b Research Activities

Introduction

One of the frontiers identified in the 1996 Long Range Plan (LRP) for Nuclear Physics is the exploration of the large region of isotopes far from the valley of stability, about which little is known today. The nature of these nuclei is important for modeling astrophysical environments and understanding the cosmological origin and evolution of the elements. Studies of nuclei far from stability will allow tests of nuclear structure models in regions which are so far from the known existing nuclei that the parameters determined from them are not realistic , and will thus deepen our understanding of the nuclear force. Qualitatively new features may emerge since nuclei far from stability are characterized by large differences in the proton and neutron Fermi energy levels, relative closeness of the ground and continuum states, and large differences between the proton and neutron density distributions at the nuclear surface. In addition, understanding the isospin dependence of the equation of state of nuclear matter will be an important aspect for understanding the formation and properties of neutron stars [1,2].

Major advances are possible with beams of rare isotopes ("radioactive nuclear beams", RNB) produced either by projectile fragmentation plus in-flight separation or by target fragmentation plus reacceleration (isotope separation on line, ISOL) techniques. The LRP recommends that both techniques be pursued vigorously in the US, and identifies the corresponding construction projects as the highest priority new initiatives. By 2001, the ongoing coupled cyclotron upgrade of the NSCL will provide unique capabilities due to the large gains (×1000) in RNB intensities. Further, significant planning is underway for the construction of a second generation ISOL facility in the US. As identified in a recent workshop at Lawrence Berkeley National Laboratory [3], the effective use of these new RNB facilities requires new instrumentation. The present proposal describes a very effective instrument for nuclear structure and reaction studies at these new facilities.

The proposal calls for the construction of a granular, large solid-angle detector-array with good energy, angle, and isotope resolution. The proposed detector consists of a closely packed array of telescopes comprised each of two planar silicon strip ΔE-detectors backed by CsI(Tl) E-detectors with PIN-diode readout. The present collaboration has built a small prototype array and used it with excellent results in a recent series of experiments. The proposed detector, based on this design, can be upgraded and has a flexible geometry. A sketch for one possible configuration, a closely packed forward array covering laboratory angles $5° \leq \theta \leq 40°$, is given in Figure 1. In this configuration, the array covers a solid angle of 1.4 sr with an angular resolution of about 0.25° in the laboratory frame. As discussed in Section 5c, the prototype detectors exhibit excellent energy and isotope resolution over a broad range of energies and particle types.

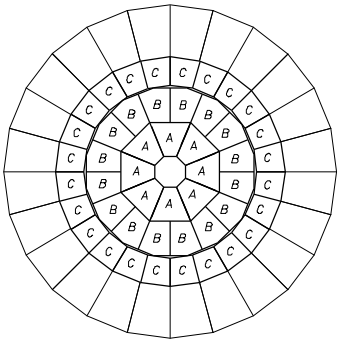

Figure 1: Front view of the array in a standard configuration arranged in three rings of detectors, with front faces labeled A, B and C, which subtend $5° \leq \theta_{lab} \leq 40°$.

When it comes into operation in 2001, the NSCL coupled cyclotron facility will permit a large number of studies of many new neutron-rich nuclei, including the particularly interesting ones at the neutron dripline up to sulfur (the present limit is oxygen), and the important T=0, N=Z nuclei up to the doubly magic nucleus ^{100}Sn. A large number of nuclei near and at the proton drip-line, important for the rapid proton capture process (rp-process) in hot stellar environments, will be accessible for detailed study. The new beams available at the NSCL will not only allow important investigations in nuclear structure and nuclear astrophysics, but also new measurements relevant to the isospin-dependence of the equation of state (EOS) and the liquid-gas phase transition. Radioactive beams offer the opportunity of exploring the differences between neutron- and proton-rich hot nuclear matter. Many of the measurements envisioned require granular detectors with large solid angle coverage and good energy, angle, and isotope resolution and are therefore very well suited to the proposed detector.

Experiments with RNBs present a significant experimental challenge. For example, in many interesting cases the evolution of nuclear structure must be studied with beams of intensities as low as 10^4 particles/second (p/s) -- or less. To be useful at low beam intensities, the new detectors must cover most if not all of the interesting solid angle. To allow optimization for a given reaction, the detector should be capable of rearrangement into a variety of

geometric configurations, and it must be versatile enough to allow its incorporation into other experimental set-ups when more detailed coincidence information is needed (e.g., for background suppression, neutron detection, etc.).

The immediate use envisioned for the proposed detector will be aimed at the effective exploitation of the new research opportunities at the upgraded NSCL facility. However, construction of this detector and the development of its high-density, low-cost integrated electronics address pressing needs identified at the ISOL detector workshop [3]. Thus the proposed array will also be of great use at other RNB facilities including the future ISOL facility envisioned in the LRP. In the remainder of this section, the impact of this proposed array upon a wide variety of different research topics is presented with a focus upon the immediate needs of the envisioned experimental program at the NSCL. Since many of the experiments discussed below will need strip detector arrays similar to the one proposed here, the proposed array will serve as a broad range instrument available to users.

Direct Reactions

Reliable nuclear structure information is best obtained by employing well-understood experimental probes like inelastic light-ion scattering, pick-up, and stripping reactions. For example, reactions such as (p,p′) can be used to probe changes in nuclear deformation; (p,d) reactions can probe neutron orbits and allow mass measurements relevant to the nucleosynthesis of A=50 - 100 nuclei; and (d,p) reactions provide important information about the shell structure and pairing in neutron-rich nuclei and allow additional ways to perform mass measurements. For short-lived isotopes, these probes must be used in inverse kinematics where the traditional roles of target and projectile are reversed. These measurements require light-particle coincidence detectors of outstanding angular, energy and isotopic resolution. To be useful at low beam intensities, the detectors must, in addition, cover most if not all of the interesting solid angle. To allow optimization for a given reaction, the detector should, in addition, permit a variety of geometric configurations, and it must be transportable so that it can be incorporated into other experimental set-ups when more detailed coincidence information is needed to reduce the background, for example.

Nuclear structure studies with radioactive beams often require the development of new spectroscopic techniques many of which involve the detection of coincident particles with high resolution and high efficiency. The proposed array will address many of the anticipated needs. For example, low-lying particle unbound states or the unbound ground states of nuclei beyond the driplines can be explored by resonance decay spectroscopy [4]. In this technique, the particle unbound resonances are reconstructed by detecting all particles emitted from the parent nucleus with sufficient resolution to allow the reconstruction of the decay energy and angular distributions. Similar coincidence techniques are gaining important applications in nuclear astrophysics since capture reaction cross sections are being determined by measuring the inverse Coulomb breakup reaction and using detailed balance. For example, the Coulomb breakup (γ,p) in the virtual photon field of a heavy target nucleus can be used to determine astrophysically interesting (p,γ) capture cross sections [5-8]. More recently, high energy knock-out reactions have shown great promise in the determination of spectroscopic factors [9]. The proposed particle detection array will be ideally suited to the detection of recoil protons from knock-out reactions on proton targets with the goal of determining the quasi-elastic knockout component and simplifying the interpretation of knock-out cross sections.

Examples of reactions that can be performed in inverse kinematics are given in Table 1; also listed in the table are typical beam energies and scattering angles (in the lab and c.m. systems) of the recoiling light fragments.

Reaction	target,ejectile	$E_{Beam/A}$ (MeV)	C.M.Angles	Lab Angles	E_{Recoil} (MeV)
Elastic, Inelastic	p.p′ α,α′	30-130	0-40	0-90	2-200
Transfer	p,d	50-100	0-20	0-40	8-20
“	d,p	10-30	0-10	180-150	2-5
“	^{4}He,t	50	0-5	180-140	1-6
“	^{4}He,t	10	0-10	0-40	1-2
“	d,^{3}He	30-100	0-10	0-30	5-10

Table 1: Kinematic domains for measurements of various light ion direct reactions in inverse kinematics.

Typical beam energies and emission angles of light decay products encountered in decay spectroscopy measurements are given in Table 2.

Reaction	$E_{Beam/A}$ (MeV)	c.m.angles	Lab Angles	E/A Products (MeV)
Decay Spect.	30-100	0-15	0-10	20-130
Coulex.	30-100	0-10	0-8	20-130

Table 2: Characteristic energies and angles for the decay products of particle unstable nuclei produced by inelastic scattering and transfer reactions of radioactive beam nuclei on stable targets in normal kinematics.

The following subsections present a number of specific examples for direct reaction measurements. Clearly this list of examples is not exhaustive, but serves to illustrate how the proposed detector meets the specific experimental needs.

- Transfer Reactions in Inverse Kinematics:

Single nucleon pickup and stripping reactions provide spectroscopic information about the single nucleon orbits in nuclei that are the basis of microscopic models like the shell model. In addition, transfer reactions allow precision Q-value measurements and can hence provide accurate mass and excitation energy measurements needed to constrain nuclear structure and astrophysical nucleosythesis calculations.

The (p,d) reaction is well suited to inverse kinematics experiments, and it provides a powerful tool for finding and characterizing the energy levels of nuclei. Unlike (d,p) reactions, which require relatively low energies (10-25 MeV) to be sensitive to the neutron orbital angular momentum, the more negative Q-values of (p,d) reactions are better matched at higher energy. Center of mass proton energies of approximately 50 MeV (corresponding to radioactive beam energies of approximately E/A = 50 MeV) are ideal for these studies, but similar spectroscopic information can be obtained at 25 ≤E/A≤100 MeV. The (p,d) reaction can be used to study the changes in the shell structure of the N=8, 20, 28,50 and 82 isotones from the proton-rich to neutron-rich side of the valley of stability. Investigations on the neutron-rich side will reveal details about the neutron wave functions for halo and neutron skin nuclei in a region where the ordering of neutron orbits can shift significantly with nuclear charge. In addition to nuclear structure studies, (p,d) reactions on proton-rich radioactive beam nuclei will provide accurate mass measurements of astrophysically significant nuclei, such as ^{65}As, ^{79}Y, ^{80}Zr, ^{83}Nb, ^{84}Mo, and ^{84}Nb that are waiting points in the rapid proton (rp) capture process relevant to very hot stellar environments [10]. The measurements will not only provide ground state masses to 10keV, but also determine resonance energies of excited states to a similar accuracy.

As the experimental requirements for measurements of the (p,d) reaction in inverse kinematics depend little on the choice of reaction, we can illustrate their general characteristics using the ^{1}H (^{12}Be,d)^{11}Be reaction. This pickup reaction can test the mixing of a low lying intruder band in ^{12}Be with the normal 1p shell configuration [11]. Such mixing should lead to a large probability for neutron pickup from the $2s_{1/2}$ orbital leading directly to the $1/2^{+}$ ground state of ^{11}Be. In inverse kinematics, measurements of the ^{11}Be scattering angle cannot provide the c.m. energy and angle of the scattered particles with sufficient accuracy, and the deuterons must be measured instead. Figure 2 shows how the deuteron laboratory energy varies for transfer to the ground state (lower curve) and first excited state (upper curve) with the center of momentum (c.m.) scattering angle (upper scale) and laboratory angle (lower scale) at $0<\theta_{lab}<10°$ and $20°<\theta_{lab}<40°$. Due to the negative Q-value of the (p,d) reaction, deuterons are swept forward in the laboratory with modest energy. Depending on the Q-value for the reaction, the laboratory energies of the

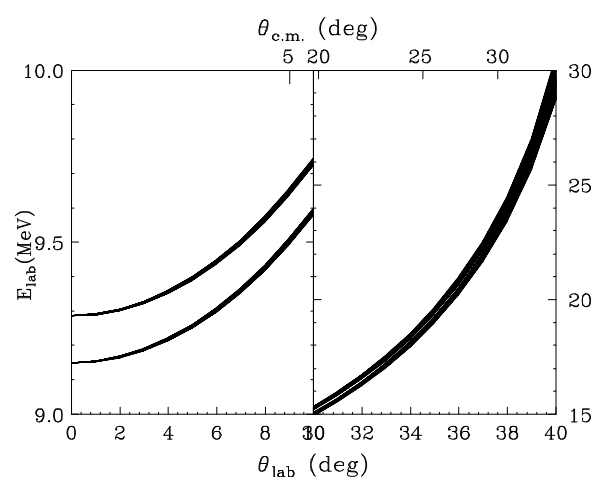

Figure 2: The deuteron energy vs. the laboratory (lower scale) and center of mass (upper scale) scattering angles for the ^{1}H(^{12}Be,^{2}H)^{11}Be reaction.

deuterons can be somewhat higher or lower, with typical values in the range of about 10 to 30 MeV.

The 1/2+ and 1/2- states in ^{11}Be are separated by about 320 KeV in excitation energy. The resolution of these states will be influenced by energy loss in the target and the angular and energy resolutions of the deuteron detector. Measurements of the time of flight of the radioactive beam permit compensation for the beam energy spread and limit its contribution to the excitation energy resolution to about 20 KeV. Accurate fast beam tracking will allow compensation for the beam phase space and remove it from being a major influence on the energy uncertainty. Thin targets (<1 mg/cm^2) are required to maintain resolution, requiring large solid angle detectors like the proposed array, in turn, to overcome the combination of thin target and low beam intensity. Accurate measurements of the detection angle are essential to reduce kinematic broadening effects and resolve close lying states. The 1.5 mm strip width of the detectors of the proposed array corresponds to an angular resolution of ±0.12° and leads to a kinematic broadening contribution represented by the widths in the curves in Fig. 2. This contribution to the resolution is negligible at small angles but broadens the ground and first excited state peaks at larger angles. The excellent resolution of the proposed array allows the two states to be well resolved at c.m. angles in excess of 25° permitting accurate spectroscopic measurements.

Comparable resolutions are achieved for (p,d) reactions with other radioactive beams in inverse kinematics . Mass measurements on proton drip line nuclei, such as ^{65}As via the p(^{66}As,d)^{65}As reaction, can be obtained from the centroids of the deuteron spectra to an accuracy of the order of 10 keV. This can be achieved in a one day experiment with a beam intensity of 2000 ions/s, assuming a 1 mb/sr cross section, a 1 mg/cm^2 target, and 120 keV resolution. At this level of sensitivity one can measure the mass (and low-lying states) of N=Z nuclei up to ^{98}Cd at the NSCL.

Similary, the (d,p) reaction can be used to study neutron single particle states in very neutron rich nuclei, to provide constraints upon mass equations, and through these constraints, to help locate the neutron drip-line. Due to the angular momentum mismatch, both large Q-values and high angular momenta are favored by (d,p) reactions for energies of 50 MeV/A. To reduce this mismatch, it is desirable to investigate (d,p) reactions at lower energies at or below 25 MeV/A. To illustrate such experiments for beam energies feasible at the Coupled Cyclotron Facility, figure 3 shows the energies expected in inverse kinematics for the ^{2}H(^{32}Mg,p)^{33}Mg reaction at E/A=20 MeV. Due to the positive Q-values of this reaction, protons are emitted at backward angles in the laboratory and would be measured in the proposed array by centering it about θ_{lab} = 180°. The (d,p) reaction will be employed, for example, to determine the evolution of the fp-shell neutron orbits.

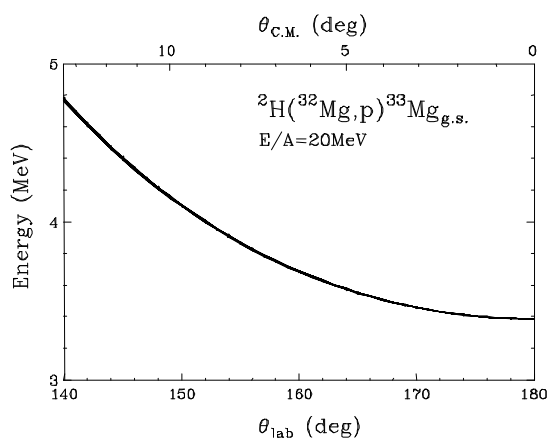

Figure 3: The proton energy vs. laboratory scattering angle (bottom scale) and center of momentum scattering angle (top scale) for the ^{2}H(^{32}Mg,p)^{33}Mg reaction at E/A = 20 MeV.

The previous two reactions provide information about neutron orbitals. Similar information about proton orbitals can be obtained from (^{3}He,d), (d,^{3}He) and (^{4}He,t) reactions. The proposed high resolution array therefore provides a broad range capability needed to explore the variations of single particle orbits with isospin near the proton and neutron drip lines. Use of the proposed array permits these studies to be performed with this array at beam intensities as low as 10^4 particles/s.

- Elastic and Inelastic scattering in inverse kinematics

Inelastic scattering provides detailed information about the strength distributions, levels and resonant structures of nuclei. Studies at lower energy typically investigate low-lying collective modes, whereas higher energies (100 MeV) are used to study isospin and magnetic resonances.

Figure 4 illustrates the relationship between c.m. and laboratory scattering angles and the laboratory energies for elastic proton scattering and inelastic proton scattering to the first excited state of ^{46}Ar. Forward elastic scattering in the c.m. corresponds to laboratory scattering angles of about 60-85 degrees, and the same angular

domain is relevant for inelastic scattering to low lying excited states. For such measurements, the proposed array will therefore be reconfigured at larger angles as shown in Fig. 5. The distance between target and array can be varied to optimize resolution and count rate. At a nominal distance of 35 cm the angular resolution of the array is approximately ±0.12° which leads to an excitation energy resolution of about 135 keV, more than sufficient to resolve these two states

Elastic and inelastic scattering measurements have already been performed in inverse kinematics for the light Ar isotopes using beams of 10^4 s [12] and this array will permit measurements with intensities of 10^3 /s. The cross sections for elastic scattering are among the largest to be measured and will allow measurements with array to be made out to modest angles in the center-of-mass system for beams of intensity as low as 100 particles/s.

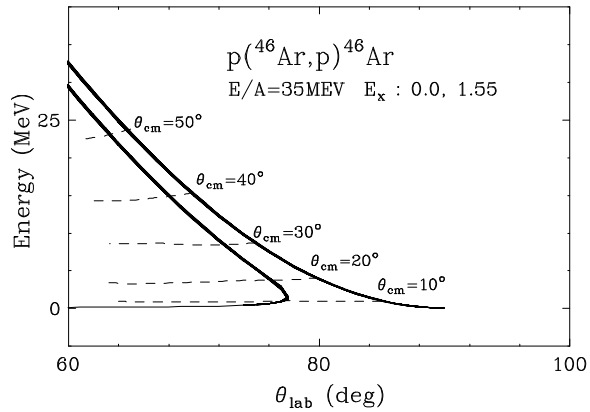

Figure 4 The proton energy is plotted vs. laboratory scattering angle for elastic scattering (upper curve) and inelastic scattering (lower curve) from ^{46}Ar in inverse kinematics at E/A = 35 MeV.

Proton, deuteron and alpha particle inelastic scattering can also be used to excite radioactive ion beams to the giant resonances. The excitation of the Giant Monopole Resonance in neutron-rich radioactive ion beam nuclei offers a unique opportunity to probe the nuclear breathing mode in neutron rich matter and test the extrapolation of the nuclear incompressibility towards neutron matter. This extrapolation would be relevant to the supernova bounce, the formation of neutron stars and their stability against gravitational collapse. Due to the large negative Q value for giant resonance excitation, the relevant final deuteron and alpha particle laboratory angles are less than 40°. For example, deuterons scattering inelasticly to $\theta_{c.m} \approx 1°$ from the Giant Monopole Resonance of ^{128}Sn are detected at $\theta_{lab} \approx 7°$ with a laboratory energy of about 1 Mev for incident ^{128}Sn ions at E/A=35 MeV. These deuterons will stop in the 100 μm ΔE_1 strip detectors and may be distinguished from other light particles via time of flight.

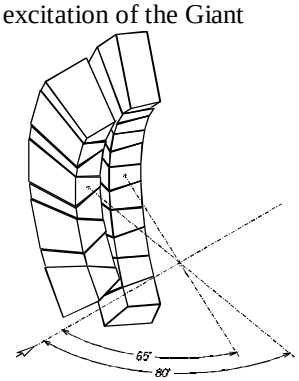

Figure 5: Drawing of the array positioned at 60°≤θ≤85°.

- Decay Spectroscopy and Inelastic Scattering to Particle Unbound Levels

Charged particle decay spectroscopy is a technique in which the outgoing momenta of the decay products are measured with sufficient precision to allow reconstruction of particle unstable nuclear states. The technique allows the measurement of energies and decay branching ratios of particle unstable states with high accuracy (especially when the relative energies of the decay products are small) and the extraction of astrophysically significant radiative capture cross sections by measuring Coulomb breakup cross sections and using detailed balance.

The study of particle unstable low excited states along the proton dripline are important for astrophysical reaction rate calculations like the hot CNO cycle and the rp-process. For example, the reactions ^{22}Mg(p,γ)^{23}Al, ^{23}Al(p,γ)^{24}Si, ^{25}Al(p,γ)^{26}Si, and ^{26}Si(p,γ)^{27}P can strongly influence the production of ^{22}Na and ^{26}Al in novae [13]. Nuclei beyond the dripline offer the unique opportunity to search for exotic decay modes like di-proton radioactivity predicted over 30 years ago [14], but not yet experimentally confirmed [17]. The inverse process to the two proton decay, two-proton capture reactions (^{18}Ne(2p,γ)^{20}Mg) could potentially allow a fast leakage out of the hot CNO cycle towards heavier masses. Although current estimates predict the rate to be small [15], the bound and unbound excited states of ^{20}Mg are not known and could influence those estimates. Another waiting point nucleus where the two-proton capture rate could influence the reaction rates of the rp-process is ^{38}Ca(^{38}Ca(2p,γ)^{40}Ti) [15].

These unbound states/nuclei are very hard to measure because the lifetimes are extremely short (~10^{-21}s). In the method of decay spectroscopy these states/nuclei can be measured by reconstructing the decay energy from the

energies and angles of the daughter nucleus and the emitted proton. It requires a good measurement of the energies and angles of the isotopically resolved decay products. Figure 6 shows the decay energy of ^{8}B produced with a stable ^{14}N beam and measured in a small array with an efficiency approximately two orders of magnitude smaller than the proposed array [16]. Decay spectroscopy measurements with radioactive beams have been limited to light nuclei (A<13) and were limited by modest resolutions of ~ 400 keV FWHM at relative energies of E_{rel}=1 MeV [18].

The resolution and efficiency of the proposed array is substantially better than the presently available detectors. The array will be placed at a larger distance compared to the previously discussed experiments, because the angular distributions for the unstable nuclei are strongly forward peaked. Figure 7 shows the resolution expected for the decay of $^{8}B \rightarrow {}^{7}Be + p$ produced in projectile fragmentation at three distances. At 120 cm, the array provides a resolution better than ≈ 48 keV FWHM for relative energies less than about 1 MeV. The efficiency at E_{rel} = 1 MeV is ~35% and can be increased to 65% by moving the array to 60 cm with some loss in resolution (see Fig. 7).

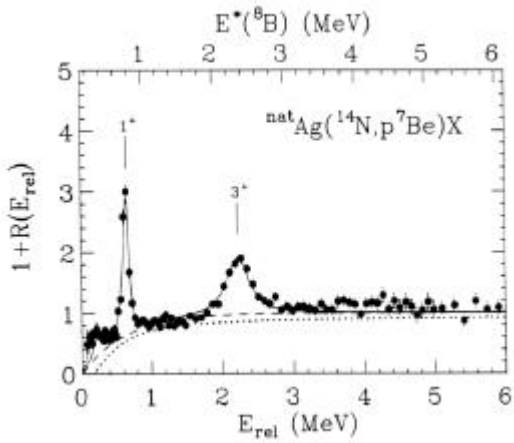

Figure 6: Decay spectrum for $^{8}B \rightarrow {}^{7}Be+p$ produced in central $^{14}N+Ag$ collisions at E/A = 35 MeV.

Present experiments measure the daughter nuclei together with the incident radioactive beam in a telescope at zero degrees, which limits the beam intensity to ~10,000 particles per second. With the higher beam intensities and higher energies of the coupled cyclotron upgrade, stopping the beam in the detector is no longer feasible and the S800 is necessary to achieve the separation and identification of the daughter following the decay. For states with very small decay energies the currently constructed sweeper magnet [19] positioned in front of the S800 will separate the fragments from the protons before they are detected in the proposed array.

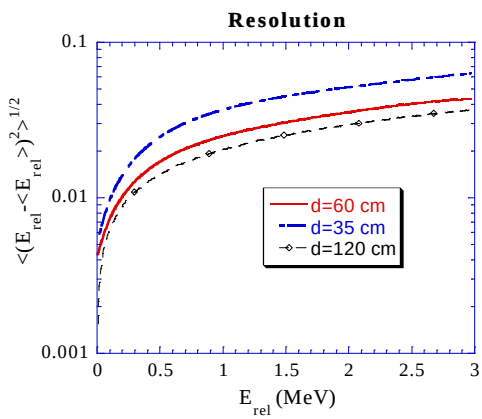

Figure 7: Resolution of the array for the decay ^{8}B fragments produced in projectile fragmentation at E/A = 50 MeV.

With such a setup, one can expect mass and excitation energy measurements of accuracy better than 10 keV and thus investigate the region of low energy resonances in the astrophyically significant nuclei such as ^{12}N, ^{20}Na, ^{23}Al, ^{24}Si, etc.. A simulation for the sequential decay of two protons from an unbound state in ^{20}Mg at 350 keV resulted in an energy resolution of 50 keV. The simulation was performed at 80 MeV/nucleon and included an energy resolution of the S800 of 1 in 4000, a 0.5% energy resolution of the array and a combined angular resolution of 0.2 degrees. The combination of the array with the S800 will allow the measurement of even more complicated decay process like the breakup of ^{8}C into four protons and an α-particle, which will allow the extension of the mass multiplet for A=8 to the proton-rich side.

- Determination of Radiative Capture Cross Sections

Proton and alpha radiative capture reactions play an important role in the nucleosynthesis of elements in stellar processes [10]. Important radiative capture reactions have been measured for the light elements, but such measurements become increasingly difficult for the heavier elements as they correspond to proton or alpha particle energies below the Coulomb barrier. This difficulty can be overcome by measuring the inverse reaction, breakup by the virtual photons in the Coulomb field of a heavy target nucleus, and using detailed balance [5]. Recently,

capture cross sections have been extracted for p+^{13}N and p+^{7}Be by measuring the Coulomb dissociation of ^{14}O and ^{8}B within the Coulomb field of a heavy target nucleus [5-8].

Such measurements are most straightforward when the Coulomb dissociation proceeds via a long lived resonance which decays far from the heavy target as is the case for the Coulomb dissociation of ^{14}O and other astrophysically interesting nuclei such as ^{23}Al (the reverse of p+^{22}Mg), etc. The proposed array will be well suited for such investigations when it is situated at forward angles. The measurements are essential the same as described in the decay spectroscopy section. Measurements, however, may be needed at several incident energies and with both heavy and light targets to verify that the cross sections scale as expected for Coulomb dissociation. These measurements require the very high efficiency and resolution of the proposed array.

Nucleus-Nucleus Collisions

Central nucleus-nucleus collisions can probe nuclear matter in extreme conditions. Compressed and highly excited matter can be produced in the region of overlap between projectile and target which subsequently expands and disintegrates [20]. The system evolves through extremes of both high and low density that approach densities encountered during the collapse and subsequent expansion of type II supernovae [1] or in neutron stars [2].

Multifragment decays of expanded nuclear systems can be explored to characterize the liquid-gas phase transition in low-density nuclear matter [21,22]. Detailed studies of radial and transverse collective flow provide information on the equation of state (EOS) of high-density nuclear matter [23]. Until now, most experiments were carried out with 4π detectors of limited isotope, angle, and/or energy resolution. These detector restrictions have limited the classes of investigations of multifragmentation, tests of transport theory and of the EOS. The proposed array will help resolve many important open issues such as the degree of N/Z equilibration, isotope production rates, thermalization, thermal fluctuations, and the role of high lying continuum states. In addition, isotopically resolved two-fragment correlation function measurements, sensitive to the space time characteristics of the disintegrating low-density system, will become possible for the first time.

- Multifragmentation

Measurements of freezeout conditions:

Measurements indicate that mixtures of intermediate mass fragments (IMF's) with $3 \leq Z \leq 30$ and light particles ($Z<3$) are emitted from hot nuclear systems expanded to sub-saturation density, on time scales consistent with a bulk disintegration ($\tau \leq 100$ fm/c) [24,25]. Many experimental observables can be reproduced by statistical equilibrium models which associate such multifragment disintegrations with a bulk transition between high and low density matter, that is closely connected to the liquid-gas phase transition of nuclear matter [26-28].

Such theoretical models rely, for simplicity, upon the assumption of equilibrium at a single "freezeout" density and temperature after which the system goes very rapidly out of thermal equilibrium. To the extent that this assumption is valid, the freeze-out volume can be determined from correlation function measurements [24,25], and the temperature can be determined from the relative populations of excited states (T_{E*}) [29] or from the isotopic yield ratios (T_{iso}) [30] of fragments emitted from well characterized collisions. Since the passage from the interacting breakup configuration to the non-interacting final state occurs over a finite time interval, however, corrections to equilibrium models due to the temporal evolution of the system are expected and evidence for radiative cooling during the disassembly has been reported [31-33]. In Fig. 8, temperatures (T_{iso})extracted from ratios of isotopes of Helium and Lithium in ^{129}Xe+^{nat}Cu collisions at E/A=30 MeV are analyzed as a function of the energy of the outgoing fragments [31]. The isotopic abundances of energetic

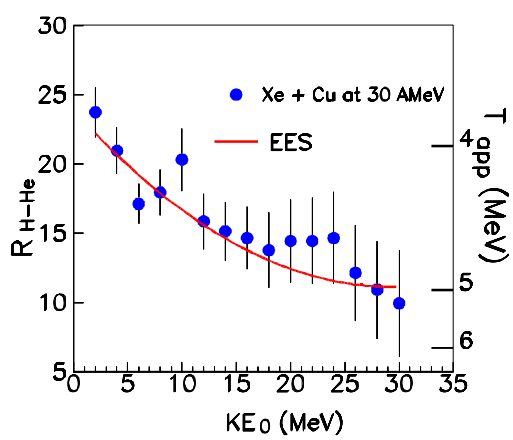

Figure 8: Temperatures extracted from the isotope ratio R≡Y(^{4}He)·Y(^{2}He) /[Y(^{3}He)·Y(^{3}H)] as a function of the kinetic energy (above the Coulomb barrier) in the C.M. system.

fragments (solid points) are consistent with higher temperatures, a trend which is consistent with evaporative calculations, shown by the solid lines, predicting that the average emission times for weakly bound light particles are shorter than those for strongly bound heavier fragments [34,35]. More investigations of temporal effects in multifragmentation are needed to understand them better and to determine whether it is possible to determine a 'Caloric curve' for the liquid-gas phase transition. The proposed array is ideally suited to perform the needed experiments. It permits measurements of isotopic abundances, excited state populations and isotopically resolved correlation functions with at high degree of precision. (The requirements for those measurements are essentially identical to those for the decay spectroscopy discussed earlier.) The resulting simultaneous determinations of correlation functions, relative populations of states, and isotopic ratios with high precision and efficiency, cannot be matched by any existing detector array.

Determination of the role of particle unbound states

Statistical models of multifragment decays predict that most fragments are highly excited at breakup. The internal excitation of the emitted fragments has a strong bearing upon the heat capacity of the system and upon the composition of the mixed phase region. In addition, experimental observables, such as the isotope and elemental distributions, can be strongly influenced by the subsequent decay of high-lying particle unbound states. A number of investigations [16,36,37] indicate that continuum states are, indeed, strongly populated, but existing experimental information is insufficient to discriminate between the different theoretical treatments of the population and subsequent decay of high-lying states. The proposed array with its excellent resolution and efficiency will be able to reconstruct these excited nuclei and address this problem with great precision..

Isospin dependence of multifragmentation

Radioactive beams offer the unique opportunity to explore isospin dependence of multifragment decays. Such investigations will provide new constraints for statistical models since branching ratios for fragment emission depend strongly on the neutron and proton content of the emitting source. As an example, Fig. 9 compares IMF multiplicities predicted by equilibrium statistical calculations using the model of ref. [28] for the decay of hot ^{180}Pb and ^{180}Yb nuclei. The calculations predict a shift of 1 MeV/nucleon for the threshold of multifragmentation. With beams from the coupled cyclotron facility, this prediction can be tested, and differences in the isotopic distributions of the emitted fragments can be investigated for the first time. (Such experiments are best performed in inverse kinematics to increase the solid angle coverage and lower the detection thresholds with respect to the rest frame of the emitting source.)

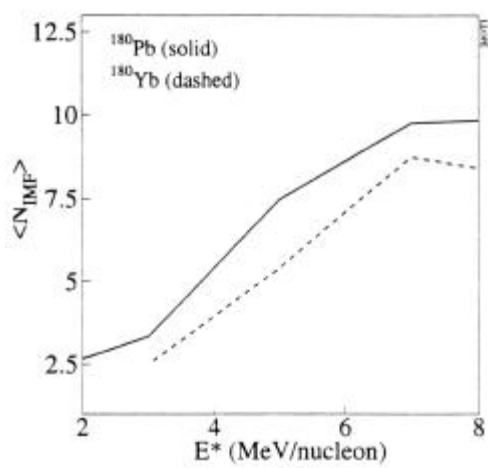

Figure 9 Upper panel: fragment multiplicities predicted by statistical multifragmentation model of ref. [26] for hot ^{180}Pb (solid line) and ^{180}Yb (dashed line) nuclei.

Measurements of isotopic distributions are needed to test models for a liquid-gas phase transition in two component (neutron and proton) nuclear matter which predict that the coexistence region for neutron-rich matter is composed of a more neutron-rich gas and a less neutron-rich liquid [22]. Analogous situations are encountered in the crusts of neutron stars [2].

- Investigations of Collision Dynamics

Intensity Interferometry Measurements

Information about the space time-evolution of the reaction zone can be obtained via intensity interferometry. This technique utilizes the fact that the relative wave functions of emitted particles are modified by final-state interactions or quantum statistics and that this modification strongly depends on the spatial separation of the emitted particles.

For intermediate-energy nucleus-nucleus collisions, two-proton intensity interferometry is understood best and has been developed furthest. Two-proton correlation functions at small relative momenta can probe the space-time characteristics of a reaction zone created in energetic nucleus-nucleus collisions, because the magnitude of nuclear and Coulomb final-state interactions, as well as antisymmetrization effects, depend on the spatial separation of the two protons at the time of emission [38]. Correlation functions are evaluated as a function of q, the magnitude of the relative momentum vector $q = |(\mathbf{P_1} - \mathbf{P_2})|/2$ in the proton-pair rest frame. The attractive S-wave nuclear interaction leads to a maximum in the correlation function at $q \approx 20$ MeV/c. Coulomb repulsion and antisymmetrization produce a minimum at $q \approx 0$. Both effects become more pronounced as the space time extent of the source becomes smaller.

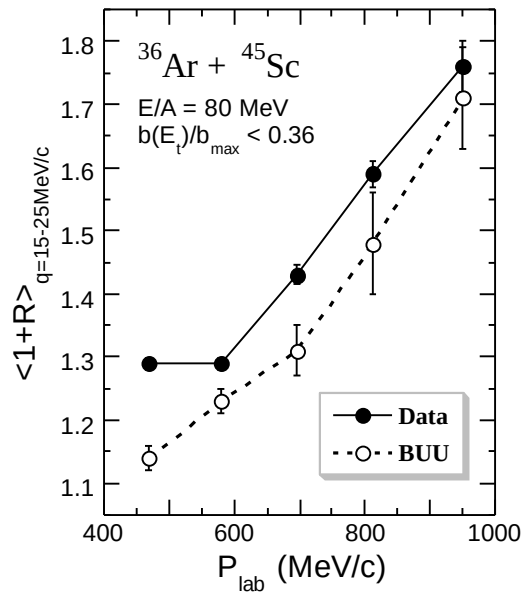

Figure 10: Total momentum dependence of the average height of the two-proton correlation function, $<1+R(q)>_{15\text{-}25\ MeV/c}$, for central $^{36}Ar+^{45}Sc$ collisions at E/A = 80 MeV. Solid and open points represent data and BUU transport model predictions, respectively. From ref. [39].

First impact-parameter filtered two-proton correlation functions were investigated for $^{36}Ar+^{45}Sc$ collisions at E/A = 80 MeV [39]. For central collisions, a strong dependence on the total momentum of the emitted proton pair was measured and well reproduced by Boltzmann-Uehling-Uhlenbeck (BUU) transport calculations [37], see Fig. 10. For these collisions, a careful analysis of longitudinal and transverse correlation functions revealed a suppression of the transverse correlation function as compared to the longitudinal correlation function, which could be understood as due to the finite time scale for proton emission [39] and which was quantitatively reproduced by the BUU model. Despite the impressive success of the BUU model, problems have emerged for collisions at higher energy -- where BUU model calculations should, in fact, have a more solid foundation. Several independent experiments [40,41] revealed a strong attenuation of measured two-proton correlation functions as compared to predictions, indicating that the BUU transport model predicts proton emission from too small a reaction zone, on too short a time scale, or both. It has been suggested that some fraction of the emitted protons may not originate directly from the reaction zone, but from delayed secondary decays of highly excited intermediate mass fragments. Estimates indicate that such secondary decay contributions might, indeed, account for the discrepancy between BUU prediction and experiment, but a quantitative confirmation of this effect is still lacking. The proposed array will make it possible to address this interesting question by measuring sequential decays of high lying resonances. In addition, the high efficiency and resolution of the proposed array will make it possible to obtain impact parameter filtered data of much higher statistical accuracy and with much better resolution at small q (< 20 MeV/c) where distortions from secondary decays will be manifest in the correlation function. Precision measurements of correlation functions at small relative momenta are also needed to apply newly developed tools for inverting the correlation functions to obtain a distribution of emitted particles [42].

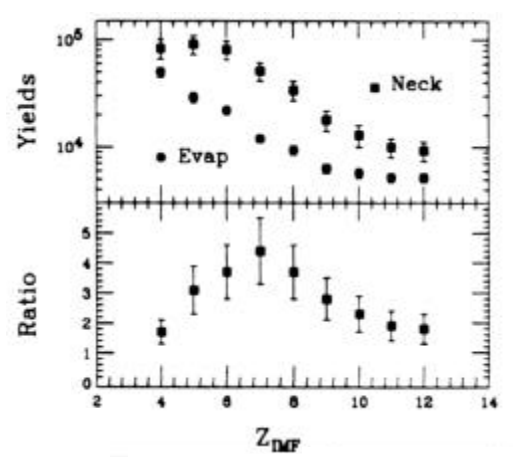

Figure 11: (Upper panel) Yield for fragment from the neck (squares) and emitted from the projectile-like residue (circles). (Lower panel) Ratios of the yields of neck fragments divided by the yield of fragments from the projectile-like residue. (lowest panel will be removed)

Neck Fragmentation

Neck fragmentation provides a promising new observable with which to test dynamical fragmentation models. Fragmenting necks are predicted to form in mid-impact parameter collisions with details depending on the compressibility [43,44] and isospin [44] of the mean field. Fragment yields resulting from evaporation and neck fragmentation have been measured for mid-impact parameter ^{129}Xe+Cu collisions at E/A=50 MeV [45], see Fig. 11. For this reaction, neck-fragmentation produces more fragments than evaporation (middle panel), and the relative abundance of neck-fragments reaches a maximum for Z_{IMF} ~ 7 [45]. Model calculations predict the production of mid rapidity neck-fragments to be particularly sensitive to fluctuations about the mean one-body trajectories [46].

Calculations predict further that the isotopic distributions of neck-fragments are sensitive to the N/Z dependence of the mean field [44]. Extreme values of N/Z can be attained in the neck region. Between the proton rich ^{108}Sn +^{112}Sn and the neutron rich ^{130}Sn+^{124}Sn systems, for example, one achieves roughly a 25% variation in the N/Z ratio of the neck region. Calculations predict that the neck region is more neutron rich than the composite system. One would therefore expect that neck-fragments to be considerably more neutron rich than fragments evaporated from projectile and target residues. The excellent isotopic resolution of the proposed array will allow detailed tests of these predictions.

c. Description of the Research Instrumentation and Needs

The proposed high-resolution charged-particle array is designed to satisfy the needs of the scientific programs discussed in the preceding sections for:

- an excellent angular, energy and isotopic resolution;
- a very large and granular solid angle coverage;
- a modular design that permits different geometrical arrangements for different applications.

In its normal operating position shown in Fig. 1, the proposed array covers a solid angle of 1.4 sr with an angular resolution of about 0.25° in the laboratory. The array covers about 80% of the solid angle relevant for nuclear structure investigations in inverse kinematics (about 50% for inelastic scattering experiments). When needed, the angular resolution of the array can be improved by giving up solid angle coverage and increasing the distance to the target. It can be reconfigured, as illustrated in Figs. 1 and 5, to address the different angular coverages demanded by different experiments.

Telescope Design

The proposed array consists of 48 Silicon-Silicon-CsI(Tl) telescopes, each composed of a 100 μm thick silicon strip detector (ΔE_1), a 1.5 mm thick silicon strip detector (ΔE_2), and a 4 cm thick CsI(Tl) scintillator (E) read out by a PIN diode. These thicknesses were chosen to ensure:

1) manufacture of the ΔE_2 detector without complex guard rings, needed for close packing geometry;
2) energy resolution better than 50 keV;
3) excellent isotopic resolution for particles with E/A > 3 MeV that penetrate through ΔE_1.

The required mass identification flight for low-energy hydrogen isotopes (E<3 MeV) that stop in ΔE_1. will be achieved by time-of-flight techniques.

The required angular resolution is achieved by utilizing strip detectors with a pitch of 1.5 mm between strips. The required granularity is achieved by individual strip readout and appropriate segmentation of the CsI(Tl) scintillators. (The proposed readout will be comparable in cost to a resistive charge-division readout of similar granularity, but it is more straightforward to operate and calibrate.)


Figure 12: Nine LASSA detectors.

The detectors of the proposed array will be similar to those developed for a prototype LArge Silicon Strip detector Array (LASSA), that was designed, constructed, and successfully used in seven experiments in 1998.To improve performance, the proposed array differs from the LASSA prototype in several details:

1) Improved angular resolution will be obtained with a 1.5 mm pitch for the silicon strip detectors (the pitch of LASSA was 3.2 mm).
2) Improved packaging density will be obtained by trapezoidal detectors (LASSA used square detectors). We anticipate designing the silicon detectors in collaboration with MICRON SEMICONDUCTOR [47]. In the past, the Washington University (WU) group worked with MICRON to develop their two-sided design "W" detector, now in common use, and the Indiana University (IU) group worked with MICRON to develop the compact packaging scheme of the LASSA detectors. The development cost for the proposed detectors is approximately $60k.
3) Improved isotopic resolution will be obtained by slightly thicker ΔE_1 and ΔE_2 detectors, 100 μm and 1.5 mm (instead of 65 μm and 0.5 or 1.0 mm for LASSA).
4) To improve energy resolution and granularity, the CsI(Tl) scintillators will be smaller than those of LASSA (4 cm thick as compared to 6 cm, and typically a factor of two smaller in lateral dimension).

Figure 13: LASSA double sided Silicon detector.

A picture of LASSA, is shown in Fig. 12. Protection foils have been removed to expose the 9 ΔE1 detectors. The square shape of the LASSA telescopes limits the packing density between the vertical rows. The trapezoidal shapes of the proposed array will allow an active detector coverage of about 80% of the solid angle spanned by the physical boundaries of the array. This close packing is possible by the mounting technique developed at IU for the LASSA array. The silicon wafers are held by G-10 frames which are only 1 mm wider than the active area of the Silicon wafer. Further losses in packing density are avoided by transmitting the signals from the silicon strips to the preamplifiers via flexible circuit boards. A photograph of a double-sided 500 mm silicon detector with two attached flexible circuit board cables is shown in Fig. 13.

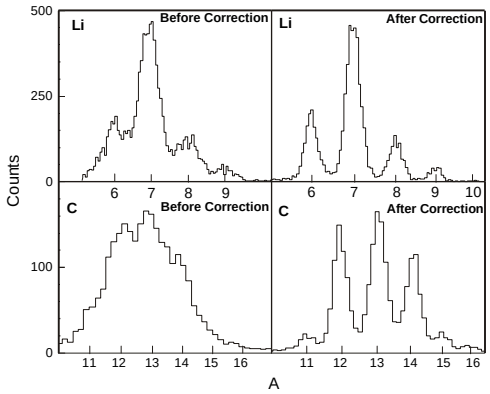

Figure 14: (Left panels) Lithium (upper panels) and Carbon PID spectrum without correction for the thickness non-uniformity of the first silicon. (Right panels) Corresponding spectra after the data have been corrected for the thickness non-uniformity.

For alpha particles, an energy resolution of 35 keV was measured for the silicon detectors of LASSA. Similar resolution will be achieved for the proposed array. The 65 μm thick ΔE_1 strip detectors of LASSA have a thickness non-uniformity of the order of 10% across the surface area of the detector. Such non-uniformities can be mapped and corrected by using the position readout, allowing excellent isotopic resolution. This is illustrated in Fig. 14. The top panel shows the particle identification (PID) spectrum obtained from the raw ΔE_1-ΔE_2 matrix, and the bottom panel shows the resolution obtained after correction for detector non-uniformities. Due to the increased silicon detector thickness, the PID for the proposed array will be even better.

Particles of more than 15-20A MeV may stop in the CsI(Tl) scintillators. (This will be the case for decay spectroscopy, Coulomb excitation, and many of the nucleus-nucleus collision experiments.) Resolving isotopes that penetrate through the 1.5 mm silicon detector will be straightforward. For LASSA, an energy resolution of 0.5 MeV was measured for 240 MeV alpha particles. By virtue of being smaller, the CsI(Tl) E-detectors of the proposed array will have significantly better energy resolution.

Electronics Readout

The WU group has significant experience in developing cost-effective computer-controlled electronics (both linear and logical) that includes developing the electronics for the LASSA array. The scale of the proposed array will require a more cost-effective technology, however. We therefor plan to adapt the high-density strip detector readout electronics developed for RHIC, CERN and space science experiments. This generation of electronics uses

specialty Application Specific Integrated Circuits (ASIC's) which couple to multiplexed high speed flash ADC's. One ASIC chip could, for example, provide signal amplification, shaping, sample and hold for 32 strips of one ΔE_1 detector, replacing many NIM or CAMAC modules.

The cost advantage offered by the proposed approach is illustrated as follows: The typical cost of reading out a strip using high density CAMAC or VLXI electronics (the LASSA electronics is CAMAC) is of the order of $400, half of which is the cost of the ADC channel. Using this technology, the readout cost for the 5400 channels of the present array would be about $2M. By developing a readout scheme in which ASIC's sequentially feed flash ADC's that digitize the linear signals of the array, this cost can be reduced. We plan to group the ASIC's into 3 groups, each group feeding one flash ADC, allowing event processing in about 80us/event. We estimate the corresponding cost of this readout scheme to be about $300k, of which $80k is the estimated cost of prototyping the system.

We propose to modify advanced ASIC's to enable an optimization for each experiment to the dynamic range of input signals that must be processed by the electronics. This will permit high resolution to be obtained in all the planned experiments. This flexibility adds to the cost, but is essential. We believe this development to be the most cost-effective approach for the proposed array, and its development will be of great benefit for other low-energy nuclear physics experiments.

A number of options can be pursued which allow changes of dynamic range. One would be to develop an ASIC with a computer adjustable gain; however, one must be careful not to introduce noise. Alternatively, one could install several ASIC's with different gains and switch from one gain to another with plug-in modules -- or operate them in parallel, giving several different gain outputs simultaneously. Prototyping and testing will be required to choose among the various options. We envision doing this in conjunction with engineers at INTEGRATED DETECTOR & ELECTRONICS (IDE), a Norwegian company and have based the cost estimate for the electronics on this assumption. In greater detail:

1) The principal linear and logic ASIC's will the VA and TA series of chips fabricated by INTEGRATED DETECTOR & ELECTRONICS (IDE) [48]. For several years, this Norwegian firm has produced and supplied these chips to high-energy experiments. Recent improvements in the VA line and the newer TA (trigger) line make the application of these chips to our needs very promising.
2) The linear and logical ASIC's will be mounted on a smart MOTHERBOARD which will AC couple the Silicon to the inputs of the VA32_HRD chip, supply the power to the ASIC's, bias the Silicon detector and control the gain if remote gain switching proves feasible. (The possibility of event generated gain changing is also under consideration.) Tests will be required to determine whether this board must be attached to the Silicon detector. The board will be developed at WU which will have a wire bonding facility to allow efficient prototyping and quick and cost-effective repairs to broken wire bonds on the silicon detectors.
3) Because of the great potential benefit offered by remote gain switching, we request R&D funds to explore and evaluate the possible modifications of the VA32_HRD ASIC to make it gain adjustable before freezing in the final design. If the noise is unsatisfactory, parallel circuits of ASIC's will be adopted. This will definitely work. Either option will allow completion of the project within budget.
4) The ADC costs were calculated by assuming that the linear output of the VA chips will be read by the WIENER SDRS series (V-686 -V689) VME flash ADC system. As the ΔE_1 and the two layers of the ΔE_2 will run with different gains and have separate logical sequences, we plan to run three such systems to reduce the conversion and readout time.
5) We plan to process the logical and time information using the TA series ASIC's, but some modifications to the TA ASIC will be required. The time digitization will be needed for a logical OR of all signals in each TA chip (48*3) and all the individual strips in one TA chip (48*32) for each telescope. The cost estimate was based upon the assumption that the digitization will done externally in VME TDC's, but the possibility of using a time (difference) to amplitude converter and multiplexer followed by another flash ADC will be explored.

5d Impact of Infrastructure Projects

The proposed array addresses a need identified at the recent Berkeley workshop on the instrumentation required for effective exploitation of the scientific opportunities at RNB facilities; i.e. a large solid angle,

segmented, position sensitive, high-resolution charged-particle detector array for inverse-kinematics nuclear structure and reaction studies. It is designed so that it can be reconfigured to provide the necessary angular coverage for these studies. It is portable and can be run as in a stand alone mode or in conjunction with other devices such as the S800 spectrometer. It can be moved between experimental vaults at the NSCL and outside of the NSCL for experiments at a second generation ISOL facility. The time for reconfiguration between standard operating configurations at the NSCL will be approximately two weeks, with one additional week safety margin needed for shake down of the electronics and computer system.

Several classes of experiments are discussed in the main body of the proposal that show how the presence of this array will enhance the capabilities of the NSCL experimental program and of the RNB program nation-wide.

The NSCL has a tradition of being a "hands on environment" for the training of graduate students and post-doctoral fellows and the presence of the proposed array will enhance the opportunities for undergraduates, graduate students and post-doctoral fellows to perform state-of-the-art research. The development plan involves graduate students and post-doctoral fellows at MSU, IU and WU in the design, construction and commissioning of the device and in its experimental program. In addition to the training of the undergraduates, graduate students and postdoctoral fellows from MSU, IU and WU, the very active outside user program at the NSCL involves an additional large number of graduate students and post-doctoral fellows. Additionally, undergraduate students from around the U.S. will become involved in research with the array through their participation in the MSU research experiences for undergraduates (REU) program.

e. Project and Management Plan

The proposal calls for the construction of a granular, large solid-angle detector-array with good energy, angle, and isotope resolution. The design of the array is sufficiently flexible so as to broadly address needs for high-resolution and high-efficiency charged-particle detection at the NSCL and to provide capabilities suitable for later experiments at a second generation ISOL facility.

The development of this array involves principal investigators from Michigan State University (MSU), Indiana University (IU) and Washington University (WU) who have collaborated on the development the LASSA and Miniball/Miniwall arrays. Both projects were completed on time (1-1.5 y), within budget and are very successful, serving a broad community of scientists. Technical responsibilities for the development of the proposed array will be divided between the three Universities following a blueprint utilized in the development of its prototype, LASSA: Washington University will take responsibility for the development of the electronics. Indiana University will take responsibility for the development of the Silicon detectors. Michigan State University will take responsibility for simulations of the apparatus, mechanical design, data acquisition and development of the CsI(Tl) detectors. Consultation between these group will occur on a regular basis, following a pattern established during the previous collaborative projects, to ensure compatibility of the distributed design and construction tasks.

The total project time will be 24 months. The proposed starting date is September 1, 1999, which will allow completion by September 1, 2001 and utilization during the first running period of the NSCL coupled cyclotron project.

The project will be funded by the National Science Foundation through a Major Research Instrumentation grant. Matching funds will be provided by Michigan State University, Indiana University and Washington University. Additional support will be provided to the project from NSF and DOE contract-supported scientific and engineering manpower redirected to this effort as a scientific pursuit. The project includes the development and construction of the array, its superstructure, electronics and data acquisition.

The total estimated cost is $1,839k, of which we request $889k from the NSF. Matching funds from Michigan State University ($395k), Indiana University ($95k) and Washington University ($38k) accounts for a total university matching contribution of about 37%. Additional funds will be provided to the project from the NSCL NSF operating grant PHY-95-28844 ($298k), and L. Sobotka's WU DOE ($59.5k) in the form of contract supported scientific manpower that have been redirected to this project. The IU group has also committed a postdoc to this effort from their DOE grant as well.

The overall project will be managed at the NSCL which is located on the campus of Michigan State University in East Lansing, Michigan. The project leader is William Lynch and he will report to the director of the

NSCL. It will be his responsibility to monitor the progress of the project and report the project cost and status of the schedule to the director

Users will be involved in the planning of this detector array through workshops organized at the NSCL. Upon completion, the detector array will be property of MSU and available to users. It will be maintained by the staff of the collaboration.