gamma_\alpha/\Gamma_\gamma$ obtained from the Q-value spectra which were corrected for detection efficiency.*

## a.3. Study of the $^{12}$C($^{11}$C,α)$^{19}$Ne Reaction

(A. H. Wuosmaa, K. E. Rehm, J. Caggiano,* P. Collon, A. Heinz, D. Jenkins,† R. V. F. Janssens, C. L. Jiang, C. J. Lister, J. P. Schiffer, F. Guo,‡ P. McMahan,‡ J. Powell,‡ M. Rowe,‡ and I Wiedenhöver§)

The astrophysical importanace of the $^{15}$O(α,γ)$^{19}$Ne reaction has encouraged us to try several alternative indirect approaches to measuring the breakup of the $J^\pi$ = 3/2+ 4.033-MeV state in $^{19}$Ne. $^{19}$Ne is of crucial importance in the production of elements heavier than C, N, and O through its role as a breakout path from the CNO cycle. Briefly, the CNO cycle, which produces energy through a series of proton-capture, $\beta^+$ decay, and (p,α) reactions, cycles through isotopes of carbon, nitrogen and oxygen, beginning and ending with $^{12}$C. In the appropriate environment, however, it is possible to exit the CNO cycle via the alpha-capture reaction $^{15}$O(α,γ)$^{19}$Ne. This alpha capture proceeds dominantly through a few near-threshold, low-spin levels in $^{19}$Ne, the most important of which is the $3/2^+$ state at an excitation energy of 4.033 MeV. The fraction of nuclei leaving the CNO cycle is thus determined by the competition between alpha, and gamma decay of this state; alpha decay leads back to the CNO cycle, whereas gamma-decay exits the cycle producing $^{19}$Ne. The single most important piece of nuclear physics data relevant to this issue is the branching ratio for alpha decay of the 4.033-MeV $3/2^+$ state in $^{19}$Ne, currently thought to be approximately B(α) ~$10^{-3}$ to $10^{-4}$.

A number of attempts have been made to isolate this quantity; none have yet been successful. Typically, $^{19}$Ne has been produced by few nucleon transfer reactions, such as $^{20}$Ne(d,t)$^{19}$Ne, or the kinematic inverse d($^{20}$Ne,t)$^{19}$Ne, or $^{19}$F($^3$He,t)$^{19}$Ne. Such methods have the advantage that the state of interest may be populated with reasonable cross section (>10 s of μb/sr). Efforts to observe the subsequent alpha decay, in the inverse kinematic regime benefit from strong kinematic focusing of the reaction products but can be hampered by high beam-related backgrounds. All

efforts to study this alpha decay suffer from the complex level scheme of $^{19}$Ne at low excitation energy, which contains a 9/2$^-$ state just ~100 keV away at Ex = 4.140 MeV.

We have performed a test experiment to produce $^{19}$Ne through an alternative method via the $^{12}$C($^{11}$C,α)$^{19}$Ne reaction using a 33 MeV $^{11}$C beam from the BEARS facility at LBNL. Alpha particles from the $^{12}$C($^{11}$C,α)$^{19}$Ne reaction and elastically scattered $^{11}$C ions were detected in two Position-Sensitive Strip Detectors (PSSDs) placed on either side of the beam. Two surface barrier detectors at small angles monitored the quality and intensity of the $^{11}$C beam. The beam intensity on target was estimated to be between 1 and $2 \times 10^8$ particles per second. Figure I-3a shows a representative $^{11}$C + $^{197}$Au elastic scattering Q-value spectrum, and Fig. I-3b displays the Q-value spectrum for the $^{12}$C($^{11}$C,α)$^{19}$Ne reaction. The lines in Fig. I-3b indicate the positions of various groups of states in $^{19}$Ne. The estimated cross section for this reaction for the ground-state group is approximately 100 μb/sr.

A number of improvements in terms of collimation, beam quality, and detection efficiency must be explored before it can be known whether this method can successfully compete with alternative methods of studying the very weak alpha-decay branch of the 4.033-MeV state in $^{19}$Ne. It is clear from this test, however, that with the current beam intensities available from BEARS, light-heavy-ion reactions of this type are within reach of current experimental methods.

*Argonne National Laboratory and Yale University, †Argonne National Laboratory and University of Pennsylvania, ‡Lawrence Berkeley National Laboratory, §¶Florida State University

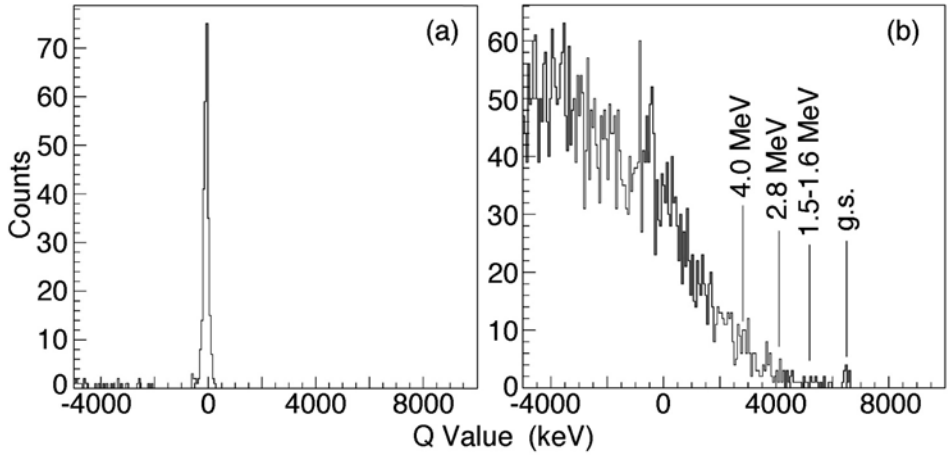


*Fig. I-3. (a) Q-Value spectrum for $^{11}$C + $^{197}$Au elastic scattering. (b) Q-Value spectrum for the $^{12}$C($^{11}$C,α)$^{19}$Ne reaction. The vertical lines indicate the positions of various groups of excited states in $^{19}$Ne.*

## a.4. Observation of γ-Ray Transitions in the rp Breakout Nucleus $^{20}$Na

(D. Seweryniak, A. Heinz, R. V. F. Janssens, T. L. Khoo, H. Mahmud, E. Rehm, P. J. Woods,* F. Sarazin,* J. Goerres,† A. Aprahamian,† M. Shawcross,† J. Shergur,‡ M. Wiescher,† and A. Woehr‡)

The reaction sequence $^{15}$O(α,γ) $^{19}$Ne(p,γ)$^{20}$Na is thought to be the dominated nucleosynthetic mechanism responsible for breakout from the hot CNO cycles into the rp-process. However, neither of these reaction rates have yet been determined. One of the key uncertainties in the $^{19}$Ne(p,γ)$^{20}$Na reaction is the structure of the resonance states in $^{20}$Na at an excitation energy of about 2.6 MeV near reaction threshold, which are thought to dominate the astrophysical reaction rate.

An in-beam γ-ray experiment was performed using the Argonne Fragment Mass Analyzer to study γ-decaying states in $^{20}$Na. The $^{10}$B($^{12}$C, 2n) reaction was used to populate excited states in $^{20}$Na. Gamma rays were detected using 2 Ge clover detectors and a 4π array of

BGO scintillators placed around the target. Recoiling reaction products were separated from the beam and dispersed according to their mass over charge state ratio in the FMA. Mass-20 residues, selected by the slits at the focal plane of the FMA, were stopped in an ionization chamber and their atomic number was deduced based on the energy loss and energy measurement. Several γ-ray transitions were assigned to $^{20}$Na. Figure I-4 shows the spectrum of γ rays detected in the Ge detectors and associated with $^{20}$Na. The proposed preliminary partial $^{20}$Na level scheme is shown in Fig. I-5. The energies of the first two excited states are in agreement with results of previous transfer reaction studies. The state deexcited by the 1029 keV γ-ray was seen for the first time. Evidence for other transitions feeding the 798-keV state, including a possible transition deexciting the 2650 keV state, is currently under evaluation.

*University of Edinburgh, United Kingdom, †University of Notre Dame, ‡University of Maryland

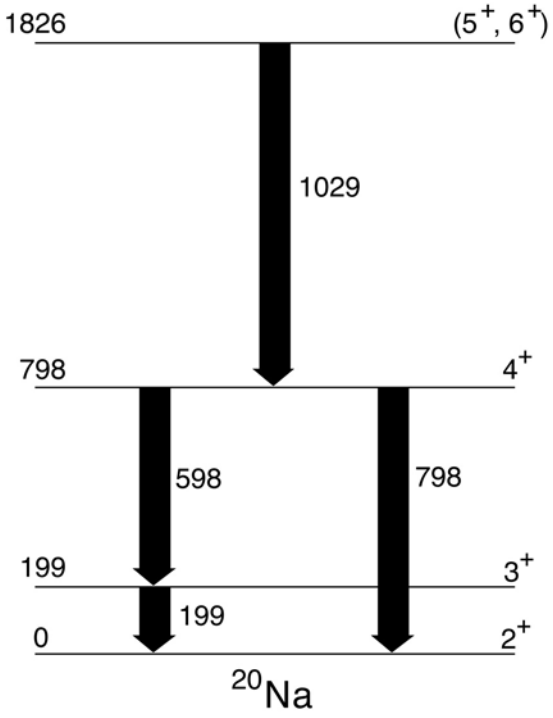


*Fig. I-4. Preliminary partial $^{20}$Na level scheme.*

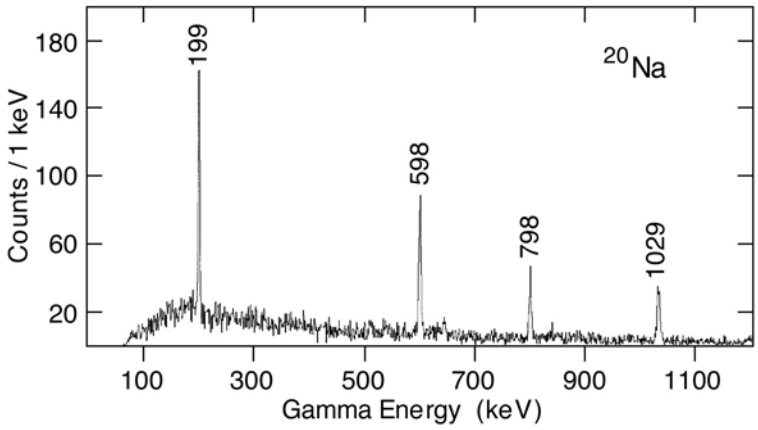


*Fig. I-5. Ge γ-ray spectrum tagged by $^{20}$Na residues selected in the FMA.*

## a.5. Production of a $^{20}$Na Beam Via the In-Flight Technique

(K. E. Rehm, J. Greene, A. Heinz, D. Henderson, R. V. F. Janssens, C. L. Jiang, E. F. Moore, R. C. Pardo, T. Pennington, J. P. Schiffer, G. Zinkann, M. Paul,* and W. Winter†)

For our study of the $^{8}$B neutrino spectrum using the implantation technique (see contribution a.1) a calibration source with $\alpha$-energies in the range of 2 - 5 MeV was required. In order to implant the nuclei sufficiently deep into a Si detector they needed to be available as a beam and should have a half-life of about 1 sec. The best candidate decays were found to be $^{20}$Na which decays via $\beta^{+}$-emission to high-lying states in $^{20}$Ne which then subsequently decay into $\alpha + {}^{16}$O.

The optimum reaction to produce $^{20}$Na would be $^{20}$Ne(p,n)$^{20}$Na. However, because of its negative Q-value of Q = -14.66 MeV it requires a $^{20}$Ne beam of at least 300 MeV in order to produce it with sufficient intensity via the inverse p($^{20}$Ne,$^{20}$Na)n reaction. This cannot be done with the present resonator configuration at ATLAS. Since for a calibration experiment even a low intensity beam is sufficient we have chosen the $^{3}$He($^{19}$F,$^{20}$Na)2n reaction, which has a Q-value of only -9.54 MeV.

A gas cell, filled with 700 mbar of $^{3}$He at T = 93 K was bombarded with a 200-MeV $^{19}$F beam from the ATLAS accelerator. After optimizing the beam transport system downstream of the production target a rate of 10 $^{20}$Na/(sec pnA of incident beam) was measured in the scattering chamber of the magnetic spectrograph. Although the intensity is considerably smaller than the one obtained for beams produced via (p,n) or (d,n) reactions, it was nevertheless sufficient to perform an in-situ calibration of the Si detector used in the $^{8}$B experiment.

After treating all ATLAS resonators with the new high-pressure rinse technique it can be expected that $^{20}$Ne beams with sufficient energy will be available to produce $^{20}$Na via the more favorable (p,n) reaction which would lead to a 100 fold increase in beam intensity for producing this proton drip line nucleus.

*Hebrew University, Jerusalem, Israel, †University of California, Berkeley

## a.6. Ne, Na and Al Burning in Astrophysically Important (p,γ) Reactions

(C. J. Lister, M. P. Carpenter, G. Mukherjee, K. E. Rehm, A. H. Wuosmaa, D. G. Jenkins,* B. Truett,† B. R. Fulton,‡ J. Pearson,‡ R. A. Kaye,† M. Freer,§ A. O. Macchiavelli,¶ P. Fallon,¶ and A. Görgen¶)

The breakout from the CNO burning cycle that is needed to produce heavier elements is through thermonuclear processes involving (p,γ) and (α,γ) capture reactions. The synthesis sites need to be hydrogen and helium rich, and are thought to occur in massive stars (T ~ $10^{8}$ K) or in nova explosions (T > $10^{9}$ K). The reactions rates are sufficiently high that many of the target nuclei are unstable, as they undergo new reactions faster than they can decay back to stability. The reaction rates are dominated by the properties of a few levels near the reaction threshold. Locating these key states and their quantum numbers is crucial in establishing the reaction rates, which, after suitable modeling, can tell us a great deal about both the synthesis sites and the final isotopic abundances. For stable nuclei, the (p,γ) and (α,γ) capture rates can be studied directly in the laboratory. The particle unbound states of interest are those with relatively large gamma branching ratios ($\Gamma_{\gamma}/\Gamma_{tot}$). For unstable nuclei, which are very important in this problem, the issue is more challenging and a variety of ingenious experimental approaches have been used to infer reaction rates. These include fabrication of radioactive targets, using direct reactions like ($^{3}$He,d), producing radioactive beams then studying kinematically inverse reactions, and invoking isospin symmetry to infer the positions and properties of the key states.

Big arrays, like Gammasphere, can shed new light on this interesting problem. Using near-barrier heavy-ion reactions, a broad range of states in the excitation region of interest can be populated. As only γ-rays are measured, the experiments are most sensitive to the key states of interest, those with relatively large γ-branches. The excitation energy of the states can be determined to a few keV, angular distributions can constrain spins, lifetimes can determine total widths, and γ–γ coincidences can resolve close-lying doublets. These data, when taken in conjunction with information from reaction studies (which can measure the far-stronger charged-particle breakup branches), can strongly constrain the problem. We have used the

$^{12}C(^{12}C,n)^{23}Mg$, $^{12}C(^{12}C,p)^{23}Na$ and $^{12}C(^{16}O,n)^{27}Si$ reactions to investigate the $^{22}Na(p,\gamma)^{23}Mg$, $^{22}Ne(p,\gamma)^{23}Na$ and $^{26}Al(p,\gamma)^{27}Si$ sodium, neon, and aluminum burning processes. The experiments used intense (up to 150 pna) beams of low energy (20-30 MeV) carbon and oxygen from the ATLAS accelerator at ANL and the 88" cyclotron at LBNL, impinging on thin, (50-100 μg/cm$^2$) isotopically enriched carbon targets. Many results were obtained for the astrophysically critical states, and some new states found. The impact of these new measurements has been evaluated by recalculating the reaction rates as a function of temperature. The predicted reaction rates have been redetermined. In some places they have changed by orders of magnitude and the uncertainties are greatly reduced. It appears that this technique is quite general and many similar problems might be addressed this way. The A = 20 case is discussed in section a.4. of this chapter. One example is shown in Fig. I-6, where the recalculated reaction rate for $^{22}Na(p,\gamma)^{23}Mg$ is shown as a function of $T_9$, the temperature in billions of degrees. Both the reaction rate envelope and its uncertainty are now more tightly defined.

*University of Liverpool, United Kingdom, †Purdue University Calumet, ‡University of York, United Kingdom, §University of Birmingham, United Kingdom, ¶Lawrence Berkeley National Laboratory

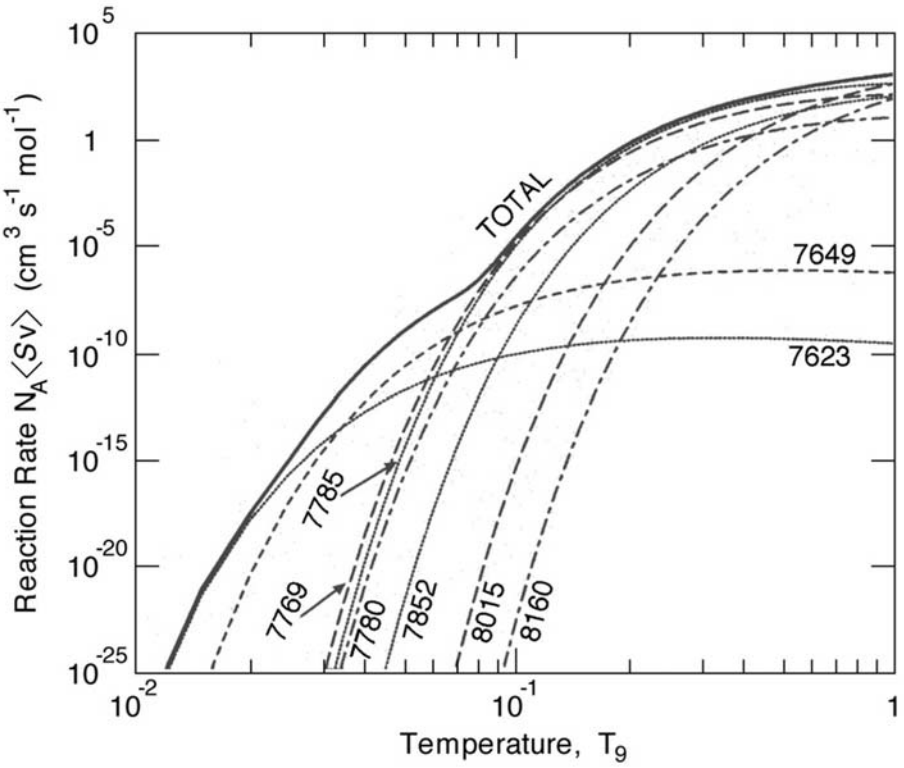


*Fig. I-6. The $^{22}Na(p,\gamma)^{23}Mg$ reaction rate recalculated with the new spectroscopic information gathered from the present Gammasphere study. At some temperatures the new reaction rates are more than two orders of magnitude different from the current literature estimates.*

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

We have continued the measurement of $^{44}$Ti half-life at Argonne and Jerusalem, which we started in March 1992, with the aim of improving the precision in the half-life value. The half-life determined from 5 years decay was published[1] in 1998. Now we have data for about 10 years decay; the last set of spectra was measured in December 2001. The half-life is being measured by recording spectra of a mixed source of $^{44}$Ti and $^{60}$Co with a 25% germanium detector at regular intervals. At Argonne the spectra of the mixed source

are being measured at two source-to-detector distances of 5.2 cm and 10.2 cm. The half life values were obtained by analyzing the 1157/1173 and 1157/1333 ratios of the $^{44}$Ti and $^{60}$Co gamma rays. The preliminary analysis shows that the half-life of 59.2 ± 0.6 yr reported in our 1998 article is still correct within the quoted uncertainty. The decay of the 1157/1173 ratio measured for a source-to-detector distance of 5.2 cm is displayed in Fig. I-7. We plan to measure one more set of spectra and then analyze and publish the result.

*University of Vienna, Austria, †Hebrew University, Jerusalem, Israel

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

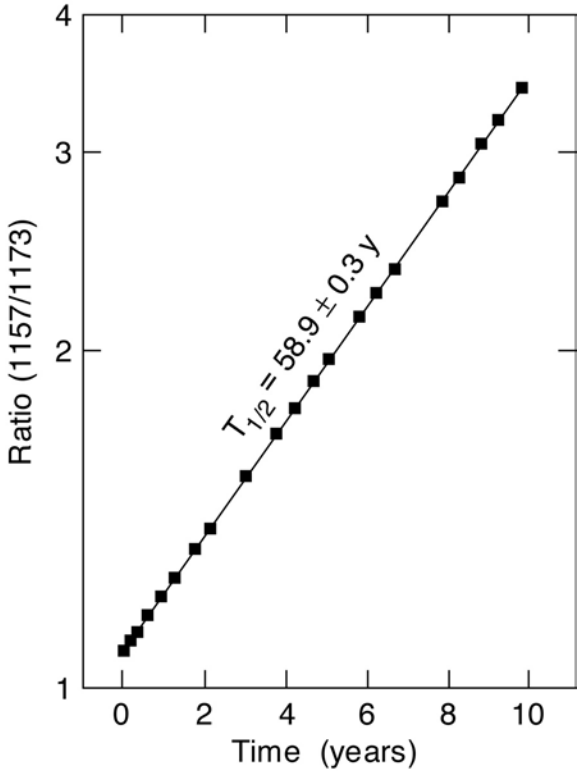


*Fig. I-7. Semilogarithmic plot of the ratio of counts in the 1157-keV peak of $^{44}$Ti and 1173-keV peak of $^{60}$Co against decay time. The measurements were performed at ANL using a mixed source of $^{44}$Ti and $^{60}$Co.*

## a.8. The $^{40}$Ca(α,γ)$^{44}$Ti Reaction Measured by Counting of $^{44}$Ti Residual Nuclei

(I. Ahmad, J. Caggiano, J. Greene, A. Heinz, D. Henderson, R. V. F. Janssens, C. L. Jiang, R. C. Pardo, T. Pennington, K. E. Rehm, G. Savard, R. Vondrasek, I. Wiedenhöver, M. Paul,* C. Feldstein,* D. Berkovits,† C. Bordeanu,‡ J. Goerres,§ M. Hass,‡ S. K. Hui,* S. Jiang,* G. Verri,* and M. Wiescher§)

The importance of $^{44}$Ti production in supernova nucleosynthesis was emphasized in the last years by the measurement of the 1.157 MeV light of supernova remnants by γ-ray astronomy.[1,2,3] Produced in the decay of 59.2-yrs $^{44}$Ti ground state to $^{44}$Sc and stable-$^{44}$Ca isobars, it clearly indicates fresh nucleosynthesis of $^{44}$Ti in these sites and confirmed the hypothesis of a type-II supernova in the case of the Cassiopaea A remnant.[4,5] Among the many production and destruction nuclear reactions that bear on the net $^{44}$Ti yield in the supernova environment,[6] the α capture on $^{40}$Ca stands out due to the importance of the α-rich freezeout phase conjectured by astrophysical models.

The $^{40}$Ca(α.γ)$^{44}$Ti reaction has been studied only by prompt γ-ray spectroscopy, yielding values for the resonance strengths and partial γ widths of excited levels in $^{44}$Ti for $E_{cm}$ > 7.6 MeV.[7,8,9] We propose here

the counting of $^{44}$Ti ground state nuclei produced in a laboratory activation experiment of $^{40}$Ca on He. The recoiling $^{44}$Ti ions are collected in a catcher, chemically separated using a $^{nat}$Ti carrier and directly counted by accelerator mass spectrometry (AMS). Unlike the prompt γ-ray technique, this method yields values which are independent of the γ decay scheme and γ branching ratios in the $^{44}$Ti compound nucleus. The AMS measurement of the $^{44}$Ti/Ti ratio, together with the known amount of Ti carrier added, determine the number of $^{44}$Ti nuclei produced in the activation, independent of any chemical yield or accelerator-transmission efficiency.

A ~1 eμA beam of $^{40}Ca^{11+}$ ions from the ECR-ATLAS system bombarded a high-purity-He filled chamber (12 Torr); a 1.5-mg/cm$^2$ Ni rotating window was used to contain the gas and dissipate the beam power loss. The mean laboratory beam energy in the He gas was selected to populate a strong resonance at $E_{cm}$ = 1.13 MeV/n. Recoiling $^{44}$Ti nuclei were implanted in a water-cooled Cu catcher. A small Bragg chamber monitored continuously ions scattered off the entrance Ni window. Correction was made for a 8.5% contamination of $^{40}$Ar in the incident beam; these ions cannot produce $^{44}$Ti in the He target. After irradiation (11 pmC) and radioactive cooling, a thickness of 10 mg/cm$^2$ was etched from the Cu catcher surface by an acid solution containing 3 mg $^{nat}Ti^{4+}$. After chemical separation of Ti and purification from Ca contamination, the ~4 mg sample of $TiO_2$ obtained was inserted in the cathode holder of the high-intensity Cs sputter source of our AMS system at the Weizmann Institute. A group of 20 $^{44}$Ti counts was clearly identified and discriminated (Fig. I-7A) from the main background of $^{44}$Ca (chemical impurity). An off-resonance activation, an activation made on Ar gas instead of He and the measurement of an unactivated Cu catcher lead to 0 or 1 $^{44}$Ti count in the same conditions. The resonance strength measured by the on-resonance activation is 7.4 ± 2.5 eV in excellent agreement with previous prompt-γ measurements for two close-by levels in $^{44}$Ti. We hope to extend now the technique to the lower energy range important for supernova nucleosynthesis.

*Hebrew University, Jerusalem, Israel, †Soreq NRC, Yavne, Israel, ‡Weizmann Institute, Rehovot, Israel, §University of Notre Dame

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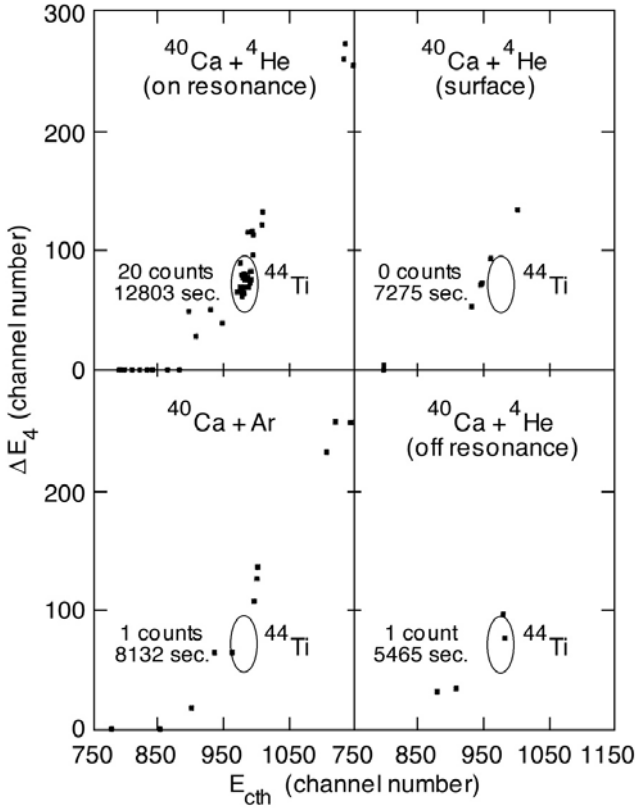


*Fig. I-7A. Two-dimensional identification spectra of residual energy ($\Delta E_4$) versus energy ($E_{cth}$); the events are first filtered through a software window on energy-loss parameters $\Delta E_1$ and $\Delta E_2$ to eliminate most of the $^{44}$Ca background. The spectra are measured for Ti extracted from Cu catchers after He activation on resonance ($E_{cm}$ = 4.0 - 4.2 MeV; upper left) and off resonance ($E_{cm}$ = 3.8 - 4.0 MeV; lower right) and a background run (activation on Ar gas; lower left). The upper right spectrum was obtained from the etching of the surface of the on-resonance Cu catcher; the absence of $^{44}$Ti atoms shows that $^{44}$Ti was implanted in Cu at a depth ≥1 mg/cm$^{-2}$).*