Physics with Radioactive Beams at MSU/NSCL

SAM M. AUSTIN
For the NSCL A1200 Group
National Superconducting Cyclotron Laboratory
Michigan State University, East Lansing, MI 48824/USA

ABSTRACT. Since commissioning of the A1200 Fragment Separator in October 1990, research with radioactive beams has become a major part of the research program at the NSCL. This paper will describe the A1200, present some early results in detail, and discuss briefly the nature of the overall program.

RESUMEN. Desde que se inició la operación del separador de fragmentos A1200 en octubre de 1990, la investigación con haces radioactivos se ha convertido en una parte principal del programa de investigación en el NSCL. Esta contribución describe el A1200, presenta en detalle algunos de los primeros resultados obtenidos con este separador, y discute brevemente la naturaleza del programa completo.

PACS: 29. 25. Ea

1. INTRODUCTION

With the development of fragment separators capable of producing high energy beams of radioactive nuclides many new physics opportunities have become available. It is now possible to study reactions of nuclei with extreme values of isospin near the driplines for both neutrons and protons. Some of these nuclei have unusual properties. For example, neutron rich light nuclei that are also lightly bound (the archetypical case is $^{11}$Li) appear to have neutron halos that extend far beyond the nuclear core, and exhibit large reaction cross sections and strong low-lying electric dipole (E1) strength. The breakup products of these nuclei also have anomalously narrow momentum distributions. At the other isospin extreme, proton-dripline nuclei important for the astrophysical rp process have been observed in the mass 60 to 90 region. In another astrophysically important experiment, the Coulomb breakup process for an $^{14}$O beam has been used to obtain the cross sections for radiative capture processes important in the hot CNO cycle; similar measurements of $^8$B breakup are in progress and are expected to yield the radiative capture cross sections for the $^7$Be(p,$\gamma$) reactions, important for an understanding of the production of solar neutrinos and interpreting the ongoing measurements at SAGE and GALLEX.

These measurements, and other measurements of reaction or scattering cross sections clearly require high energy beams. However, many experiments carried out with fragment separators involve stopping the beam in a detector and measuring its decay properties. It might seem that ISOL type ion sources would be superior for such experiments, since the ions are produced at low energies and do not have to be slowed and stopped. However,
the fragment separators have the advantage that the nuclide production process is not
element specific, as it is for ISOL ion sources, and that short lived isotopes can be studied;
one is limited only by the flight time of the nuclide through the separator, perhaps 200
nsec, and not by the much longer extraction time from the ion source. In addition, it is
sometimes desirable to be able to implant the radioactive nuclide deep inside a detector
so as to detect its decay products in the stopping detector.

Several such experiments are underway at MSU/NSCL. One is a search for 17 keV
neutrinos in the decay of $^{35}$S, avoiding the problems of an external source by imbedding
$^{35}$S produced and purified by the A1200 fragment separator in the center of a thin high
resolution Ge electron detector. Other studies involve studies of beta-delayed neutron
emission from $^{15}$B and other light nuclides, two-proton emission from $^{11}$Li and $^{22}$Al, and
many related studies. One of these, observation of the beta-delayed proton emission from
$^{20}$Mg is aimed at elucidating the structure of a state in $^{20}$Na, whose properties are critical
to an understanding of the stellar sites where breakout from the hot CNO cycle to the rp
process will occur.

2. FRAGMENT SEPARATORS

The radioactive beam facility [1] at the NSCL, Michigan State University, operates on
the basic principles developed at LBL and at GANIL. An intense primary beam, typically
with an energy of 50 MeV/nucleon or more, bombards a light production target, and the
forward focussed reaction products from peripheral reactions are collected and filtered to
produce (in the ideal case) a beam of a single isotopic species. This beam can then be
used to induce further reactions, or it can be stopped for study of its own properties. The
collector/filter at the NSCL is the A1200 Fragment Separator; because it is located at
the exit of the K1200 cyclotron, the resulting radioactive beams can be transported to all
other experimental areas and apparatus in the laboratory. Experiments have been done
in the large scattering chamber and radioactive beams will be used for experiments in the
NSCL's 4π Array.

Fig. 1 shows a schematic diagram of the A1200. It is constructed from superconducting
dipole and quadrupole magnets identical to those used in the NSCL beam transport
system and can operate in several modes. As a chromatic device, with an energy resolution
of 1:10,000 it is used to fix the resolution and emittance of the primary cyclotron beam.
In this mode it has been used to show that the energy spread of the raw K1200 beam
is less than 0.05%. When operating as a fragment separator, the A1200 is used in an
achromatic mode, with the first and second halves of the separator bending the beam
in opposite directions; in this mode, its momentum acceptance is $\pm 1.4\%$, and its angular
acceptance is 0.8-4.3 msr. Images of the secondary beam are formed at two intermediate
positions which have space for a variety of devices, for example, an energy degrading
wedge to provide additional filtering or PPAC detectors to provide position and angle
information. Beams can be transported to the NSCL Reaction Products Mass Separator
(RPMS) whose Wien filter can provide further selection (by velocity) if required.

The A1200 in its achromatic mode can also be used as an energy loss spectrometer;
radioactive beams induce a reaction at a target located at Image 2 (see Fig. 1) and
the reaction products are detected at the focal plane. Momentum resolution of 1:1500 should be possible with a radioactive beam energy spread of 6% corresponding to the full A1200 momentum acceptance; a value of 1:850 has already been achieved with essentially no tuning for optimization. This capability will make possible a variety of experiments aimed at elucidating the structure of light nuclei near the driplines. A comparison of the properties of the A1200 and other fragment separators is given in Ref. [2].

3. Experiments

Experiments with radioactive beams presently comprise about half of the NSCL experimental program and this fraction seems likely to increase. It is not possible to review all of these experiments here, but I will try to give some sense of the scope of experiments performed to date and the direction of future programs.

3.1 Momentum Distributions from the Breakup of Lightly Bound Neutron Rich Nuclei

The unusual properties of these nuclei: their large interaction cross sections, their large Coulomb breakup cross sections and the narrow momentum distributions of their reaction products, can apparently be understood qualitatively in terms of a simple model in which a halo of lightly bound neutrons surrounds a tightly bound core. These nuclei may then
provide an opportunity to study a new range of nuclear phenomena in which tenuous distributions of neutrons are bound in the nuclear mean field and are largely free of proton contaminants. $^{11}$Li is an extreme example of such nuclei, with an uniquely large N/Z ratio and a low binding energy, near 300 keV. It appears to be well described as a $^9$Li core surrounded by two neutrons whose motion is strongly correlated, much like that of a di-neutron.

We will concentrate here on the implications of measurements of the distribution of momentum of the $^9$Li products from the breakup of $^{11}$Li by light and heavy targets. Early measurements of the momentum distributions of the projectile fragments resulting from a peripheral breakup reaction at energies in the GeV/nucleon range were interpreted in terms of the Fermi momentum of the particles stripped from the projectile. The distribution of momenta was closely Gaussian, roughly centered about the beam velocity, and was characterized by $\sigma_\parallel$ and $\sigma_\perp$ for the components of the momentum parallel and perpendicular to the beam direction. Later Friedman [3] showed that the momentum widths were more closely related with the binding energy of the removed nucleons than with their Fermi momentum.

When Kobayashi, et al.[4] measured $\sigma_\perp$ for the peripheral breakup reaction $^{11}$Li + $^{12}$C $\rightarrow$ $^9$Li + n + X at 0.8 GeV/nucleon they found that the momentum distribution apparently had two components, one very narrow, with $\sigma_\perp$ about 23 MeV/c, a quarter of the value found for tightly bound nuclei, and the other wider, similar to that for a tightly bound nucleus. A similar narrow component was found for $^{11}$Be breakup into $^{10}$Be + n. Later measurements showed a dependence on binding energy similar to that predicted by the Friedman model.

However, as described by Tanihata [5], the situation now appears to be more complex. For example, the narrow distribution of $p_\parallel$ is not found for heavy targets. Nor do measurements of coincident neutron and heavy fragment distributions agree for $^{11}$Be breakup at 800 MeV/nucleon [6]. Finally, very narrow distributions (corresponding to about 10 MeV/nucleon) are observed in the breakup of $^{11}$Li at 30 MeV/nucleon [7]. It has become clear that more detailed models are required to provide a consistent picture of the breakup process, at least at non-relativistic energies. In order to provide data on $^{11}$Li so as to confront models with a broader range of observables, we have undertaken a measurement of momentum distributions for $p_\parallel$. Measurements of $p_\perp$ do not provide an accurate measurement of momentum distributions because of the large expected effects from Coulomb deflection at these energies. Measurements of $p_\parallel$ do not suffer from this problem, but such measurements require excellent energy resolution and have not previously been possible.

To provide the required resolution we [8] have used the A1200 in its energy loss mode. An 80 MeV/nucleon beam of $^{18}$O incident on a Be production target produced 67 MeV/nucleon $^{11}$Li ions. The $^{11}$Li nuclei interacted with Be and Ta targets placed at the Image 2 position of the A1200, and the resulting $^9$Li products were detected at the A1200 focal plane. An energy resolution of 1:850 was obtained for $^9$Li for a $^{11}$Li energy spread of 1:16. Preliminary results for breakup on Ta are shown in Fig. 2. Similar data for the $^9$Be target are very well described by a fit with two Gaussians, the narrow one having a width of about 20 MeV/c. The interpretation of this data is not yet clear. Recent
calculations of Esbensen and Bertsch [9] find significant E1 strength below 1 MeV in $^{11}\text{Li}$. To the extent that Coulomb excitation dominates the reaction cross section, the $^{11}\text{Li}$ will be excited to its E1 state, which will then decay far from the target. The spread in $p_\parallel$ will then arise from the momentum imparted to $^9\text{Li}$ when the excited $^{11}\text{Li}$ nucleus emits neutrons. In this picture the width of the momentum distribution measures the average excitation energy of the soft dipole excitation. The predicted momentum distribution is shown in Fig. 2—it describes the data very well.

Other measurements are in progress to better determine the shape of the wings of the distribution, so as to allow a more detailed comparison with models. However, interpretation of the $^{11}\text{Li}$ data is inevitably complicated: descriptions of the correlated initial and final states are difficult [9] and sequential decay processes, $^{11}\text{Li} \rightarrow ^{10}\text{Li} + n \rightarrow ^9\text{Li}+2n$, contribute to the momentum distributions. A proposal to study $^{11}\text{Be}$ and $^{15}\text{C}$, which decay by single neutron emission, has been approved (Orr et al.); these data should be more easily interpreted. Further measurements for the breakup of $^8\text{He}$ and $^6\text{He}$ (Kolata et al.) should shed further light on these questions and on the prevalence of the low lying E1 strength.

### 3.2 Nuclei at the Proton Dripline—The $rp$ Process

Mapping of the proton dripline has been an important part of the programs at GANIL
and LBL. With the availability of the A1200 and high energy beams of $^{78}$Kr from the K1200 cyclotron at the NSCL it became possible to determine the location of the dripline for masses between 60 and 90. These observations test nuclear mass formulae and also bear on the path of the astrophysical rp process which synthesizes proton rich nuclei in hot, violent astrophysical events. This experiment, Mohar et al.[10], was one of the first carried out at the A1200, because it involved only production of radioactive nuclides in a $^{58}$Ni target by a $^{78}$Kr beam, and their detection and identification in a four element Si detector telescope located at the focal plane. Measurements of magnetic rigidity, total energy, delta-E and time-of-flight unambiguously identified the detected particle. The resulting mass spectra provide evidence for six new nuclides that live longer than the flight time (about 150 nsec) through the A1200. The upper limit on the observed abundance of $^{73}$Rb indicates that this nucleus is unbound. A comparison of the positions of these nuclei with calculations [11] of the rp process path for a Type I X-ray burst is shown in Fig. 3. The existence of $^{65}$As and $^{69}$Br shows that the rp process can extend beyond these nuclei. However, the probable instability of $^{73}$Rb means that the process must slow beyond this point, since $^{72}$Kr must have time to beta decay before the rp process can continue. Measurements of other properties of these nuclides are necessary to determine whether they are sufficiently bound to avoid photodisintegration in astrophysical environments. A first step in this direction has been made by the measurement of their lifetimes by Winger,
et al. [12]. The nuclei were stopped in a Si detector, identified by an on-line calculation, and if one of the candidate nuclides was identified, the beam was turned off by changing the rf phase on the K1200 cyclotron. The decay electrons were observed as a function of time to obtain the lifetime; known lifetimes of nearby nuclides were reproduced. It appears that lifetimes or lifetime limits will be obtained for $^{61}$Ga, $^{63}$Ge, $^{67}$Se, and $^{65}$As. Another experiment by Yennello et al. [13] has succeeded in identifying dripline nuclei up to mass 86.

### 3.3 Some Other Experiments

The experiments discussed previously make use only of the A1200. However, in many other experiments the beam is transported to other devices for use. For these experiments the beam properties are important. An example is a study of the elastic scattering of $^{11}$C, $^{11}$Be and $^{11}$Li from $^{12}$C at 60 MeV/nucleon carried out by Kolata et al. These secondary beams have two properties that change the nature of experiments. First, the intensity is low compared to that of a primary beam. One therefore typically uses large solid angle detectors, or takes advantage of inverse kinematics to increase the effective solid angle. The higher energies also make thicker targets possible. A second characteristic is that beam emittance and/or energy spread are relatively large. However, beam particle tracking and time of flight on a particle by particle basis often compensate for this, and are common practice. I now list briefly, some other experiments that have been completed to date.

(a) Measurement of momentum distributions in the products of peripheral reactions for $^{18}$O (Souliotis, et al.); (b) Production of a beam of $^{18}$F in its isomeric state and studies of its elastic scattering (Becchetti, et al.); (c) Measurements of fraction of $^{26}$Al and $^{38}$Cl formed in their isomeric states in fragmentation reactions (Benenson, Young, et al.); (d) Determination of the lifetime of $^{32}$Si in a direct counting experiment (Chen, et al.); (e) Measurement of the beta delayed neutron emission from $^{15}$B (Harkewicz et al.); (f) Measurement of beta delayed neutron emission from $^{18}$N (Görres, et al.); (g) Coulomb breakup of $^{6}$He and $^{6}$Li (Balamuth, et al.); (h) Observation of heavy fragments resulting from Xe collisions with several targets with the A1200–isotopic resolution is obtained for A near 130 (Hanold, et al.).

### 4. Future Directions

Many additional experiments have been allocated time on the A1200. Most of these are nuclear structure studies, but searches for the 17 keV neutrino using implanted targets, reaction mechanism studies, searches for new nuclear species, nuclear astrophysics related measurements, and mass measurements are also important parts of the program. We anticipate that reaction mechanism experiments using large solid angle detectors and the A1200 directly will become more important. On the technical side, the greatest effort will be devoted to increasing the available beam energy and intensity. Construction of the S800 spectrograph remains a high priority; its construction continues, but is limited in speed by the availability of funds. Its good energy resolution (1:10,000), large acceptance (20 msr) and bending power will greatly benefit studies of radioactive products. The new
University of Michigan 7 Tesla solenoid is now sited at the NSCL and has very large solid angles for energies up to 50 MeV/nucleon—it will play an important role in the NSCL radioactive beam program.

5. ACKNOWLEDGEMENTS

This research was supported by the U.S. National Science Foundation.

REFERENCES

8. N. Orr, B. Sherrill, et al., unpublished.