POSSIBILITIES FOR EXPERIMENTS WITH NEUTRON-RICH BEAMS IN NUCLEAR ASTROPHYSICS.

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While prototype experiments with proton-rich radioactive beams have been performed at various existing facilities, investigations with accelerated neutron-rich beams have to await the availability of the next-generation facilities. In this contribution possible future experiments with neutron-rich beams in the areas of nuclear structure and nuclear astrophysics, as well as novel production and detection techniques for these beams are discussed.

1 Introduction.

Stellar explosions, such as Novae, Supernovae or X-ray bursts\(^1,2\) are a prolific source of exotic, short-lived nuclei. Network calculations have shown that in these cataclysmic events light seed nuclei, through repeated capture of protons or neutrons, followed by weak decays, can be transformed into heavier nuclei. On the proton-rich side of the mass valley this process is called the rapid proton capture (\(rp\)) process which converts CNO material into Ne, Mg, Si..., Ni and elements beyond. Since the reaction flow in these astrophysical events proceeds mainly through the region of \(\beta^+\) unstable nuclei, it was only recently that some of these rates have been determined experimentally using beams of short-lived nuclei\(^3\).

On the neutron-rich side it is the so-called \(r\)-process, a sequence of rapid neutron capture reactions and \(\beta^-\) decays, leading to a reaction flow through very neutron-rich nuclei, that produces, starting from \(^{56}\text{Ni}\) (or its decay product \(^{56}\text{Fe}\)) all the heavier elements up to U. Together with the slow neutron capture (\(s\))-process which follows a route mainly along the valley of stability, these two processes are the main sources of heavy nuclei which are observed in the cosmos. The site for these types of reactions and the exact route of the \(r\)-process are still under intense discussion. A typical \(r\)-process path on the N-Z plane is given in Fig. 1. The shaded areas are the regions where beams of exotic nuclei have been produced using standard ISOL techniques\(^4\). While the borders in Fig. 1 are not sharp, it is clear that, because in the standard ISOL technique the exotic nuclei have to diffuse out of the production target,
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the region of accessible nuclei is limited to longer-lived ($T_{1/2} > 1\text{ sec}$), non-refractory elements and isotopes. From Fig.1 it is clear that so far only in two mass regions (around $A=80$ and 130) experimental nuclear structure data for r-process nuclei are available which can be used as input for the underlying network calculations. For the majority of the reactions one is still forced to rely on theoretical estimates for masses, halflifes and n-capture cross sections. In this area next generation radioactive beam facilities will likely bring a major breakthrough in our understanding of the nucleosynthesis of the heavy elements.

Neutron-rich nuclei are also of strong interest in nuclear structure studies. On the proton-rich side of the mass valley the dripline is much closer to the stable nuclei and has been reached for many elements up to about $Z=80$ using compound nucleus reactions. The neutron drip line on the other hand is considerably farther from the line of stability and it is only for the lightest nuclei
that isotopes at the neutron-drip line have been produced so far.

Extending our knowledge into the neutron-rich region of the nuclide chart requires innovative techniques for producing these nuclei as well as high efficiency detector systems to perform experiments within a limited amount of time. Reaching the neutron drip line for medium mass or heavy nuclei in a terrestrial laboratory might not be possible in the near future. However, studies of some critical (e.g. neutron-rich closed shell) nuclei which can be performed at the next-generation facilities will strongly influence our knowledge of the exotic nuclei that remain beyond our reach for the foreseeable future.

2 Production Techniques for Neutron-rich Radioactive Beams.

As can be seen from Fig.1 the majority of the nuclides involved in the r-process have half-lifes which are of the order of seconds or less. Because of the long diffusion times, the efficiency for extracting these short-lived isotopes from an extended production target in the standard ISOL technique are quite small, especially for refractory elements. Therefore, in order to obtain beams of these exotic nuclei with intensities above $10^4$ particles/sec different production methods have to be used.

A new and very promising approach is the so-called 'fast gas catcher' method, which is an evolution of the IGISOL\textsuperscript{5} and SPIG\textsuperscript{6} techniques. This technique, which should give a considerable improvement in efficiency, especially for short-lived isotopes, is presently being tested at Argonne and is described in more detail in a recent ATLAS Newsletter\textsuperscript{7}. Isotopes produced in heavy-ion induced fragmentation reactions are separated in a fragment separator from the primary beam, slowed down to energies of $\sim 5$ MeV/u and stopped in a high-pressure helium gas cell where, due to the high ionization potential of the He stopping gas, they come to rest as $1^+$ ions. With a combination of RF and electrostatic fields they can be extracted from the gas volume with high efficiency ($\sim 20\%$) within a few milliseconds. The important point is that contrary to the standard ISOL technique where the effusion and diffusion of the isotopes strongly depends on the chemistry, the fragmentation/He gas catcher technique is independent of the chemical properties of the produced elements.

A schematic layout for this technique is shown in Fig.2. A high-intensity driver beam (e.g. $^{238}$U at 400 MeV/u) bombards a well cooled high-power production target. A liquid Li target developed to stop 10 MW deuterium
Figure 2: Schematic layout of a two-step production target consisting of a fragment separator and a gas catcher.
beams for the thermonuclear fusion program is a viable possibility. Calculations, based on previous work done at ANL by the fusion energy group, show that the temperature in a 6 cm thick liquid Li target at a flow rate of 5 m/s, which is bombarded by a 100 kW 100 MeV/u $^{18}$O beam does not exceed 700 °K. Cooling circuits for these and even higher beam powers have been built and operated at Argonne. The large range of the secondary particles (e.g. n-rich fission fragments) allows them to escape from the production target. The particles of interest are separated from the primary beam by a high acceptance mass spectrometer (see Fig. 2) which includes two wedge-shaped absorbers for Z/A separation and reduction of the energy spread. After slowing them down in a second absorber they enter the He-filled gas stopper with energies of ~5 MeV/u. The setup for the He-gas catcher used in recent experiments is shown in Fig. 3. First tests with the Canadian Penning Trap at Argonne have

Figure 3: Detailed view of the gas catcher used in preliminary release studies at ATLAS. The cylindrical stack of electrodes guides the ions towards the exit plate.
demonstrated extraction efficiencies of 20% and extraction times of less than 60 ms. An accelerator that provides high-intensity primary beams of stable particles up to U will thus be able to produce exotic, short-lived secondary beams even for short-lived refractory elements which are unaccessible by other techniques.

3 Detection Techniques.

There are two classes of experiments that can be performed with these new neutron-rich beams. Similar to the present ISOLDE program, non-accelerated exotic beams can be implanted into various detector systems to measure their properties, e.g. masses, halflifes, decay schemes, moments etc. Equipment needed for these types of measurements include traps\textsuperscript{10}, and various particle and gamma detectors. Required beam intensities are of the order of particles/min. A contour plot of beam intensities expected at a next-generation facility for n-rich nuclei in the mass region A=60-150 is shown in Fig.4. The production methods include neutron-induced fission reactions (for longer-lived isotopes), heavy-ion induced fragmentation and in-flight fission of 400 MeV/u uranium beams\textsuperscript{11}. Wherever possible, experimental cross sections (e.g. from the system U + Be\textsuperscript{12}) and measured extraction efficiencies have been used. The beam power in the production accelerator was 100 kW. From a comparison with the r-process path (shown by the shaded area) it can be seen that masses, halflifes and other nuclear structure information for a large number n-rich nuclei which have been unaccessible so far can be measured at such a facility.

There is a second class of experiments which can provide critical information about the r-process, such as spins and spectroscopic factors or cross sections for (n,\gamma) reactions in n-rich nuclei. Since the halflifes of these exotic nuclei are too short (typically less than 1 s) to produce targets for studies of the (n,\gamma) reactions, the relation between spectroscopic factors (measured e.g. in (d,p) reactions) and neutron-capture cross sections\textsuperscript{13} can be used to obtain the required structure information. Transfer reactions will be studied in inverse kinematics, i.e. bombarding a light target with a heavy beam. The kinematics (energy of the light reaction product as a function of the scattering angle) is shown in Fig. 5 for various one-proton and one-neutron transfer reactions induced e.g. by a \textsuperscript{132}Sn beam at an energy of 10 MeV/u. The center of mass angles are indicated by the thin solid lines. Depending on the Q value of the reaction, the light reaction products produced in inverse (d,p), (d,t), (\textsuperscript{3}He,d) or (d,\textsuperscript{3}He) reactions extend towards 180° (for positive Q values)
Figure 4: Contour plot of expected beam intensities for ions in the mass range A~70-130 that can be obtained at a next generation ISOL facility. The squares indicate stable isotopes and magic proton or neutron numbers are given by the thick solid lines. The production methods include two-step neutron-induced fission reactions (for longer-lived isotopes), heavy-ion induced fragmentation and in-flight fission of 400 MeV/u uranium beams. See text for details.

or have a maximum scattering angle (for negative Q-values). The energy of these particles is generally quite small and thus well suited for detection with available Si detectors. The kinematic shifts for some of these reactions, however, require the use high granularity detectors arrays. These detector arrays can have large solid angles (e.g. 5 sr) which allows to perform experiments with beam intensities down to $10^5$ particles/sec. Because in some cases the purity of the secondary beams will not be 100%, the light particles have to be measured in coincidence with the heavy reaction products which are identified according to mass and nuclear charge in e.g. a recoil separator. Several studies using these high efficiency arrays have been performed recently, using stable
Figure 5: Kinematic curves (energy of the light reaction product as function of the scattering angle) for various one-proton and one-neutron transfer reactions induced by a $^{132}$Sn beam at an incident energy of 10 MeV/u. The three curves correspond to excitation energies of 0, 2 and 4 MeV. The center of mass angles are indicated by the thin solid lines.

$^{14}$[$d(^{136}Xe,p)^{137}Xe$] or radioactive beams$^{15,16}$[$d(^{58}Ni,p)^{57}Ni$, $p(^{11}Be,d)^{10}Be$]. The typical energy resolution which has been achieved with these arrays is 50-100 keV, mainly determined by the granularity of the detectors and the size of the beam spot, emphasizing the need for high-quality beams with good emittance and small beam spots. In order to improve the resolution to about 10 keV, detectors are needed that can compensate for the (in some cases) large kinematic shifts.

Magnetic spectrographs have been built for these purposes and resolutions of $\Delta E/E \leq 10^{-3}$ have been achieved$^{17}$. The small solid angles of these spectrographs, however, result in unacceptable long running times for reactions with low-intensity beams. The next generation spectrometers will require solid an-
gles of ~ 0.1 sr and will thus cover an angle acceptance of ~ ± 10°. In order to make use of the full power of these devices momentum and angle of the detected particles need to be measured in the focal plane. Since the reactions envisioned will be studied mainly in inverse kinematics (see Fig.5) there is (for negative Q values) a strong correlation between scattering angle and excitation energy spectrum. Especially around the maximum scattering angle the excitation energy maps directly into the scattering angle. An optical mode that decouples the momentum measurement from the angle measurement can be achieved by a vertical orientation of the spectrometer, generating an ideal high resolution instrument to study transfer reactions in inverse kinematics. A spectrometer operating in this mode is the S800 spectrograph at the NSCL at MSU. Experience with this Ω=20 msr device shows that it is possible to obtain high resolution energy and angle spectra using an xy-position sensitive detector in the focal plane.

4 Summary and Outlook.

A next generation ISOL facility will provide beams of exotic nuclei with intensities orders of magnitude higher than what is available today. While at existing ISOL facilities the ion beams are presently limited to chemical elements that have a high release efficiency, the new facilities can use techniques that are independent of the chemical properties. Fragmentation reactions followed by ion-optical separation and slowing-down of the reaction products in a gas catcher is one of these possible production schemes. With this improved capability and with novel high-efficiency experimental equipment detailed studies of elements and isotopes that play a role in stellar explosions will be possible.

Acknowledgment

The production calculations for secondary beams described in this contribution have been performed in collaboration with B. Back, I. Gomez, W. Henning, C. L. Jiang, J. Nolen, G. Savard, J. P. Schiffer (all ANL) and B. Sherrill(MSU). This work was supported by the Department of Energy, Nuclear Physics Division under contract No. W-31-109-ENG-38.

References

11. C. L. Jiang et al., to be published