

## Scientific Opportunities with the NSCL Coupled Cyclotron Facility

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The National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU) is primarily devoted to the study of exotic nuclei. The Laboratory is funded by the United States National Science Foundation (NSF) to operate two coupled superconducting cyclotrons (the K500 and the K1200) and a diverse array of experimental devices. This paper describes this facility, some of the planned research and its future directions. The planned program will cover three main areas; nuclear structure, nuclear astrophysics, and the equation of state of compressed nuclear matter. In nuclear structure, one of the major goals will be to study the structure of very neutron and very proton rich nuclei with mass  $A < 100$ . The tools for these studies are presented. Nuclear astrophysics studies will cover the full range of stellar evolution from main sequence burning to exploration of the properties of neutron stars.

### §1. Introduction

Exotic nuclei are increasing more accessible as facilities and experimental techniques continue to improve. This paper highlights the progress in two ways. First, it illustrates progress in accelerator facilities. Namely, in this case, the newly commissioned Coupled Cyclotron Facility, CCF, at the National Superconducting Cyclotron Laboratory, NSCL, is described. This new facility uses two cyclotrons to accelerate intense beams up to 200 MeV/nucleon. The higher energies and intensities available will dramatically increase, by a factor of 1000, the available exotic beam intensities. The second aspect of progress in the study of exotic nuclei is illustrated in some of the new experimental techniques described in this paper. Sensitive  $\beta$ -decay,  $\gamma$ -array, and reaction techniques allow detailed experiments with secondary beam intensities of less than 1 atom/second.

### §2. The NSCL facility

The National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU) is the primary rare isotope user facility in the United States for experiments with fast, secondary beams. The Laboratory is funded by the United States National Science Foundation (NSF) to operate two coupled superconducting cyclotrons (the K500 and the K1200) and a diverse array of experimental devices for a community of researchers from the U.S. and abroad. The recently completed coupled cyclotron facility (CCF) can produce intense beams of primary heavy ions from

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hydrogen to uranium with maximum beam energies of 200 MeV/nucleon for lighter elements and 90 MeV/nucleon for uranium. A high-acceptance fragment separator, the A1900, immediately downstream of the coupled cyclotrons allows efficient production and separation-in-flight of a broad range of secondary rare isotope beams produced by projectile fragmentation or fission.

The new CCF facility is expected to have nearly a factor of 1000 increase in secondary beam intensities compared to the previous NSCL facility, which used only the K1200 cyclotron and the A1200 fragment separator. This increase comes from the ability to accelerate higher-intensity, low charge-state, ions in the K500 to around 15–20 MeV/nucleon and then strip in the center of the K1200 into an accelerated orbit for further acceleration of fully stripped ions up to 200 MeV/nucleon. The K500/K1200 stripping ratio is 2.67 and both cyclotrons operate at the same RF frequency. Initial operation of the facility has achieved the design injection and extraction efficiencies for both the K500 and K1200 cyclotrons.

Research at the NSCL is primarily devoted to basic experimental and theoretical nuclear physics, nuclear astrophysics, accelerator physics, related instrumentation development, and applications to meet specific societal needs. Most experiments require beams of rare isotopes for studying the properties of nuclei far from stability. About one quarter of the experiments require beams of stable isotopes, and 5–10% supports cross-disciplinary research. Located on the campus of a major research university, the NSCL offers excellent educational opportunities for graduate and undergraduate students.

The Laboratory has a history of technical innovation. It has been a pioneer in applying superconducting magnet technology to the design and construction of cyclotrons, magnetic spectrographs, and beam transport systems. The production of radioactive beams via projectile fragmentation and in-flight separation has helped open new vistas for nuclear structure physics and nuclear astrophysics research. Insight and experience gained in recent years at MSU and other laboratories played a crucial role in developing the concept for RIA, the Rare Isotope Accelerator now recommended as the highest priority for new construction for nuclear physics in the U.S.

### §3. Experimental equipment

There is a variety of experimental equipment available at the NSCL. This is schematically illustrated in Fig. 1. Acceleration begins with ions created in one of the two electron cyclotron resonance (ECR) ion sources. The older ECR source has a superconducting solenoidal magnet; the newer one uses normally conducting magnet coils and builds on the A-ECR design from Lawrence Berkeley National Laboratory. Both ECR ion sources are coupled to a beam switchyard that allows injection from either ion source into either cyclotron.

As part of the coupled cyclotron project, the K500 cyclotron was completely refurbished and modernized. Ions accelerated in the K500 pass through a new coupling line to the K1200 cyclotron where they are stripped and accelerated to full energy.

The new A1900 fragment separator/beam analysis system has a momentum ac-

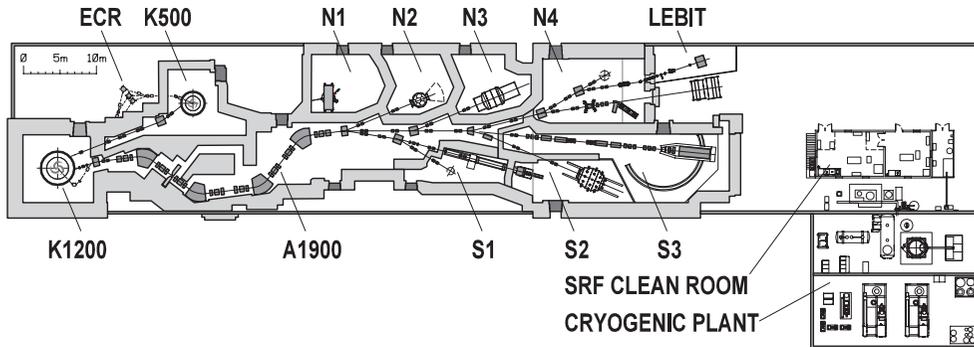


Fig. 1. Floor plan of the NSCL high bay experimental area showing the two superconducting cyclotrons (K500 and K1200 on the left), the superconducting A1900 beam analysis system and subsequent beam lines, the various experimental vaults, the SRF R&D area, and the new cryoplant.

ceptance  $\Delta p/p = 5.5\%$  and maximum rigidity  $B\rho_{\max} = 6.0 \text{ Tm}$ . Compared to the NSCL's previous fragment separator, the A1900 has about an order of magnitude higher acceptance and a 50% higher bending power. The A1900 can be used as a spectrometer to define the energy and emittance of the primary beam from the CCF, as a zero-degree magnetic spectrograph or, most importantly, as a projectile fragment separator to select beams of rare isotopes produced by projectile fragmentation. The separation possible with the A1900 is so sensitive that one nucleus out of  $10^{18}$  can be selected and studied. This level of sensitivity, of course, also relies on the identification of ions by particle identification. This sensitivity was illustrated by experiments at GANIL on the identification of  $^{48}\text{Ni}^{1)}$  where they were able to identify ions with production rates of atoms/week. Downstream from the A1900 is a beam switchyard that allows transportation of all radioactive ion beams to any experimental station at the NSCL.

The S1 vault contains the Reaction Product Mass Separator (RPMS) and a new multi-purpose beam line that is primarily devoted to studies of Single-Electron-Events (SEE) in semiconductors under a beam-time purchase agreement. The RPMS consists of a Wien velocity filter followed by a magnetic dipole for mass separation; it achieves a mass resolution of  $10^2$  and a primary beam suppression factor of approximately  $10^8$ . The RPMS is used for low-background studies of nuclei far from stability, and the Wien filter provides additional purification of radioactive beams, particularly for reaction studies with proton-rich nuclei. We plan to improve the acceptance of the RPMS by placing a superconducting doublet at the RPMS entrance and moving the large room-temperature doublet to the tail. The experimental apparatus for measuring nuclear magnetic moments is situated in S1 just upstream from the RPMS. The "Superball" in the S2 vault is a high-efficiency neutron multiplicity meter constructed by a group from the University of Rochester. The Superball contains approximately  $17 \text{ m}^3$  of Gd-doped scintillator for the detection of neutrons in  $4\pi$  geometry. The internal scattering chamber of the Superball is large enough to accommodate the Miniball/Miniwall  $4\pi$  charged-particle-detector array to allow

simultaneous  $4\pi$  detection of neutrons and light charged particles.

The S800 in the S3 vault is a superconducting high-resolution magnetic spectrograph with specifications well-matched to experiments with rare isotopes: energy resolution  $E/\Delta E = 10^4$ ; maximum rigidity  $B\rho_{\max} = 4 \text{ Tm}$ ; momentum acceptance  $\Delta p/p = 5\%$ ; and solid angle  $\Delta\Omega = 20 \text{ msr}$ . The S800 beam line can be used to dispersion-match the beam to the S800 magnetic spectrograph. Alternatively, the S800 beam line can function as a fragment separator with a momentum acceptance  $\Delta p/p = 6\%$ , maximum rigidity  $B\rho_{\max} = 5.35 \text{ Tm}$ , momentum resolution  $p/dp = 2000$ , and solid angle  $\Delta\Omega = 6 \text{ msr}$ . Both the S800 spectrograph and the S800 beam line deflect the ions vertically.

The  $4\pi$  array in the N2 vault is a low-threshold “logarithmic”  $4\pi$  detector consisting of thirty-two position sensitive parallel plate multiwire detectors, backed by segmented Bragg ionization chambers, backed in turn by an array of 170 phoswich detectors, each consisting of a fast-slow plastic scintillator combination. A number of forward arrays have been constructed by outside user groups for experiments requiring higher resolution and/or granularity at small angles. The granularity in the forward hemisphere will be increased to allow studies of very heavy systems at the higher energies now available (e.g., Au+Au at  $E/A = 40 \text{ MeV}$ ).

The N3 vault is the major general-purpose vault in the NSCL facility and contains a 92" scattering chamber. This large cylindrical multi-purpose scattering chamber (diameter: 231 cm, length: 271 cm) is used for a variety of reaction studies and nuclear structure experiments with beams of rare isotopes. The chamber shell can be lifted from the vault to provide a large free space. The N4 vault has undergone a substantial reconstruction since the end of the experimental program with the K1200 stand-alone facility in June 1999.

The N4 vault will be the normal location for a large-gap superconducting “sweeper” magnet (4 Tm) that is being constructed at the High Magnetic Field Laboratory at Florida State University. The sweeper magnet will serve as a high-acceptance magnetic spectrometer and can be combined with large area neutron detectors (neutron walls) for neutron time-of-flight (TOF) spectroscopy at very small angles. The N4 shielding wall behind the sweeper magnet can be opened to allow long flight-paths to the movable neutron walls. The sweeper magnet can also be mounted in the S3 vault so that the charged particles swept away from zero degrees can be detected with the S800 magnetic spectrograph positioned at the appropriate angle. The central beam line in N4 will feed the new LEBIT facility<sup>2)</sup> described in more detail further below.

In addition to the fixed major equipment described above, a number of special purpose detector arrays exist for the coincident detection of  $\gamma$ -rays, neutrons, and charged particles. A set of 18 segmented germanium detectors with associated electronics and cryogenic support is well matched to detect gamma-rays emitted in flight from fast rare isotopes. The detectors can also be closely packed for on-line decay studies. A pair of neutron time-of-flight walls ( $2 \text{ m} \times 2 \text{ m}$ , position sensitive in two dimensions, and liquid-scintillator filled) is used for studies of nuclei with loosely bound neutrons, primarily at lower energies. A modular neutron array (MONA), of comparable area and an efficiency of about 70% for neutron energies above 50 MeV,

is under construction by a collaboration of several universities and undergraduate colleges. The Miniball multifragment detection array is a transportable and granular, low threshold,  $4\pi$ -plastic-scintillator CsI(Tl) phoswich detector. Typically, it is mounted in the 92" chamber, but it can also be mounted inside the Superball.

A number of experiments require low-energy beams of high quality that are usually not available at projectile fragmentation facilities. Providing such beams and making them available for experiments is the task of the LEBIT (Low Energy Beam and Ion Trap) facility<sup>2)</sup> shown at the right of Fig. 1. The key element of the LEBIT facility is a high-pressure (up to 1 bar) helium gas cell for slowing down and collecting energetic rare isotopes from the A1900 fragment separator.<sup>3)</sup> Ions slowed down in the gas cell remain singly charged and can be extracted with good efficiency. Electric fields guide the ions from the stopping volume through an exit nozzle into a radio-frequency quadrupole (RFQ) system that guides the ions through a differential pumping system. The continuous ion beam is then transported into a linear RFQ ion trap, which acts as a beam accumulator, cooler, and buncher. The energy for the extracted ion bunches can be varied between 5–60 keV by means of a pulsed drift tube in order to satisfy the requirements of a variety of envisaged experiments. The system is in the advanced stage of construction, and gas-stopping tests are underway. Experience gained with gas stopping and beam manipulation in LEBIT will provide valuable insight for the design and construction of a similar facility at the future Rare Isotope Accelerator (RIA).

The first experiment to be set up is a Penning trap system for precision mass measurements.<sup>2)</sup> A superconducting solenoid magnet with a field of 9.4 T will allow the extension of Penning-trap mass-measurements to isotopes with half-lives as short as 10 ms. The expected accuracy for masses of isotopes close to the drip lines is a few ten keV if a few hundred ions are detected. If the yields are higher and the half-lives longer, an accuracy of 1 keV or better should be achievable. The LEBIT Penning trap system can also be used to study decays of free ions at rest, e.g., via low-energy conversion electron spectroscopy.

#### §4. Science at the NSCL

The NSCL Coupled Cyclotron Facility (CCF) can provide a broad range of nuclides for experiments in basic nuclear physics and nuclear astrophysics and related applications. To illustrate the scientific reach of the CCF, Fig. 2 depicts the predicted intensities after separation in flight with the A1900. The intensities are determined from the expected CCF primary beam intensities, the measured A1900 acceptances and the EPAX2 cross section parameterization.<sup>4)</sup> For orientation, the approximate paths of nucleo-synthesis via the astrophysical rapid proton (rp) and rapid neutron (r) processes are indicated in the figure. Since most rare isotope production rates are unknown, most intensities must be extrapolated from existing empirical models. Hence, the intensities in Fig. 2 have considerable uncertainties that generally increase for isotopes more distant from the line of beta-stability.

With beams from the CCF it may be possible to extend our knowledge of the neutron drip line from oxygen to silicon or even sulphur. It will be possible to study

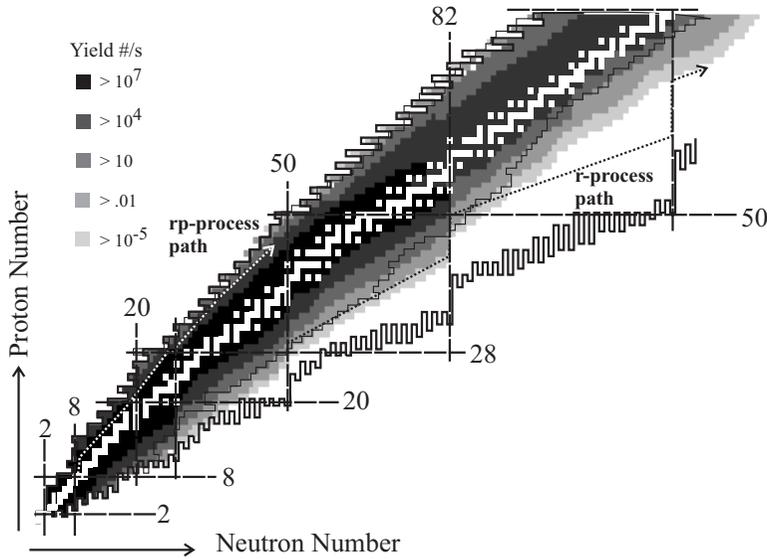


Fig. 2. The scientific reach of the NSCL Coupled Cyclotron Facility is illustrated in terms of the projected intensities for fast beams of rare isotopes. Note of caution: Far from stability, the predicted intensities become increasingly uncertain due to a current lack of experimental data. (A color version of this plot can be found at the website: <http://www.nsl.msu.edu/technology/ccf/reach/index.html>.)

a large number of rp-process nuclei and r-process nuclei up to  $A < 140$ . However, investigation of the heavy r-process nuclei is beyond the reach of the coupled cyclotron facility, and will require construction of a dedicated high-intensity facilities such as RIA or the RIKEN radioactive beam factory.

With the availability of an increasing number of rare isotope beams, a number of remarkable experimental and theoretical tools have been (and continue to be) developed, that allow the extraction of pertinent spectroscopic information with beam intensities of a few particles per second or less. With the availability of new experimental apparatus now under construction and with the increased availability of beams of rare isotopes worldwide, the pace of development is likely to increase. In the present context, one cannot do justice to the many new activities underway at the NSCL. Instead, a few illustrations and results must suffice.

The determination of the beta decay properties of nuclides with extreme neutron-to-proton ratios has been significantly enhanced with the advent of particle-detection techniques that are particularly well suited for fast fragmentation beams. Fast beams from projectile fragmentation offer the advantages of fast (microsecond), highly efficient, and chemistry-independent separation and the option to use “cocktail” beams containing several species of rare isotopes, tagged particle-by-particle. The beta implantation system at the NSCL uses silicon micro-strip detectors as a high granularity implant medium to ensure sufficiently long time intervals (many seconds) between consecutive fragment implants. Clean particle identification for each implanted nucleus, permits the direct correlation of an individual fragment with its subsequent

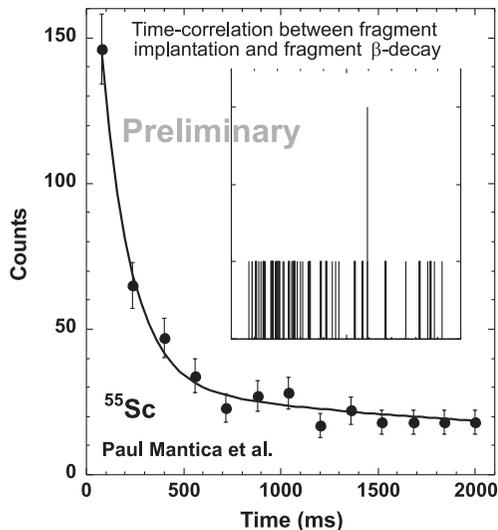


Fig. 3. Lifetime curve for the decay of  $^{55}\text{Sc}$ . The data are fitted considering contributions from the parent decay and daughter ( $^{55}\text{Ti}$ ,  $T_{1/2} = 1.3\text{s}$ ) growth and decay, along with an exponential background. The delayed gamma-ray spectrum for  $^{55}\text{Sc}$  is shown in the insert. A single gamma ray at 593 keV was observed.

regarding the appearance of a subshell gap at  $N = 32$  for very neutron-rich nuclides.<sup>5)</sup>

In recent years, in-beam gamma-ray spectroscopy with fast beams of rare isotopes has evolved from a novel technique into a workhorse for nuclear spectroscopy.<sup>6)</sup> The use of thick targets makes it feasible to do experiments with beam rates lower than one particle per second. Position-sensitive gamma-ray detectors are used to measure the gamma-ray's laboratory energy and emission angle and reconstruct its energy in the ejectile rest frame on an event-by-event basis. Experiments at the NSCL can make use of an existing position-sensitive NaI(Tl) detector array and a newly commissioned array of 18 highly segmented high-purity germanium detectors. To illustrate the technique, Fig. 4 shows on-line spectra obtained by scattering  $^{11}\text{Be}$  nuclei from a  $968\text{ mg/cm}^2$  thick gold target at 121 MeV/nucleon using six segmented Germanium detectors from the new NSCL Segmented Germanium array located 14 cm from the target. The energy spectrum in the  $^{11}\text{Be}$  rest frame shows a sharp peak with an energy resolution of 2.5% corresponding to the  $1/2^+$  to  $1/2^-$  transition. This illustrates that the new Germanium array is working as expected.

Knockout reactions have been used with ever increasing precision to provide a high-energy equivalent to conventional low-energy transfer reactions of the type (p,d), (d,t), and (d, $^3\text{He}$ ), which are an important tool for the nuclear spectroscopy. Recent results suggest that the reaction theory based on the eikonal approximation provides accurate spectroscopic factors (perhaps good to 20%) with standard sets of input parameters. The most remarkable feature of the technique is its high sensi-

beta decay. The system is well suited to measure the decay properties of short-lived nuclides that can only be produced at low rates.

The sensitivity of the beta implantation system with fast fragmentation beams is illustrated in Fig. 3. In this experiment,  $^{55}\text{Sc}$  fragments were produced by fragmenting a primary beam of  $^{86}\text{Kr}$  at  $E/A = 140\text{ MeV/nucleon}$  on a Be target. Beta-fragment correlations were measured over a 45-hour period at an implantation rate of 1.8  $^{55}\text{Sc}$  ions per minute. The time correlation between the implantation of  $^{55}\text{Sc}$  fragments and their subsequent beta decays revealed a beta decay half-life of  $103 \pm 7\text{ ms}$ . A single beta-delayed gamma-ray transition has also been identified at  $593 \pm 1\text{ keV}$  using an array of six segmented germanium detectors placed around the beta implantation system. Beta decay studies carried out at the NSCL in the region around  $^{52}\text{Ca}$  have provided new data re-

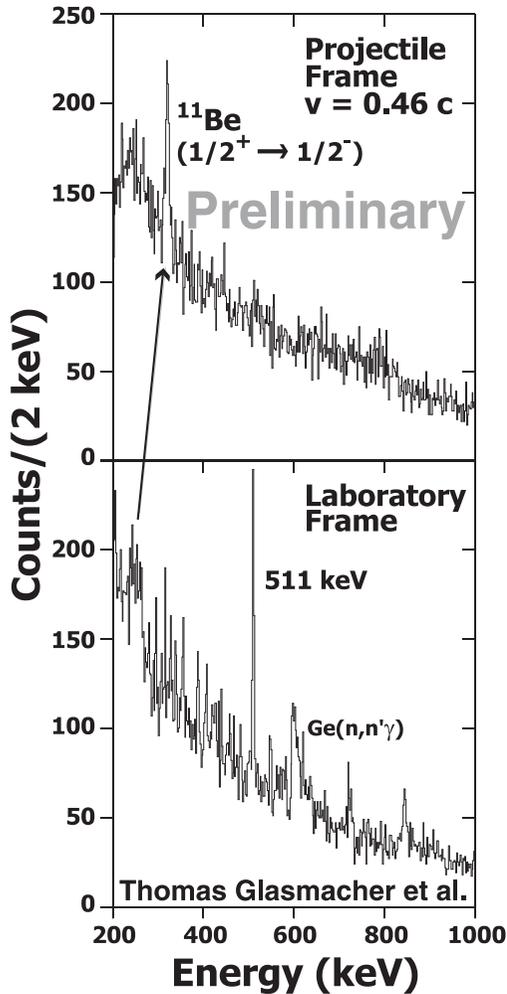


Fig. 4. Intermediate-energy Coulomb excitation of  $^{11}\text{Be}$  at 121 MeV/nucleon. Gamma-rays were detected in six 32-fold segmented Germanium detectors. The resolution of the reconstructed on-line spectrum is not yet optimal since projectile and ejectile tracking information has not yet been utilized.

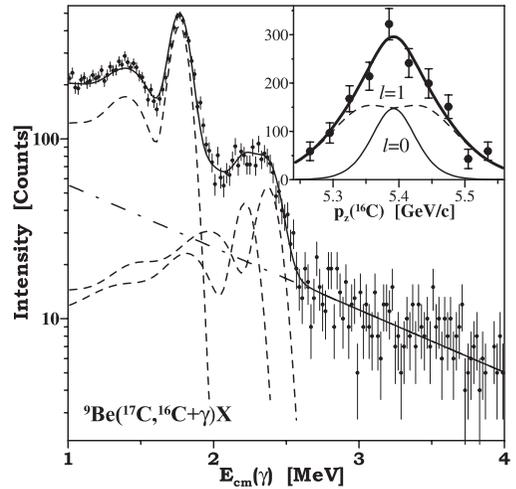


Fig. 5. Gamma ray spectrum in the rest frame of coincident  $^{16}\text{C}$  residues from the reaction  $^9\text{Be}(^{17}\text{C}, ^{16}\text{C}^*)\text{X}$  at  $E_{\text{beam}}/A = 62$  MeV. The strong peak at 1.77 MeV signals that approximately half of the cross section goes to the  $2^+$  first-excited level of  $^{16}\text{C}$ . The momentum spectrum of coincident  $^{16}\text{C}$  nuclei (inset) demonstrates that this partial cross section has two components,  $l = 0$  and  $l = 2$ . (From Ref. 7).

tivity, which extends the possibility of obtaining spectroscopic information to beams produced at the rate of only 0.01 to 0.1 ions/s.

As an example, Fig. 5 shows a spectrum of gamma rays measured<sup>7)</sup> in coincidence with  $^{16}\text{C}$  residues from the reaction  $^9\text{Be}(^{17}\text{C}, ^{16}\text{C}^*)\text{X}$  at 5.4 GeV/c, for an incident  $^{17}\text{C}$  beam intensity of 100–300/s. The gamma ray energies were transformed on an event-by-event basis into the  $^{16}\text{C}$  rest-frame using the measured  $^{16}\text{C}$  velocity and the emission angle and energy of the gamma rays recorded with a position-sensitive gamma-detector array. The calculated line shapes (dashed) are from a Monte-Carlo

simulation, and the dot-dashed line represents a measured background, presumably associated with target fragmentation. The absolute intensities extracted from these simulations provide the cross sections to the ground state, to the 1.77 MeV  $2^+$  state, and to a group of states near 4.1 MeV, and the corresponding spectroscopic factors. The shape of the momentum spectrum shown in the insert allows the determination of the single-particle angular momentum  $l$ . For the present example, the partial cross section of 60 mb to the  $2^+$  state is explained by two contributions, approximately 44 mb for  $l = 2$  and 16 mb for components. The implication is that the ground state has spin  $3/2^+$  corresponding to a complex wave function of the form  $|3/2^+\rangle = c_2 |2^+ \otimes d_{5/2}\rangle + c_0 |2^+ \otimes s_{1/2}\rangle + \dots$ . This is an example of the commonly encountered situation in which a configuration  $j^3$  has spin  $(j - 1)$  as the lowest level.

Similar work succeeded in characterizing the ground state of  $^{19}\text{C}$  with an incident beam intensity as low as 0.5–1/s. The reason for this high sensitivity is the high energy of the beam particles and the detection of only the heavy residue. The high energy allows the use of thick targets and gives a strong forward focusing and hence a detection efficiency close to unity. It also allows particle-by-particle tracking of the incident and outgoing nuclei, so that there is essentially no background. An overview of the work done so far is given in Ref. 8).

### §5. A vision of the future: RIA

The next several years should be an exciting time at the NSCL. The CCF will provide a number of new nuclei for study as outlined above. In the longer term, the hope is to develop an even more powerful facility, RIA.

In developing plans for a next generation rare isotope research facility in the U. S., NSCL faculty proposed to replace the existing plans for a conventional ISOL

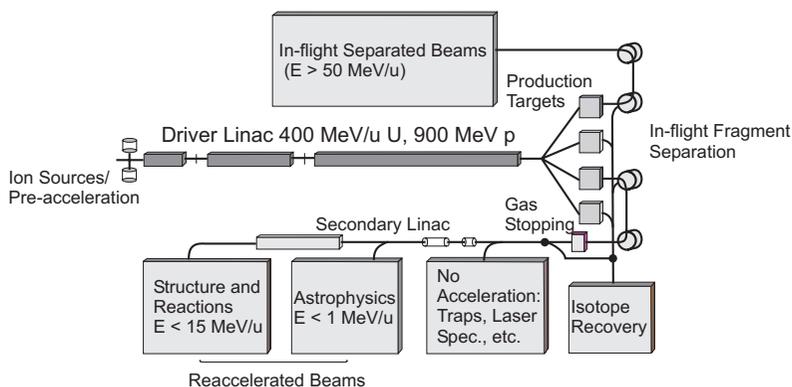


Fig. 6. Simplified schematic of the RIA facility. Rare isotopes can be produced at rest via target fragmentation (or fission) or in flight via projectile fragmentation (or fission). Fast fragments, separated in flight, can be used directly for experiments, or they can be stopped in a gas cell from where they can be extracted for experiments at rest or for re-acceleration. Re-acceleration is also available for isotopes produced at rest. At least two experiments can be performed simultaneously.

facility and instead to build a high-power heavy-ion facility capable of accelerating all elements up to energies per nucleon of at least 400 MeV. A high-acceptance fragment separator similar to the NSCL's A1900 would be used for in-flight separation of rare isotopes produced by projectile fragmentation or fission. After separation from the primary beam, the fragments could either be used directly for experiments or they could be stopped in a medium suitable for fast and efficient extraction and further manipulation, such as trapping or re-acceleration.

The science of RIA has been discussed in many documents.<sup>9),11),12)</sup> The Rare Isotope Accelerator (RIA) concept<sup>10),12)</sup> is schematically illustrated in Fig. 6. RIA has been enthusiastically embraced by the U. S. Nuclear Science Community<sup>12)</sup> and is now the highest priority for new construction in the new (2002) long range plan for nuclear science of the DOE/NSF Nuclear Science Advisory Committee (NSAC). RIA is the logical extension of the NSCL's rare isotope research program. Many of the experimental techniques developed for RIA can be developed and used for research at the NSCL until RIA comes on line.

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