I. HEAVY-ION NUCLEAR PHYSICS RESEARCH

OVERVIEW

The Heavy-Ion program in the Argonne Physics Division addresses key questions about the structure and dynamics of the nuclear many-body system. Nuclear structure and reactions are studied in collisions between complex nuclei with heavy-ion beams mostly from the Argonne Tandem-Linac Accelerator (ATLAS), a national heavy-ion users facility. Some important studies are performed at forefront facilities elsewhere. The major thrusts of this program are three-fold: a) the understanding of the nucleus as a many-body system built of protons and neutrons and governed by the strong force, b) the exploration of the origin of the chemical elements and their role in shaping the reactions that occur in the cataclysmic events of the cosmos and c) tests of the limits of validity of the Standard Model, the fundamental theory that currently best represents our understanding of the laws and fundamental symmetries of Nature. The specific current research topics include the development and acceleration of short-lived nuclei and their use in measurements of cross-sections of astrophysics interests as well as in nuclear structure and reaction dynamics studies; the production and study of nuclei at the very limits of stability, in particular the discovery of new proton emitters near the drip line and the study of the level structure of very heavy elements ($Z > 100$); the study of exotic nuclear shapes, including superdeformation; the delineation of the essential parameters governing dynamics of reactions between heavy nuclei such as fusion, fission, transfer and deep inelastic reactions; tests of current descriptions of the weak force. Smaller scale efforts complementary to the main research program focus on the behavior of cooled ions confined in storage rings and ions traps, and on the study of collisions between heavy ions at relativistic energies. These efforts are based on forefront instrumentation available at ATLAS which includes Gammasphere, the Fragment Mass Analyzer (both systems are also used in combination), the Canadian Penning Trap, and exploit the unique capabilities of the accelerator to produce radioactive beams either through reactions in a production target or directly from the ion source. Participation to the PHOBOS detector construction is at the core of the research with relativistic heavy ions.

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

- Develop and utilize short-lived nuclear beams (1) to measure reactions of astrophysics interest ($^{17,18}F$, ^{21}Na and the break-out of the hot CNO cycle, ^{25}Al, ^{44}Ti and ^{56}Ni and the rp process), (2) to study the properties of proton-rich nuclei (single-particle states near the unstable doubly-magic nucleus ^{56}Ni), and (3) to investigate aspects of reaction dynamics (the impact of weakly bound states on fusion).

- Discover new isotopes and determine the properties of these nuclei at the limits of proton-stability by measuring (1) groundstate quantum numbers, (2) particle decay modes (proton, alpha and beta decay) and (3) gamma decay of excited states taking advantage of the resolving power of Gammasphere and the selectivity offered by the Fragment Mass Analyzer (FMA).

- Study the importance of shell effects on nuclear structure as a function of mass, excitation energy and spin. In particular, understand the properties of heavy nuclei ($Z > 82$), of superdeformed nuclei, and of light ($A < 30$) nuclei (in the regime where particle and gamma decay compete) by comprehensive measurements with the highest detection sensitivity (Gammasphere).

- Determine time scales of dissipation processes in nuclei through the characterization of the gamma decay of giant dipole resonances (utilizing the LEPPEX array of BaF_2 detectors) with mass or angular momentum selection.

- Measure with high precision nuclear masses with the CPT, in particular the mass of super-allowed 0^+ to 0^+ beta emitters ($50 < A < 100$). These mass determinations have a direct impact on the determination of the fundamental weak vector coupling constant and the unitarity test of the top row of the Cabbibo-Kobayashi-Maskawa matrix.

- Use the high quality beams of ATLAS to pursue unique applications with energetic heavy-ion beams such as defects in high Tc superconductors, and accelerator mass spectrometry of heavy (transactinide) radioisotopes.

- Understand the behavior of nuclear matter at high density by exploring collisions between relativistic heavy ions. Studies focus on particle production, phenomena associated with collective flow and in-medium modification of meson masses.

A. EXPERIMENTS WITH SECONDARY BEAMS

Over the last few years, a number of secondary (e.g. radioactive) beams of short-lived nuclei have been produced and accelerated at ATLAS. So far, beams of ^{18}F ($t_{1/2}$ = 110 m), ^{56}Ni ($t_{1/2}$= 61 d), ^{56}Co ($t_{1/2}$ = 77d), ^{44}Ti ($t_{1/2}$ = 60 y) have been produced and accelerated via the so-called two-accelerators method where beam material is being produced at another accelerator, and subsequently transformed into a cone for the SNICS source of the tandem. Beams of shorter lived isotopes have been produced directly at ATLAS with the in-flight technique where a primary beam undergoes a reaction in a gas cell. These beams are: ^{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 experiments being performed cover issues of interest in nuclear astrophysics and in nuclear structure. This section also contains a description of efforts by members of the Heavy-Ion group towards the Rare Isotope Accelerator (RIA) described in detail elsewhere in this report.

a.1. Spin Determination of States in ^{18}Ne via the ^{17}F(p,p)^{17}F Reaction

(B. Harss, J. Caggiano, P. Collon, J. P. Greene, D. Henderson, A. Heinz, R. V. F. Janssens, C. L. Jiang, J. Nolen, R. C. Pardo, T. Pennington, K. E. Rehm, J. P. Schiffer, R. H. Siemssen, I. Wiedenhoever, M. Paul,* R. E. Segel,† and P. Parker‡)

Our measurements of the ^{17}F(p,α)^{14}O reaction (see annual report 1998) identified several new levels in ^{18}Ne which contribute to the breakout from the hot CNO cycle via the ^{14}O(α,p)^{17}F reaction. The angular distributions of the (p,α) reactions, however, are not very sensitive to the angular momentum transfer and therefore for some of the states no definite spin assignment could be made. Elastic proton scattering on ^{17}F, on the other hand, is expected to provide a better signature between positive and negative parity states. We have therefore measured elastic and inelastic scattering of ^{17}F on a hydrogen target.

The ^{17}F beam was produced by the in-flight technique via the d(^{16}O,^{17}F)n reaction with a ^{16}O beam from ATLAS incident on a gas cell filled with deuterium. Details of the production technique can be found in the 1998 annual report.

Elastic scattering of ^{17}F on hydrogen was separated from scattering of the beam contaminant ^{16}O by detecting the scattered protons in kinematic coincidence with the heavy beam particle (^{17}F or ^{16}O) which was identified with respect to mass and Z by an annular parallel plate avalanche counter/Bragg Curve ionization chamber combination. The protons were detected by two annular Si detectors surrounded by six 5 × 5 cm^2 Si strip detectors. The detection efficiency of the whole array was typically 60%.

Excitation functions for two states in ^{18}Ne at E_x = 7.16 and 7.60 MeV were measured with this setup. The data are presently being analyzed.

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a.2. Production of a ^{44}Ti Beam at ATLAS

(K. E. Rehm, I. Ahmad, J. P. Greene, J. Nolen, R. C. Pardo, A. A. Sonzogni, B. Zabransky, D. L. Bowers, F. Brumwell,* G. McMichael,* and M. Paul†)

Satellite-based gamma detector arrays have recently been used to identify remnants of supernovae through the detection of the ^{44}Ti afterglow. Nuclei of ^{44}Ti($T_{1/2}$ = 60 y) are produced in supernovae in the so-called alpha-rich freeze-out. The amount produced in the explosion is governed by a subtle interplay between nuclear reactions that produce it and those that destroy it. Network calculations have shown that the number of ^{44}Ti nuclei produced in a supernova depends strongly on the cross section of the ^{44}Ti(α,p)^{47}V reaction. For a first measurement of this reaction in the laboratory we have developed a ^{44}Ti beam at ATLAS. The ^{44}Ti material was produced via the ^{45}Sc(p,2n) reaction, using a 50-MeV, 20-μA proton beam from the linac injector of Argonne's Intense Pulsed Neutron Source (IPNS) facility. The target, a 25 mm diameter, 5 mm-thick disk of Sc, was mounted inside a water-cooled Cu holder, whose front face was made of graphite, acting both as a collimator and an energy degrader. The irradiation lasted ~70 hours. Two weeks later, the Sc disk was removed from the holder and placed in front of a Ge detector. The dominant source of gamma radiation originated from the decay of ^{44}Sc. Nuclei of ^{46}Sc ($T_{1/2}$ = 83.8 d) were also produced by neutron capture. A ^{44}Ti activity of ~180 μCi was obtained from the γ spectrum, which represents ~ 1.8×10^{16} atoms or ~ 1.3 μg of ^{44}Ti.

About four weeks later, the ^{44}Ti activity was chemically separated from the Sc material. The Sc disk was dissolved in a HNO_3/HCl solution and the Sc then precipitated by the addition of HF. The solution containing the Ti activity was then dried and heated. A part of the resulting material, left as a $^{44}TiO_2$ compound, was mixed with 50 mg of $^{nat}TiO_2$ and placed inside a copper insert for a negative-ion Cs-sputter source. The ^{44}Ti activity from the pellet was measured to be ~38 μCi. From the ion source a beam of $^{44}TiO^-$ was extracted and injected into the tandem accelerator at ATLAS. After stripping in the terminal of the tandem, a $^{44}Ti^{8+}$ beam was accelerated in the linac part of ATLAS to an energy of 133.5 MeV. Two guide beams were used to optimize the beam tuning of the ATLAS accelerator for the weak $^{44}Ti^{8+}$ beam: the optics of the ion source and the tandem injector were tuned with $^{48}TiO^-$, while the superconducting linac was tuned with $^{66}Zn^{12+}$.

In order to measure the composition of the accelerated mass 44 beam, a 2 mg/cm^2 Ti foil was used to degrade its energy and the Fragment Mass Analyzer (FMA) was set to separate the beam particles in m/q. Ions with the same m/q value but different nuclear charge experience a different energy loss in this foil and can thus be easily identified in the focal plane of the FMA. Figure I-1 shows a ΔE--E plot measured in an ionization chamber in the focal plane of the FMA. The different components of the beam are indicated. From these measurements it was concluded that 38% of the beam consisted of ^{44}Ti, 54% of ^{44}Ca while ^{33}S and ^{11}B accounted for the remaining 8%. The ^{33}S and ^{11}B ions are injected as mass 60 molecules from the ion source and ions with the same charge-to-mass ratio are accelerated to the same velocity in the linear accelerator. Intensities of ~ 5×10^5 ^{44}Ti/s on target were observed. This allowed a first measurement of the ^{44}Ti(α,p)^{47}V reaction (see Sec. a.3).

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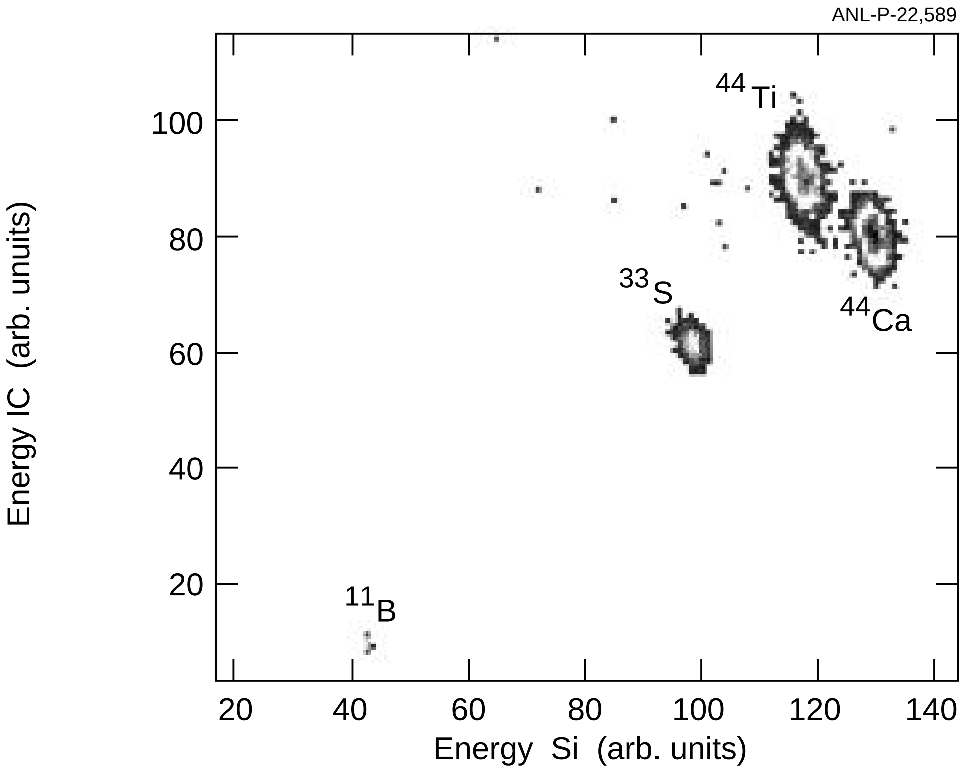

Fig. I-1. Energy loss (measured in the ionization chamber) vs. residual energy (measured in a Si detector) for particles detected in the focal plane of the Fragment Mass Analyzer. The different components of the beam are indicated.

a.3. The ^{44}Ti(α,p) Reaction and Its Implication on the ^{44}Ti Yield in Supernovae

A. Sonzogni, K. E. Rehm, I. Ahmad, J. Caggiano, C. N. Davids, J. P. Greene, B. Harss, A. Heinz, D. Henderson, R. V. F. Janssens, C. L. Jiang, J. Nolen, R. C. Pardo, J. P. Schiffer, D. Seweryniak, R. H. Siemssen, J. Uusitalo, I. Wiedenhöver, B. Zabransky, F. Borasi,† D. L. Bowers,¶ F. Brumwell,* G. McMichael,* M. Paul,‡ R. E. Segel,† and J. W. Truran§)

The recent observation of γ rays associated with the decay of ^{44}Ti by the COMPTEL space telescope from the Cassiopeia A and from the Vela supernova remnants have demonstrated that the ^{44}Ti gamma afterglow can be used to locate individual supernova remnants. It is expected that with the next-generation of space-based gamma-ray observatory INTEGRAL (scheduled for launch in 2001), new supernova remnants will be discovered and the total mass of ^{44}Ti ejected in the supernova events will be determined. The use of the ^{44}Ti afterglow of supernovae for distance or age determination depends critically on the amount of ^{44}Ti produced in the explosion which is governed by a subtle interplay between the nuclear reactions that produce it and those that destroy it. This subject was studied in detail for type II supernovae by The et al.[1] From these calculations, it was concluded that the amount of ^{44}Ti produced in a supernova depends strongly on the cross section of the ^{44}Ti(α,p)^{47}V reaction. Since ^{44}Ti(α,p)^{47}V reaction destroys ^{44}Ti, an increase in its rate will decrease the final amount of ^{44}Ti and vice-versa. Due to the relatively high value of the Coulomb barrier for the ^{4}He + ^{44}Ti system, the influence of this reaction is felt at temperatures of 2.2-4.2 × 10^9 K. This temperature range corresponds to center-of-mass energies (Gamow peak values) of 4-6.1 MeV. In order to put the nuclear astrophysics part of ^{44}Ti production in supernovae on a more solid ground we have performed the first measurement of the ^{44}Ti(α,p)^{47}V reaction.

The production of the ^{44}Ti sample and details of the beam production are described in a separate contribution (see Sec. a.2). The ^{44}Ti beam bombarded a ^{4}He gas target consisting of a 2.2-mm-long cell with two 1.3 mg/cm^{2} titanium metal windows, filled with 600 mbar of ^{4}He and cooled to LN_2 temperature. The areal density was 80 μg/cm^{2}. For the separation of the ^{47}V reaction products emitted at small scattering angles (typically 2°) from the primary mass 44 beam particles the Fragment Mass Analyzer (FMA) was used. To further identify the ^{47}V particles an Ionization Chamber (IC) and a Si detector were placed behind the Parallel Grid Avalanche Counter (PGAC) at the focal plane of the FMA. The PGAC provided position and timing signals, while the IC-Si detectors gave energy and Z information.

To avoid a re-tuning of the linac at each energy change, which, for low intensity beams, can be quite time-consuming, Ti degrader foils ranging in thickness from 0.6 to 2 mg/cm^{2} were used. The energy measurements of the beam were done by time-of-flight using the isochronous property of the FMA. Before the ^{44}Ti experiment the experimental arrangement was tested with stable ^{40}Ca and ^{46}Ti beams. For ^{40}Ca as well as for ^{44}Ti, the (α,p) reaction dominates in the energy range of interest. With a transport efficiency through the FMA which was calculated taking the charge-state distributions, the kinematics and small angle scattering into account, the measured excitation function for the ^{40}Ca(α,p)^{43}Sc reaction was found to be in very good agreement with the results from the literature.

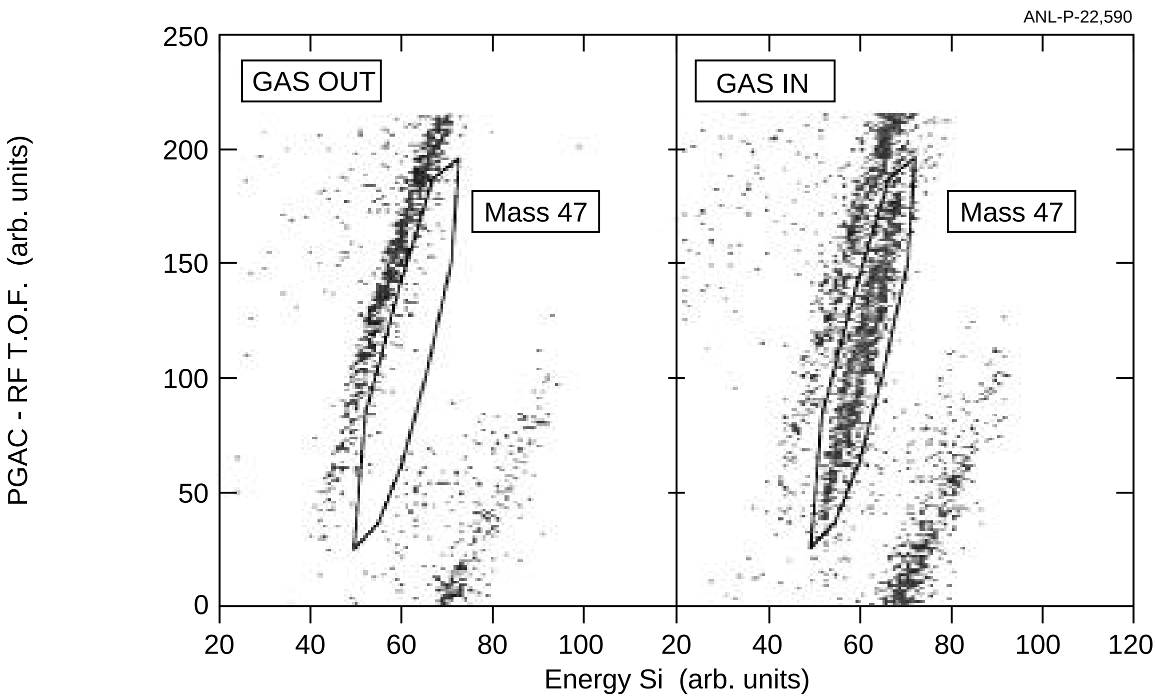

Fig. I-2. Time of flight (measured with the parallel-grid-avalanche-counter relative to the rf timing from the accelerator) vs. energy (measured in the Si detector). The left panel corresponds to an empty gas cell, the one at the right to a full gas cell. The reaction products with mass 47 are indicated by the solid contour line.

Plots of the time-of-flight through the FMA versus the energy measured in the Si detector behind the focal plane are shown in Fig. I-2 for an incident ^{44}Ti energy of 122.1 MeV. The left panel corresponds to an empty gas cell, the right one to a gas cell filled with 600 mbar of He. With the empty cell only mass 44 particles are observed, produced by beam particles scattered in the gas cell windows or on various components in the FMA. The plot for the full gas cell shows the mass 47 reaction products, well separated from the scattered mass 44 particles. To measure the contributions from the reactions products from the ^{44}Ca component of the beam (mainly ^{47}Ti and ^{47}Sc produced via the ^{4}He(^{44}Ca,n) and ^{4}He(^{44}Ca,p) reactions) a pure beam of ^{44}Ca was used. To correct for the charge-state distribution of ^{47}V detected in the focal plane, the distributions were measured in a separate experiment (see Sec. a.4) using stable ^{51}V beams in the energy range E_{lab} = 25-110 MeV and adjusted to the same velocities.

The resulting cross sections for the $^{44}Ti(\alpha,p)^{47}V$ reaction can be seen in Fig. I-3. The solid line is the result from the statistical model code SMOKER[2] which is used in many astrophysical network calculations to estimate astrophysical reaction rates that cannot be studied in the laboratory. At the two higher energies the agreement between our experiment and the theoretical prediction is excellent. However, the falloff in the cross section due to the penetration of the Coulomb barrier appears to be shifted towards lower energies resulting in cross sections that are larger by about a factor of two compared to the SMOKER predictions. The astrophysical reaction rate for the $^{44}Ti(\alpha,p)$ reaction is shown by the solid line in Fig. I-4. The reaction rates from the SMOKER calculations as well as those by Woosley et al.[3] are given by the dashed and dot-dashed curves, respectively. These two sets of theoretical calculations give basically the same result for the $^{44}Ti(\alpha,p)^{47}V$ reaction rates, which is lower than the experimentally determined rate by about a factor of two.

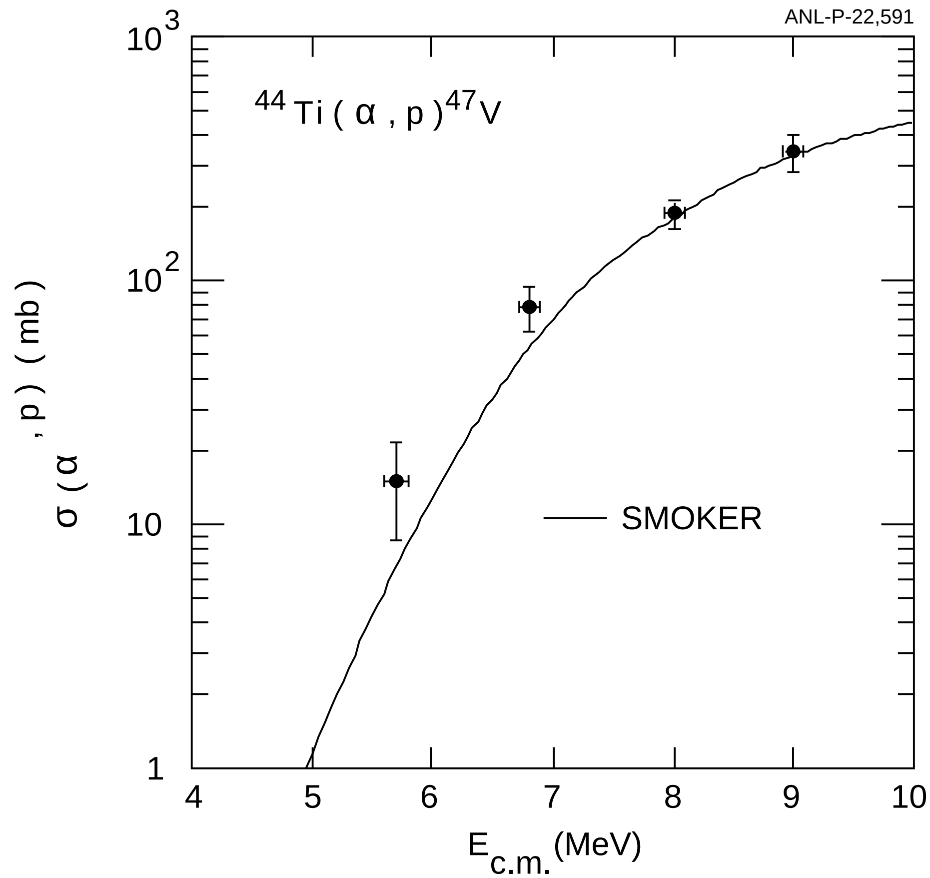

Fig. I-3 Measured excitation function for the $^{44}Ti(\alpha,p)^{47}V$ reaction. The solid line corresponds to a calculation done with the code SMOKER.

The higher astrophysical reaction rate results in a reduction of the amount of ^{44}Ti produced in supernovae explosions. With the increased reaction rate shown in Fig. I-4 one expects a 25% decrease in the ^{44}Ti yield of a type II supernova. For a measurement of the ^{44}Ti gamma-ray flux from a supernova, this decrease in yield translates into a 12% larger distance or a 20 y earlier occurrence. It should be noted that changes in other reaction rates which have not been measured so far (e.g. the $^{45}V(p,\gamma)$ reaction) could effect the ^{44}Ti yield as well.

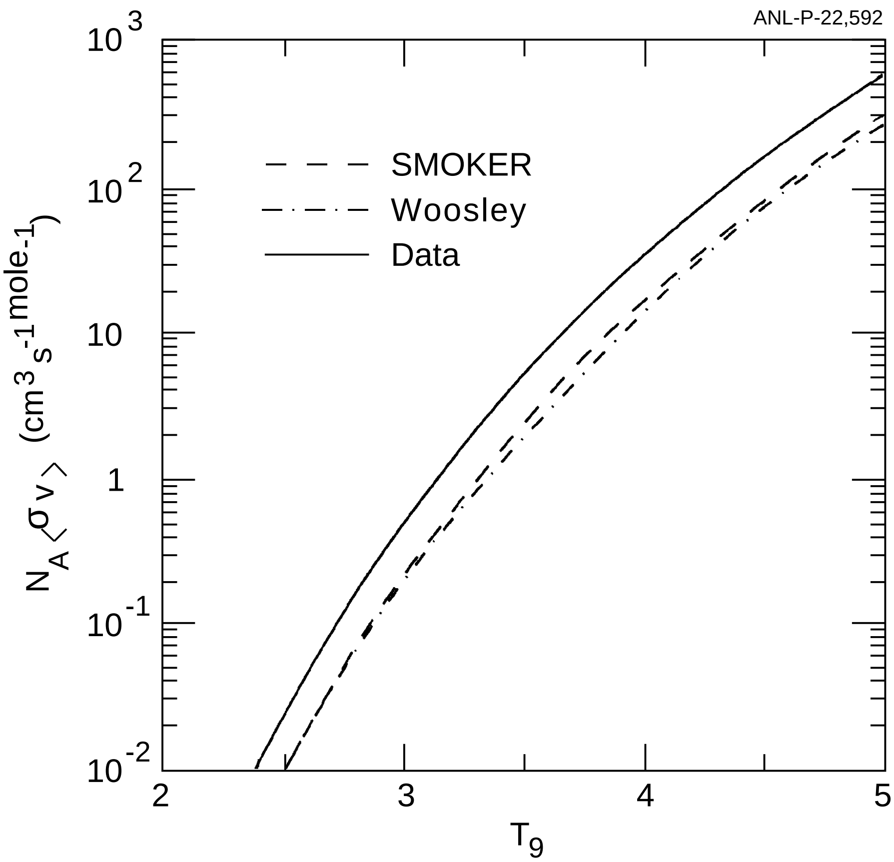

Fig. I-4. Astrophysical reaction rates for the ^{44}Ti(α,p)^{47}V reaction. The solid line was obtained from the experimental information as described in the text. The dashed line corresponds to a SMOKER calculation and the dot-dashed line to a calculation by Woosley et al. [Ref. 3].

In addition to its effects on the energetics of the light curve of supernova 1987A, and for searches for ^{44}Ti decay γ rays from galactic supernova remnants, these new experimental results also hold important implications for galactic nucleosynthesis. Observational determinations of the abundances of (elemental) titanium in the oldest (most metal deficient) stars in our galaxy reveal that titanium is over-abundant relative to iron by a factor of ~ 2-3. Preliminary calculations of supernova nucleosynthesis indicate that the higher rate for ^{44}Ti(α,p)^{47}V might result in an increased production of ^{48}Cr which decays into the most abundant Ti isotope ^{48}Ti.

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[1]L.-S. The *et al*., Astrophys. Jrnl. **504**, 500 (1998).

[2]F-K. Thielemann *et al*., Advances in Nucl. Astrophys., Editions Frontiere, **525** (1987).

[3]S. E. Woosley and T. A. Weaver, Astrophys. Journ. Suppl. **101**, 181 (1995).

a.4. Measurement of ^{51}V Charge State Distributions (A. Sonzogni, K. E. Rehm, I. Ahmad, C. N. Davids, J. P. Greene, B. Harss, D. Henderson, R. V. F. Janssens, C. L. Jiang, J. Nolen, R. C. Pardo, J. P. Schiffer, D. Seweryniak, J. Uusitalo, I. Wiedenhöver, F. Borasi,* M. Paul,† and R. E. Segel*)

As mentioned in Sec. a.3, cross sections for the $^{44}Ti(\alpha,p)^{47}V$ reaction which are of interest in nuclear astrophysics were measured using the Fragment Mass Analyzer (FMA). An important part of this project was a knowledge of the transmission efficiency of the FMA, i.e. the probability that ^{47}V nuclei produced by the reaction will reach the detector at the focal plane of the FMA. This efficiency is given by the product of two terms: the geometric transport efficiency determined by the acceptance of the FMA and the charge state distribution of the particles of interest.

In order to improve the accuracy on the measured cross sections, the charge state distributions for ^{51}V were measured at energies of 25-120 MeV using the Enge split pole magnetic spectrograph. A Ti target, whose thickness was chosen to simulate the energy loss in the ^{4}He gas cell windows, was used to scatter ^{51}V beam particles, which were detected at the focal plane of the Enge split-pole spectrograph, using the standard focal plane detector.

Since the FMA separates ions in M/Q, its capabilities to distinguish ^{47}V from beam-like particles ^{44}Ti particles can be improved by choosing an appropriate foil after the Ti windows, which will maximize the charge state distribution in a region of charge state where it is unlikely to find beam particles with the same M/Q. Several exit foil options (Be,C..) were explored and it was concluded that a thin Au foil was the most suitable one for our project.

As an example, a charge state distributions for ^{51}V ions measured at 0.5 MeV/u with a Carbon exit foil can be seen in Fig. I-5, together with calculations from Ref. 1 (full line) and Ref. 2 (dashed line).

This extensive body of data, corrected for the mass difference and interpolated to the energies of interest, was used to obtain the charge state distributions for ^{47}V.

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[1]K. Shima *et al*., At. Data and Nucl. Data Tables **51**, 173 (1992).
[2]Y. Baudinet-Robinet, Nucl. Instrum. Methods **190**, 197 (1981).

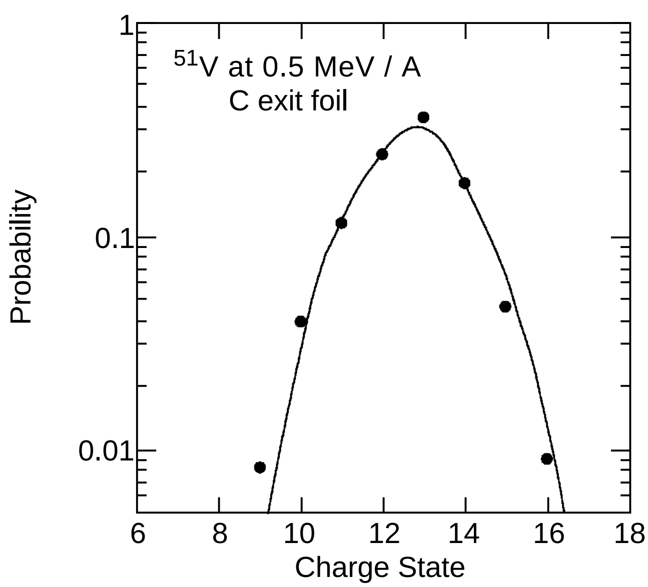

Fig. I-5. Charge-state distribution measured with a 0.5-Mev/u ^{51}V beam and a C foil.

a.5. Study of Proton-Unbound States in Astrophysically-Interesting Nuclei

(J. A. Caggiano and K. E. Rehm)

An important task in nuclear astrophysics is linking observational gamma ray astronomy to laboratory studies of nuclei. The availability of data from COMPTEL/CGRO has provided measurements to constrain for models used to understand explosive events such as nova and supernova in the heavens. For example, the ability to detect gamma rays from ^{26}Al and ^{44}Ti, and the absence of gamma rays from ^{22}Na have provided such constraints.

^{26}Al and ^{22}Na are predominantly made as unstable proton rich nuclei in the rp process and then decay to these nuclei as daughters. Thus, in order to understand how much of these isotopes was made in the event, an understanding of the production rates of their parents is important.

Many of the proton rich nuclei have been studied with the (p,t) or (^{3}He,n) reactions which very preferentially populate natural parity states. As a consequence, many of the unnatural parity states in these nuclei remain missing (based on mirror nucleus considerations). Furthermore, investigation of the production of certain isotopes (^{26}Al for example) show that unnatural parity states can dominate proton capture rates. In these cases, where the data is missing, the models rely on reaction rates that are based solely on theoretical predictions of where the levels are, which have uncertainties of ~100 keV or so. Because the rate depends exponentially on the resonance energy (level energy less the Q-value), a 100 keV uncertainty can mean orders of magnitude uncertainty in the rates, which renders the calculation essentially useless.

The (^{3}He,^{6}He) reaction will be used to populate important states in proton rich nuclei, such as ^{26}Si (ATLAS proposal #835) and ^{22}Mg (experiment at Yale University to be done in February 2000). The Enge split-pole spectrograph will be used to identify and measure the energy of the ^{6}He. This method has many advantages:

- Cross sections are of the order of 1 µb/sr, making the measurement possible.
- Resolution of 40 keV or better is possible.
- The reaction can populate unnatural parity states.
- When studying even-even nuclei, because the starting nucleus usually has an extra neutron, the Q-value gets much less negative (~ -15 to -20 MeV). This makes the cross sections larger and enables easy separation from the reactions on the inevitable target contaminants carbon and oxygen (Q-values of ~ -30 MeV), leaving no question as to the origin of the states.
- Because of this fact, carbon in the target backing provides no interference, and hence targets don’t have to be self-supporting.

Many proton-rich nuclei will be studied in this manner during the course of next year (2000).

a.6. Yield Calculations for an Advanced Rare Isotope Accelerator Facility (C. L. Jiang, B. B. Back, I. Gomes, A. M. Heinz, J. A. Nolen, K. E. Rehm, G. Savard, and J. P. Schiffer)

Over the last ten years, intense worldwide effort has been devoted to the design of facilities which can produce a broad range of radioactive nuclei at high intensities[1]. The scientific opportunities offered by these facilities have been discussed extensively at many recent national and international conferences[2].

In the course of the development of these concepts and designs, the calculation of production yields using different kinds of reaction mechanisms at different energies and different beam-target combinations plays a fundamental role.

An exciting new concept for an advanced facility of the ISOL type (Isotope Separation On Line) for beams of exotic short-lived nuclei has been developed at Argonne National Laboratory[3,4]. Such a facility is based on a high intensity driver beam that produces short-lived nuclear species which are stopped in a suitable medium. The desired isotopes are then selected, and accelerated to the appropriate energy in a second accelerator. Most importantly, it includes a novel approach that avoids the most serious drawbacks of an ISOL facility for a broad range of beams: delay between the production of the short-lived isotopes and their acceleration and the underlying sensitivity to the chemistry of the extracted species. Many reaction mechanisms (related with a special beam-target assemblies) can be used. The most important are the following four: spallation reactions, two-step fast neutron fission, projectile fragmentation and in-flight fission.

The ANL concept is based on a high-power superconducting linac providing a broad range of beams. With the intense beams and high target power densities expected from the driver linac, target cooling becomes a central issue. The four reaction mechanisms are all associated with different beam-target assemblies, optimized for the cooling problems and the extraction of the reaction products. These beam-target assemblies have been described in Ref. 4.

Predictions of production yields of secondary beam should be based on experimental data as much as possible. However, in many cases experimental cross sections are not available, and therefore yields need to be estimated using theoretical calculations. In this contribution the aim is not to calculate precise yields for some special nuclide, but to create a general idea of what yields a next generation ISOL facility can provide over the whole region of a Z-N map. Even with an uncertainty of a factor of ten, the relative trends and ratios still supply important information.

Data bases for either reaction cross sections or yields have been generated for all reaction mechanisms discussed above.

For spallation reactions (Standard ISOL method) many data have been published in the literature[5]. From the tables obtained at E_{proton} = 600 or 1000 MeV, a yield data base was created. Since in many cases the experimental data do not cover a wide enough mass region, extrapolations have been performed to obtain the yields for some isotopic chains.

For the two-step fission reaction mechanism, data bases for yields at $E_{deuteron}$ = 200, 400, 800 and 1200 MeV (at constant power 100 kW) have been generated using Lahet[6] calculations. The actual target geometry (a cooled tungsten neutron production target and a uranium carbide fission target) has been used in the calculations and contributions from fast and from slow neutrons were included. Yields for nuclides at the neutron-rich region with very small cross sections were obtained by extrapolations.

For fragmentation reactions, most of the data were obtained from calculations. For each desired product, several beams can be used for the production, and an optimum beam has to be selected. ISAPACE[7], a computer program based on the internuclear cascade program incorporated with the evaporation code PACE, requires considerable computing time. EPAX, a parametrization of the fragmentation process[8], on the other hand, provides also good estimates within very short computing time.

A program was developed to produce a data base for fragmentation reactions for all nuclides in the Z-N plane at 100 MeV/u and 100 kW with yields higher than 10^{-6}/sec. An automatic searching was done using EPAX for each desired product, by comparing the yields from all possible beams. The target thickness in the calculations was determined by the requirement that the energy of the beam after the target was 50 MeV/u, since for energies < 50 MeV/u the production yields were found to decrease rapidly. To produce different isotopes for a given element, several beams have to be used. For example, for the Sn isotopes of A = 125-128, 129-132, 133-139 and 140-145, the optimum beams are ^{130}Te, ^{136}Xe, ^{150}Nd and ^{160}Gd respectively. The target used in the calculations was ^{7}Li, since with liquid lithium the cooling problem can be solved using existing technologies as mentioned in Ref. 4.

For in-flight fission reactions, experiments with ^{238}U beams (750 MeV/u) at GSI supply a good base of reaction cross sections for the production of neutron-rich nuclide[9]. From these data we have generated a data base for in-flight fission reaction method using also calculations with the Abrasion-Ablation Model[10]. For some isotopes in the neutron-rich region extrapolations have been performed.
From these data bases predicted yields at different energies (MeV/u) and different beam power can be calculated, and various yields for nuclides in the Z-N plane can be displayed.

In the following we compare the yields from the four production methods to find out which method can provide the most intense beam for each nuclide. The resulting two-dimensional Z-N map is shown in Fig I-6. For simplification, the ISOL mechanism and two-step mechanism are combined and shown in green,

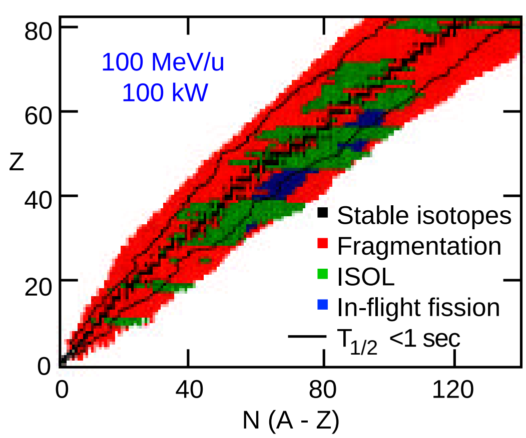

Fig. 1-6. Reaction mechanisms which give the highest yields of each separated isotope assuming 100 kW of beam power and 100 MeV/u.

the fragmentation mechanism in red, and the in-flight fission method in blue. It should be noted that this plot extends to isotopes for which the yield with a next generation ISOL facility would be on the order of a few per day (10^{-4}), and which are, for the most part, totally unknown. The assumptions in Fig. I-6 are for a facility with 100 kW of beam power at 100 MeV/u. Different assumptions (e.g. 400 MeV/u) will not change the results appreciably.

Contour plots of the production yields are shown in Fig. I-7, which gives the intensities for a next generation RIA facility, using for any nuclide the highest yield from any of the four production methods.

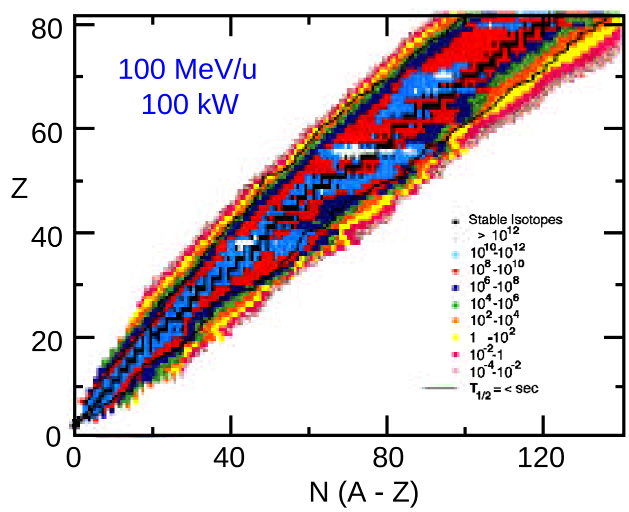

Fig. I-7. Mass-separated yields (ions/sec) for an advanced ISOL facility, assuming 100 kW of beam power and primary beams of 100 MeV/u.

The absolute production yields depend very much on the bombarding energy. At higher beam energies, thicker targets can be used. However, there are additional effects which influence the yields and have to be included in the calculations (attenuation effects of the beam and of the reaction products, production through the secondary reactions, and multiple scattering which influences the transmission efficiency of the mass separator). These effects are usually small at E_{beam} = 100 MeV/u but become more significant at higher beam energies (higher target thicknesses) especially for the fragmentation and in-flight fission production methods.

The calculations indicate that there is an optimum target thickness at each higher incident energy, which gives the maximum yields. Absolute yields for some nuclei are shown in Fig. I-8 as a function of the bombarding energy assuming a constant primary beam current (100 kW at 400 MeV/u). From Fig. I-8 we observe the wide range of intensities that can be produced by the different reaction mechanisms. Yields from the fragmentation method are shown in red, for in-flight fission method in blue, and from the standard ISOL and

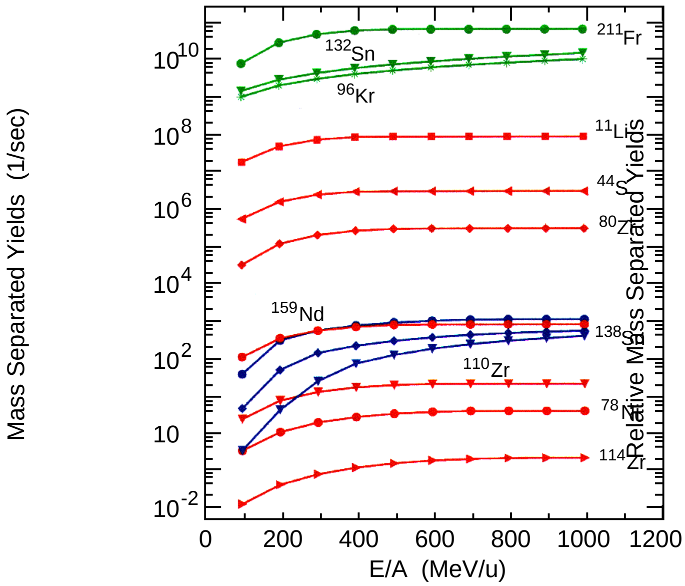

Fig. I-8 Absolute yields versus Energy (in MeV/u) for some nuclei assuming constant current (100 kW at 400 MeV/u). The green curves are for either standard ISOL or two-step fission, the red curves are for fragmentation reactions and the blue curves are for in-flight fission reactions.

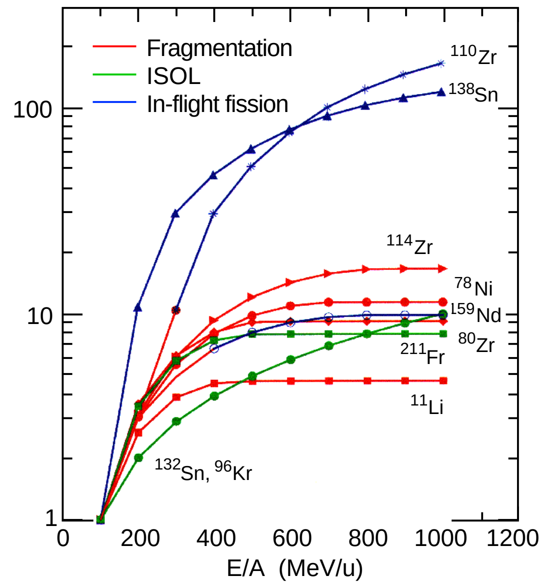

Fig. I-9. Relative yields (normalized to the values at 100 MeV/u) versus bombarding energy for some nuclei for constant current (100 kW at 400 MeV/u). The color code is the same as in Fig. I-8.

two-step fission into green. The highest intensities are observed by using the ISOL and two-step fission methods.

To emphasize the energy dependence, the same data are shown normalized to the yields at 100 MeV/u in Fig. I-9. It is clear that the production yields from the ISOL and the two-step fission methods, as well as from the fragmentation method, give a factor of 5-10 increase in yields between 100 MeV/u and 400 MeV/u. For the in-flight fission case, however, the increase is nearly two orders of magnitude. The reason for this is the relatively large momentum and angular spread that is introduced between the fragments in the fission process at low energies. Furthermore, attenuation losses of the beam and of the fragments in the target for the fission method are less pronounced, because the range of ^{238}U is short and thus the targets are thinner. It should be noted that Figs. I-8 and I-9 are calculated for constant current. For constant power, a factor of 1/10 has to be multiplied to the points at 1000 MeV/u as shown in Fig. I-10.

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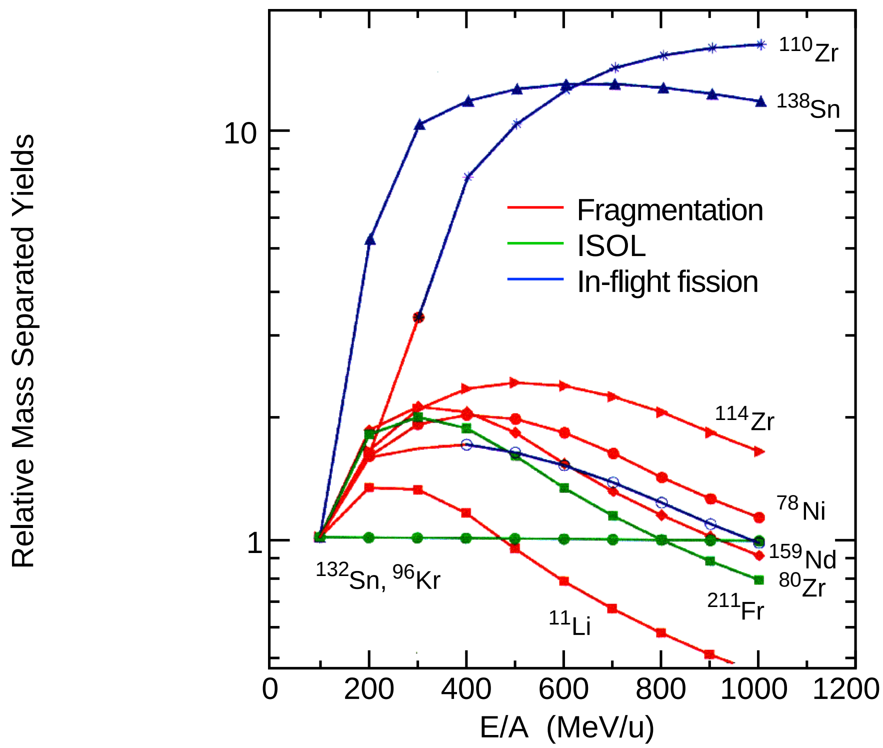

Fig. I-10. Relative yields (normalized to the values at 100 MeV/u) versus bombarding energy for some nuclei for constant power (100 kW). The color code is the same as in Fig. I-8.

a.7. The Rare Isotope Accelerator Web Page (J. A. Caggiano and R. V. F. Janssens)

The planning for the Rare Isotope Accelerator (RIA) facility has created the desire for a visible presence on the World Wide Web. A white paper was published stating the case for the construction of the facility, and a link to the file exists on the first page. The goal of the web page was to incorporate all the information in a user-friendly, navigable fashion.

Such a web page now exists and, while still in the development, provides a resource on the WWW to learn about the RIA project. There are three main categories: (1) the science case, (2) the technical aspects and (3) a short history. Figure I-11 shows the home page. To view the page and its links, go to http://www.phy.anl.gov/ria.

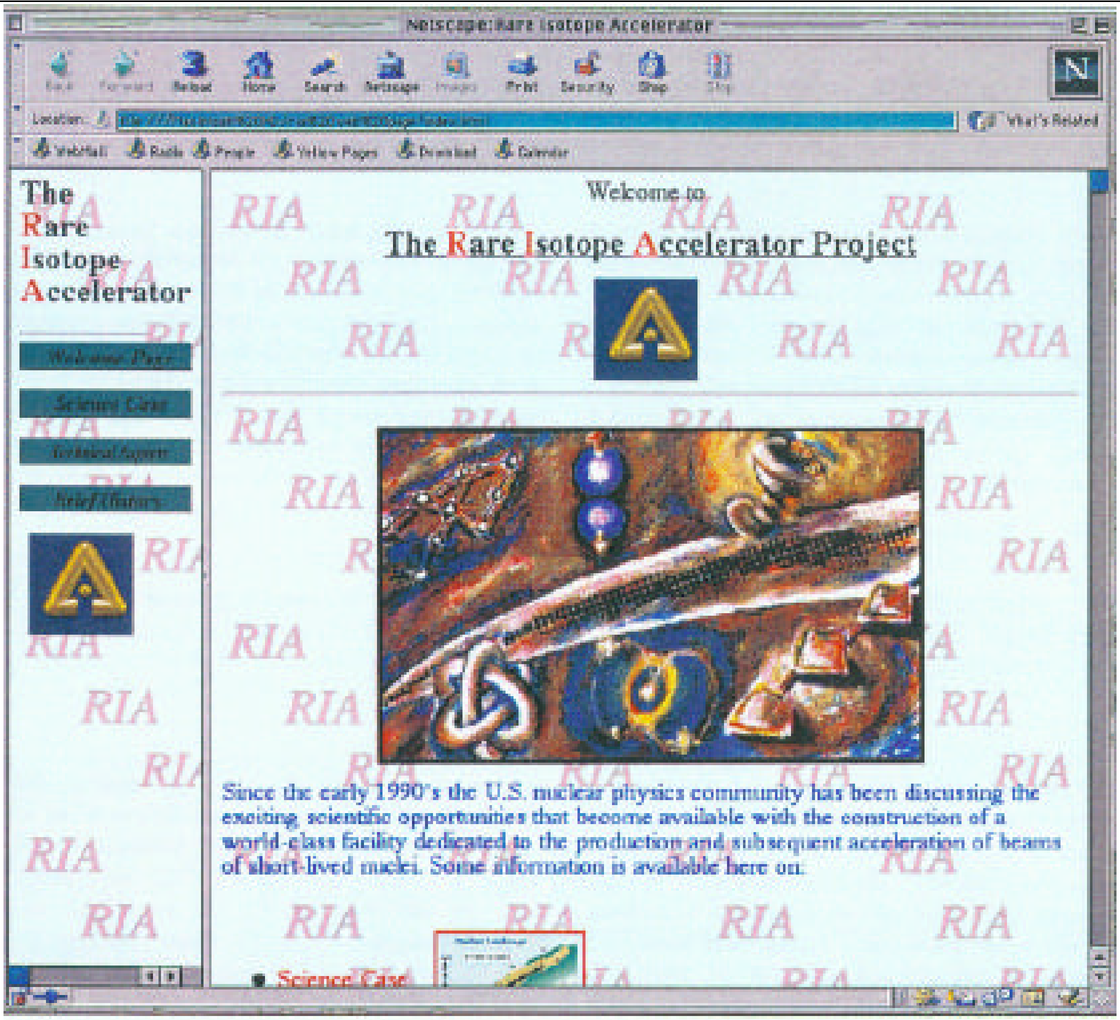

Fig. I-11. The RIA home page