a. Results from Prior NSF Support

Two of the Principal Investigators (MT and PGH) are Principal Investigators on the recently funded MRI proposal “Acquisition of a High Efficiency Segmented Germanium Detector Array for Nuclear Structure Experiments with Exotic Beams”, and Thomas Glasmacher is the project leader. The initial design options have been evaluated and the detectors will be purchased in the near future.
Introduction

The National Superconducting Cyclotron Laboratory (NSCL) has been at the forefront of nuclear physics research with radioactive beams for approximately ten years. The laboratory's success has resulted from its innovative achievements in cyclotron technology, radioactive beam production and detector design and construction. The NSCL is now embarking on a major upgrade of its facilities. The coupling of two large superconducting cyclotrons and the construction of a new beam fragment separator will increase the intensity of radioactive beams by up to a factor of 10,000. This upgrade will provide world class radioactive beam capabilities to the NSCL. National Science Foundation support for this upgrade has been leveraged with a large contribution from the NSCL's host institution, Michigan State University.

The NSCL now faces the challenge of developing the detector technology necessary to fully exploit the important physics opportunities provided by the upgraded facility. Over the past several years, the NSCL and the NSCL users have developed a variety of new detection systems that have demonstrated the laboratory's world-class capabilities in design and construction. The key components for the experiments with radioactive beams from the coupled cyclotrons exist at the laboratory. The S800, a large superconducting magnetic spectrometer designed to measure charged particles with very high resolving power, a neutron time-of-flight facility consisting of two neutron walls - each with an area of $4 \text{ m}^2$ - with excellent resolution and efficiency for the detection of high energy neutrons and a segmented Germanium array, now under construction, which is optimized for high resolution measurements with beams in the 100 MeV/nucleon range. However, the laboratory lacks the capability to measure neutrons or charged particles at zero degrees in coincidence with charged fragments, which is an important technique in studies of neutron and proton rich nuclei.

In order to detect neutrons at zero degrees it is essential to sweep the beam (and the projectile fragments) away from zero degrees and detect the charged fragments in a separate device away from the neutron detector. A fragment detector located in front of the neutron detector would produce an unacceptable large background in the neutron spectra. In addition, with the high intensity beams that will become available from the coupled cyclotrons it is no longer feasible to stop the direct beam in the detector.

Neutron-heavy fragment coincidence experiments are essential to explore the physics of nuclei along the neutron driplines. The exploration of nuclear behavior along the neutron and proton drip lines, where nuclei become unstable with respect to decay via neutron and proton emission is one of the important physics opportunities that will be available at the upgraded facility. In these regions, valence nucleons are only loosely bound to the others and the nuclei exhibit new types of behavior that challenge our understanding of these many-body systems. Here we propose to construct a "sweeper" magnet that will enable detailed spectroscopic studies of nuclei along both the proton and neutron drip lines at the high beam velocities that will be produced with the coupled cyclotron facility. A smaller sweeper magnet on loan from LBNL is now used for neutron coincidence experiments at the NSCL; however, its use is limited to the low beam energies of the present facility and is inadequate for the upgraded cyclotrons. The proposed new sweeper magnet intended for the more rigid beams the upgraded facility.

We propose to leverage the NSCL's expertise in design and construction of sophisticated detector systems by collaborating with the National High Magnetic Field Laboratory at Florida State University in constructing the sweeper magnet system. This collaboration will take full advantage
of the NSCL's long relationship with Florida State University and the magnet construction expertise at FSU's NSF-funded National High Magnetic Field Laboratory. The collaboration will also allow the NSCL staff to focus on the successful implementation of the coupled cyclotron facility.

**Experiments along the Neutron Dripline**

There is increasing evidence that new phenomena are encountered at the neutron and proton drip lines [1-4]. Close to the neutron dripline the nuclear closed shells (“the magic numbers”) are expected to shift or even to vanish, the nuclear surface can become very diffuse, and the valence particle's wavefunction can extend tens of fermi away from the central part of the nucleus [4]. The unusual structure of these “halo” nuclei also shows new resonance characteristics, such as “soft” modes of oscillation [4,5]. Most of our knowledge of halos has been amassed in experiments with the lightest elements, helium, lithium and beryllium, and it is only recently that experiments with isotopes of carbon have been undertaken at the NSCL [6,7] and elsewhere [8,9]. With the current beam intensities available worldwide, the drip line is can only be studied up to beryllium ($Z=4$) for neutrons and perhaps neon ($Z=10$) for protons. It is estimated [10] that the NSCL upgrade will greatly expand the studies of the drip lines. The neutron drip line through sulfur ($Z=16$) and the proton drip line up to near tin ($Z=50$) will be accessible with sufficient intensity secondary beams.

The key will be to study the evolution of the nuclear structure over a wide range of nuclei. A promising technique for the studies of drip line nuclei is to measure their breakup on different $Z$ targets, Coulomb dissociation on heavy targets and nuclear breakup on light targets. The Coulomb interaction is well understood and removes one uncertainty in interpreting halo results. For large halos the cross sections are also extremely large (300 barns/sr in the case of 29 MeV/A $^{11}$Li) and even very weak beams can be studied [11]. There has been much progress in the understanding of how contributions from different multipoles and from other higher-order processes can affect our understanding of the observables [12]. The application of this technique requires the detection of the pieces of the Coulomb breakup; e.g. a neutron and a $^{34}$Na in the case of $^{35}$Na breakup. The breakup momentum distribution and total cross sections are sensitive to the valence particle wavefunctions and the relative neutron fragment energy spectrum can show the nuclear resonance properties. These kind of measurements can only be done if the proposed sweeper magnet is built.

Reactions of weakly bound nuclei on light targets are dominated by nuclear breakup. Nuclear breakup shows an interplay between nuclear structure and the reaction mechanism [13]. Although the nuclear reaction mechanism is not as well defined as Coulomb breakup, experiments with $^{11}$Be and $^8$B breakup [14,15] on a $^9$Be target have illustrated that momentum wavefunction information can be obtained in the context of an acceptable reaction model [16,17]. Again the nuclear breakup cross sections are large and weak beams are sufficient for determining the valence nuclear wavefunctions and in many cases the ground state spins and parities.

In the case of the nuclear breakup of multi-neutron halo nuclei a neutron-fragment coincidence is required to reconstruct the unbound fragment. For example the $^{22}$C beam intensity will be 10 ions/s with the coupled facility and the valence configuration of the two neutrons can be studied if $^{21}$C can be reconstructed. This type of experiment will also require the sweeper magnet, because the neutrons have to be measured in coincidence with the $^{21}$C.

A recent series of experiments carried out at the GSI [23] makes the spectroscopy of unbound states even more interesting. They measured an anisotropy in the decay of the neutron unbound $^5$He relative to the recoil direction, by reconstructing $^5$He from the neutron and $^4$He observations. This offers the possibility to determine the sign of the phase of the components of multi-neutron
halo wave functions, for example the relative phase of the $s+p$ components of the $^{11}$Li halo. The coupled cyclotrons will produce many other multiple neutron halo systems, which are unaccessible at the present time, such as $^{22}$C, $^{38}$Ne (if it is stable) and sodium to sulfur nuclei which have more than 28 neutrons.

The study of extremely neutron rich nuclei is not limited to nuclei along the drip line, but can be extended beyond the drip line. Examples of such systems are $^{7,9}$He, $^{10}$Li, and $^{13}$Be and there are many more beyond the region accessible to current experiments. While the light mass region can be studied with multi-particle transfer reactions with stable beams [18-21], heavier unbound systems along the dripline can only be accessed with single neutron or proton transfer reactions from radioactive beams. At RIKEN the mass of the unbound nucleus $^{10}$He was reconstructed from two neutrons and $^8$He following the one proton stripping of $^{11}$Li [22]. These studies are interesting by themselves as input for our understanding of nuclear structure, but they also provide parameters that enter in other calculations and interpretations of heavier nuclei. A good example is the $^{11}$Li three-body problem. In order to calculate the structure of the three body system the neutron-$^9$Li interaction must be known. This information can be obtained from the decay of $^{10}$Li, by measuring the neutron at zero degrees in coincidence with the heavy fragment ($^9$Li) which requires a sweeper magnet.

**Sweeper Magnet Coupled with the S800 Spectrograph**

The exploration of the neutron dripline as outlined above relies on neutron-charged particle coincidence measurements. The earliest experiments [11,24,25] detected the charged fragments in a detector telescope placed right behind the target. Although interesting results were obtained, the technique had the double inconvenience of producing many more neutrons in reactions in the particle telescope than were produced in the target itself and of having the neutrons traverse and possibly react in the telescope. The next round of experiments [26,27,28] circumvented this problem by using a magnet for sweeping the charged fragments away from the neutrons. The experiments with the Neutron Wall [29] used a surplus dipole with a field of about 1.5 T and 1m long from the old Bevalac for this purpose. Although this setup has produced interesting results, the magnet limits the useful beam energies to approximately 30 MeV/nucleon, the limitation evidently being most severe for experiments that detect fragments with a very high $A/Z$ ratio. After the completion of the upgrade, the NSCL will be most powerful at secondary beam energies around 100 MeV/nucleon which will open up the unique opportunity to explore the physics of extremely neutron rich nuclei up through sulfur which are currently completely unknown.

The proposed sweeper magnet will give this capability to the NSCL. In connection with the high resolving power, high angular resolution, and very good particle identification of the S800 [30], simultaneous neutron and fragment momentum distribution measurements are possible. The S800 carriage is designed so that when it is rotated to an angle greater than 37°, the forward angles are available for neutron detection. The sweeper magnet has a 40° bend for rigidities up to 4.0 T-m (the limit of the bending power of the S800) and hence charged particles can be swept into the S800 leaving a 7° cone in the forward direction for the neutrons (Figure 1) The requirement for a 7° neutron acceptance comes from the 2 meter neutron wall size located at a distance of 8 meters from the reaction target. In order to be used with the S800, the sweeper magnet will be centered at the S800 target position. The new target position is then shifted to a distance approximately 1/2 meter from the original S800 target location. The solid angle of the S800 will then be reduced from 20 msr to 15 msr when used with the sweeper magnet. This acceptance is still more than adequate for detection of charged fragments and represents acceptances of 6 by 8
degrees. Typical transverse momentum distributions can be as large as 200 MeV/c FWHM, which for a 7,000 MeV/c fragment (18C at 80 MeV/c from the breakup of 19C, for example) corresponds to an opening angle of only 1.6°. 

For the kinematic reconstruction of unbound ground or excited states the resolution of these states is dominated by the angular and energy resolutions of the neutron detection system. Thus, the high resolution of the S800 is not essential, and the stand-alone mode described in the next section is also an option. The reduced acceptance of the S800 does not limit these experiments, because the acceptance is again dominated by the neutron detection. The transverse contribution of the momentum imparted to the decay product translates into a larger angular opening for neutrons compared to the fragments. As an example, the right side of Figure 2 shows the laboratory angular distributions of the neutrons (top) and the fragments (bottom) following the decay of the ground state in 21C and hypothetical states in 48S with decay energies of 330 keV and 2 MeV. For the 2 MeV decay energy the angular width of the fragment distribution increases only from 1° to 2.5° (the angular acceptance of the S800 is ≈ 5°), whereas the neutron distribution width increases to 10.5°, beyond the acceptance of the neutron wall. The calculations were performed at 50 MeV/nucleon. Higher beam energies will increase the forward focussing of the neutrons and the fragments at the cost of resolution. The left side of Figure 2 shows the reconstructed energy spectra with resolutions of 160 keV and 400 keV for the 330 keV and 2 MeV states, respectively. The simulations assumed an energy resolution of the S800 of 1 in 5000, an energy resolution derived from time of flight for the neutrons of 2.5% and a combined angular resolution of 0.3° dominated by the neutron wall.

If the daughter nuclei have bound states it is necessary to identify the γ-decay in the daughter in order to reconstruct the relative population of the states in the unbound nuclei. Figure 3 shows a schematic arrangement of 130 detectors of the ORNL/MSU/TAMU BaF2 array positioned at forward angles to measure the decay of bound excited states populated by the neutron decay of unbound nuclei. The detectors fill the gap of the magnet at forward angles leaving the 7° cone open for the neutron detection. The detectors are very close to the magnet and it is important that the fringe field of the magnet is minimized for the photomultiplier tubes of the array to
function. The estimated field at a distance of 36 cm from the magnet is 100 G. This is achieved by two trim coils, as explained later, and is sufficiently small for the operation of the BaF$_2$ PMT’s [31]. A very similar setup was applied successfully for the first time recently in the study of $^{10}$Li with the Bevalac magnet and the neutron walls in the N4 vault where the 2.7 MeV $\gamma$-ray in $^9$Li was observed as it was populated following the decay of unbound $^{10}$Li [32].

The coupling of the sweeper and the S800 presents several experimental challenges. The sweeper magnet bends in the horizontal plane and the S800 bends in the vertical plane. This will result in correlation between $x$ and $y$ at the focal plane and can introduce aberrations not normally present in midplane symmetric systems. However, since the S800 uses ray reconstruction [33] to determine the particle momentum, the coupling of $x$ and $y$ only introduces additional terms in the reconstruction matrix. The principle of reconstruction remains the same: four parameters are measured in the focal plane of the S800 (two positions and two angles) and these are used to reconstruct the horizontal and vertical angles, the vertical position and the momentum at the target. Momentum spread of the radioactive beam can be compensated for by dispersion matching or tracking in the S800 analysis line.

**Stand-Alone Operation**

The upgraded facility will deliver beams with energies that exceed the bending power of the S800 (4Tm). The neutron detection efficiency decreases with increasing neutron energy so the largest production cross section is not the only criterium that determines the optimum beam energy for experiments with these exotic nuclei. However, the S800 is not able to bend very neutron rich beams at the highest energy.

In addition, for these high energy beams the neutrons from the breakup will also have higher

---

**Figure 2:** Reconstructed decay energy spectra from simulations for the decay of the ground state of $^{21}$C at 330 keV and assumed states in $^{45}$S at 330 keV and 2 MeV. The right panels show the angular distribution of the neutrons (top) and the fragments (bottom).
energies and thus a longer flight path is necessary in order to achieve an equivalent energy resolution.

For these purposes the magnet can be used in stand-alone mode in the extended N4 vault as shown in Figure 4. In this mode the magnet by itself is the “spectrograph”. We propose to instrument the sweeper magnet with a focal plane detector for stand-alone operation similar to the S800 detection system including tracking detectors [34].

With this detection system it is possible to use ray reconstruction to determine the momentum of the ions. For a 40° bend and a 4 mm incoherent spot size, the momentum resolution should be 1 in 500. Tracking at the target can improve the resolution by up to a factor of 8 and hence would be adequate for a wide range of experiments. This resolution is of course a function of the rigidity or bending in the magnet and will be smaller for the highest anticipated rigidities.

The detector for the stand alone mode will be substantially smaller (20 cm x 20 cm) than the S800 focal plane detector system and will consist of two (x and y direction) tracking detectors, an ion chamber for energy loss measurements, and a plastic detector for energy determination. Assuming that the lighter mass radioactive beams are fully stripped the energy and momentum resolution of the device is sufficient to separate individual masses up to mass 50, which is the limit of beams at the neutron dripline ($^{50}$S).

The use of the sweeper magnet as a “spectrometer” by itself in coincidence with the neutron wall is similar to the S800 mode described before but can be used at higher beam energies. Otherwise the setups are comparable and the use of the BaF$_2$ in this mode is also possible for cases where γ-ray coincidences have to be measured in addition to the neutron detection.

**Experiments along the Proton Dripline**

Many of the arguments presented above for nuclei along the neutron dripline are also applicable
for the proton dripline. At the proton dripline the interest lies predominantly in the search for exotic decay modes and the study of bound and unbound excited states. Ground state di-proton emission was predicted over 30 years ago [35], but has not been observed experimentally up to now [36-38]. While experiments at GANIL [39] concentrated on long lived two-proton emitters in heavier nuclei, at MSU we focussed on lighter, very short lived candidates like $^{12}$O [40] and $^{16}$Ne/$^{17}$Ne* [41]. Another heavier potential candidate for diproton decay that can be studied with help of the sweeper magnet is $^{19}$Mg.

Proton unbound states along the proton dripline can play a role in astrophysically-important reaction rates. The reaction flow in the rapid proton capture process ($rp$-process) can depend on two-proton capture reactions. For example, the reaction $^{18}\text{Ne}(2p,\gamma)^{20}\text{Mg}$ could potentially allow a fast leakage out of the hot CNO cycle towards heavier masses. Although current estimates predict the rate to be small [42], the bound and unbound excited states of $^{20}\text{Mg}$ 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 $^{38}\text{Ca}(^{38}\text{Ca}(2p,\gamma)^{40}\text{Ti})$ [42]. With the sweeper magnet it will be possible to measure the unbound states in $^{20}\text{Mg}$ and $^{40}\text{Ti}$.

Presently such experiments are performed on light mass nuclei with detector telescopes, which however, are not practical anymore for heavier nuclei. For very low decay energies, telescopes with multiple $\Delta E$ segments are used to detect the fragment and proton within one telescope, because in this case both are focussed at extremely forward angles. For large decay energies ($\sim$ 500 keV) the fragments are detected around 0°, and the protons are detected in an annular array surrounding the center fragment detector. The incident radioactive beam in these experiments is also stopped in the fragment telescope, which limits the beam intensity to $\sim$ 10,000/s. With the higher intensities and higher energies of the upgrade, stopping the beam in the detector is no longer feasible and the S800 is necessary to achieve the separation and identification of the heavy fragment following the decay. However, the momentum acceptance of the S800 is not sufficient to accept both the fragments and the protons. Thus a deflecting magnet is necessary in front of the S800 to separate the fragments from the protons. The protons can then be detected in a position sensitive $\Delta E/E$ telescope array.
As an example Figure 5 shows the possible setup for the detection of the two proton decay of $^{19}\text{Mg}$. The figure shows the trajectories for the extreme cases where the two protons are emitted at forward and backward angles in the projectile frame for an incoming beam energy of 80 MeV/u of $^{20}\text{Mg}$. The trajectories take a 6% momentum spread of the beam into account. The $^{19}\text{Mg}$ is then produced by neutron stripping and immediately decays within the target into $^{17}\text{Ne}$ and two protons. The protons are detected in an array of particle detector telescopes and the $^{17}\text{Ne}$ fragments in the S800. This setup is ideal for extending such studies to even heavier masses and provides the opportunity to close the gap between the approaches for producing di-proton emitters in light nuclei (at MSU) and in heavy nuclei (at GANIL) for the first time.

The proposed setup will be able to measure proton unbound states with extremely good energy resolution. Simulations for the decay of a proton unbound state in $^{20}\text{Mg}$ 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 position sensitive telescope array and a combined angular resolution of 0.2°.

Previous measurements of unbound states at the proton dripline typically had resolutions of several hundred keV [43].

**Broad Range Spectrograph Mode**

A third possible option of the sweeper magnet is to use it as a broad range spectrometer. We plan to use a spare superconducting quadrupole triplet from the S800 project as the focussing element in front of the sweeper magnet [44]. This mode would be useful for a wide range of experiments with high rigidity beams that exceed the bending power of the S800 and which do not require the neutron wall in coincidence.

For example, relativistic Coulomb excitation relies on the highest energy beams [45]. For the most intense transitions like some E2 transitions, additional sophisticated final state selection is not necessary. For weaker channels, however, it is essential to achieve isotopic resolution of the final fragments.

One specific example is the study of octupole vibrations excited by intermediate energy Coulomb excitation and detected with the recently funded position sensitive germanium detector array in coincidence with fragments in the detector array of the sweeper magnet (Figure 4). Octupole vibrations have historically provided critical tests for models which connect the microscopic and macroscopic pictures of the atomic nucleus. These excitations are built from one particle-one hole or two quasiparticle excitations of negative parity; thus, the microscopic composition of an octupole phonon is entirely different from that of the more commonly studied quadrupole excitation, and octupole decays provide information which is complementary to that given by quadrupole vibrations.
Figure 6: The sweeper magnet (in the N4 vault) as a broad range spectrometer for high resolution γ-ray experiments.

Almost no information is available on E3 strength - $B(E3;0^+_g \rightarrow 3^-)$ - in even-even radioactive nuclei. This situation is different from that for $2^+_1$ states, for which $B(E2;0^+_g \rightarrow 2^+)$ values in both stable and β-unstable nuclei can usually be determined from lifetime measurements, because $2^+_1$ states generally gamma-decay to the ground state. For $3^-$ states, the dominant gamma-decays are usually E1 transitions to $2^+$ and $4^+$ states. Recent advances in Coulomb excitation measurements of radioactive beams in even-even nuclei [46-47] have only yielded results on $2^+_1$ states because these states are both the lowest energy and most strongly populated states.

As an example, we consider the radioactive even-Z, N=20 isotones $^{30}$Ne, $^{32}$Mg and $^{34}$Si. A sharp phase change occurs between the strongly deformed nucleus $^{32}$Mg and its rigidly spherical neighbor $^{34}$Si [48]. The octupole behavior of these two nuclei may differ strongly as well. It is likely that in $^{34}$Si and $^{36}$S the low energy E3 strength is concentrated in a single $3^-$ state. The E3 strength in the deformed nuclei $^{30}$Ne and $^{32}$Mg, where $3^-$ states are not yet identified, may be strongly fragmented, as it is in the deformed nuclei $^{24,26}$Mg [49]. The N=20 isotones may, therefore, provide the opportunity to observe the two limiting types of octupole vibrational behavior - concentrated in a single $3^-$ state in a spherical nucleus and strongly fragmented in a deformed nucleus - in isotones only two protons apart.

It is expected that the $3^-$ states being studied here will be populated less strongly - by a factor of between 5 and 20 - than the $2^+_1$ states measured previously in these nuclei. Consequently, the γ-rays deexciting the $3^-$ states may be comparable in intensity to γ-rays from nuclei which are produced in transfer reactions involving the secondary beam. To distinguish between γ-rays produced by scattered projectiles and transfer reaction products, we propose to detect the γ-rays with the MSU Position Sensitive NaI Array [50] or the new array of segmented Germanium detectors [51] in coincidence with the detection of scattered projectile-like particles in the sweeper magnet, which can provide unit mass resolution below mass 50.

Another significant use of the broad range mode of the sweeper magnet will be for Coulomb breakup studies related to nuclear astrophysics. As a beam passes a high Z target like lead, it experiences an intense virtual photon flux. From detailed balance a measurement of a $(\gamma,p)$
cross section can be used to deduce a (p,γ) rate. The technique [45] has been used to extract astrophysical S factors for $^{13}\text{N}(p,\gamma)$ [53,54] and $^7\text{Be}(p,\gamma)$ [55].

A sweeper magnet is needed because the Coulomb breakup fragments must be detected in coincidence, for example in the case of the $^8\text{B}$, a proton and $^7\text{Be}$ must be detected. These ions have essentially the same velocity but quite different charge to mass, so a dipole magnet can separate them in space, and in addition separate them from the beam. The bend can also be used to determine the momentum of the ions and very low relative energy measurement can be made with high accuracy. There are many potential applications including all (n,γ) type measurements. One interesting possibility is a re-measurement of the rate of the $^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma$ reaction in order to reduce the uncertainties in the predicted production of $^7\text{Li}$ in the Big Bang ($^7\text{Be}$ decays to $^7\text{Li}$). Present results for this reaction are inconsistent [56] and Coulomb breakup would provide a new independent measurement. A final example is the $^{56}\text{Ni} + p \rightarrow ^{57}\text{Ni} \gamma$ reaction which determines the time evolution of X-ray bursts at the surface of accreting neutron stars. The reaction rate is determined by a single resonance. The resonance strength and energy can be measured by Coulomb mediated breakup of $^{57}\text{Cu}$ through this resonance [57].

The option to use the magnet as a broad range spectrometer would be in general useful for all experiments that need to cover a large range of outgoing particle momentum, require low magnetic field near the reaction target, or have magnetic rigidity requirements higher than could be met by the S800 (4.0 T-m). The focusing of the quadrupole triplet magnet will also minimize the area of charged particle detection required and increase the solid angle of charged particle detection. Generally, because the target would be moved an additional 1.5 m in front of the sweeper magnet this mode would not be useful for neutron coincidence experiments. A typical use would be for projectile breakup experiments where neutron detection is not needed, γ-rays are detected at the target location and the momenta of the fragments are measured in the spectrograph.

The energy resolution of the magnet as a broad range spectrometer will be 1 in 4000 for the maximum rigidity of 4 T-m corresponding to a 40° bend in the sweeper magnet. The quadrupoles could focus up to 7.1 T-m, in which case the corresponding bend in the sweeper is 22.4° and the resolution is reduced by almost a factor of two. Although the resolving power would be low, this bending limit would match the highest energy light fragments, e.g., 180 MeV/u $^{11}\text{Li}$. It is possible to increase this resolution by a factor of 4 by using the proposed tracking detectors based on the design of the current S800 focal plane detectors which have a resolution of 0.2 mm FWHM.

This mode of operation requires the construction of focal plane detectors with tracking capabilities. The triplet would provide a first order focus, but higher order aberrations would be corrected in software. The same system developed for the stand alone mode could be used.

**Personnel Using the Instrumentation for Research or Research Training**

The sweeper magnet is not only a detection system by itself (in the stand alone mode) but will be used in coincidence with several other detection systems. These devices are either presently available at the NSCL (S800, neutron wall, BaF$_2$ array) or under construction (segmented Germanium array [51]) and will be ready at the time of completion of the coupled cyclotron upgrade. The sweeper will be available to all users of the NSCL. We foresee that the magnet will be used in a large fraction of the experiments proposed for the period following the upgrade. Several outside users already expressed interest (see section d) and described the impact on their future research projects in letters of support. Especially users from colleges and universities in the vicinity of MSU who are using the S800 or who are planning to use it for the research see it as a great opportunity to broaden and enhance their experimental possibilities.
c. Description of Research Instrumentation Needs

The proposed sweeper magnet is a C magnet with superconducting coils. The factors which drive its cost and complexity are: the highly compact design, the requirement for open access across the median plane, and a low external fringe field. The need to fit the sweeper magnet in front of the S800 and into the N4 vault dictates that the magnet be compact which means that its magnetic field must be at least 4T. Since iron saturates at 2T, considerable external field will be produced, and a large amount of iron will be required to return the magnetic flux. Additionally, the high field and large current density in the superconductor results in large forces. The inability to support the forces with simple structures which cross the median plane, results in a more complicated support system.

Figure 7: Basic design of sweeper magnet.

A magnet has been designed which meets these requirements and is at the same time economical. Initial calculations were done with a two dimensional magnet code, then dimensions and required current densities were checked with the three dimensional code TOSCA. In order to avoid the complications associated with winding a coil which has a negative curvature side, (required for a minimum mass magnet as was done for the S800 dipoles), a straight side was substituted. This is the approach taken with the A1900 dipoles of the coupled cyclotron project which have a similar shape. The design is a C-magnet, so called because all of the return yoke is on one side of the magnet, although the basic design uses flat coils characteristic of an H-magnet. The amount of iron is approximately independent of its location and depends on how much saturation
Sweeper magnet design parameters.

<table>
<thead>
<tr>
<th><strong>Magnet</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bend angle</td>
<td>$40^\circ$</td>
</tr>
<tr>
<td>Gap</td>
<td>14 cm</td>
</tr>
<tr>
<td>Pole width</td>
<td>16 cm</td>
</tr>
<tr>
<td>Maximum field</td>
<td>4 T (5.5 T at the coil)</td>
</tr>
<tr>
<td>Iron weight</td>
<td>59,000 lbs</td>
</tr>
<tr>
<td>100 Gauss line</td>
<td>36 cm at 4 T</td>
</tr>
<tr>
<td>Design heat load</td>
<td>10 l/hr of liquid helium</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Superconducting coils</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire size</td>
<td>0.898 X 1.898 mm$^2$</td>
</tr>
<tr>
<td>Copper-to-superconductor</td>
<td>3.7:1</td>
</tr>
<tr>
<td>Inductance</td>
<td>14 H</td>
</tr>
<tr>
<td>Stored energy</td>
<td>900 kJ</td>
</tr>
<tr>
<td>Operating current</td>
<td>360 A</td>
</tr>
<tr>
<td>Short sample at 4 T</td>
<td>750 A</td>
</tr>
<tr>
<td>Turns</td>
<td>2310 (35 turns X 66 layers)</td>
</tr>
<tr>
<td>Current density in coil package</td>
<td>14.8 kA/cm$^2$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Trim coils</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Turns of 1/4° conductor</td>
<td>56 (4 double pancakes)</td>
</tr>
<tr>
<td>Maximum current</td>
<td>230 A</td>
</tr>
<tr>
<td>Power</td>
<td>6 kW</td>
</tr>
<tr>
<td>Water flow</td>
<td>2.5 gal/min</td>
</tr>
</tbody>
</table>

is allowed. We minimized the saturation to keep the external fringe field as low as possible. It was found, however, that the fringe field was too high where photo-tubes will be used. A resistive trim coil has been added to the outside of the yoke which greatly reduces the fringe field. The 100 Gauss line is reduced from 70 cm to 36 cm, allowing the detectors to be properly placed. The parameters of the magnet are given in the table, and the initial design is shown in Figure 7.

Supporting the magnetic forces while at the same time keeping the heat load on the liquid helium system low and keeping the detector area and the neutron path free from obstruction is difficult. The support system will have radial links that carry 40,000 lbs each, similar to that in the K1200 (35,000 lbs). Keeping the lengths short results in a liquid helium consumption rate of 10 l/hr, which represents an additional 2% of the present NSCL capacity. Increasing the coil size is an unattractive option since the space for heat isolation is already as small as it can be made and any increase would necessitate larger magnet dimensions. Keeping the large gap, and hence, the effectiveness of the device results in this larger than ideal heat load. Reducing the required current density by reducing the gap would result in smaller links and smaller heat loads, but the solid angle would be reduced.

Quench calculations were performed to assure the survival of the coils in case of a quench. The hot spot temperature is a maximum of 225 K in the most pessimistic case. The maximum voltage between adjacent layers of conductor is only 26 V, so the only high voltage point is the connection across the median plane which can readily be isolated.

The magnet is designed to separate into pieces of no more than 20,000 lbs, which is well within the crane capacity for easy moving between the S800 vault and N4. The cryolines will be the same type as on the S800 which are Ni seals which do not require cutting to change location. Reconnecting only requires the application of new superinsulation.
d. Impact of Infrastructure Projects

The presence of the proposed sweeper magnet at the NSCL will greatly increase the capability of the laboratory’s operating facility for fast radioactive beam experiments. The magnet is designed so that it can operate in either a stand alone mode or in conjunction with the $800 spectrometer system. It will be constructed so as to be movable between different experimental vaults at the NSCL. The time for warmup, disassembly-assembly and cool down is two weeks, based on previous experience at the NSCL with other magnet systems.

Several classes of experiments are discussed in the main body of the proposal that show how the presence of this magnet will enhance the NSCL’s experimental capabilities.

The NSCL has continued its tradition of being a “hands on” environment for the training of graduate students and post-doctoral fellows and the presence of the sweeper magnet will enhance the opportunities for undergraduates, graduate students and post-doctoral fellows to perform state-of-the-art research. In addition to the training of the undergraduates, graduate students and postdoctoral fellows from MSU, the very active outside user program involves an additional large number of students and postdocs. Several strong letters of support from users for the sweeper magnet\(^1\) indicate that the users community of the NSCL plans to use the sweeper magnet for their research which will most certainly include the training of graduate students and postdocs.

e. Project and Management Plan

The project describes the construction of a compact 4 tesla sweeper magnet to enhance the versatility of the experimental nuclear physics program at the NSCL. The design of the magnet is tailored to fit the specific range of radioactive beams that will be available here after the completion of the coupled cyclotron project.

The detailed design and construction will take advantage of the expertise of the National High Magnetic Field Laboratory at Florida State University (NHMFL) and at the same time allow the National Superconducting Cyclotron Laboratory to concentrate on the timely completion of the upgrade. At the NHMFL the project will be lead by Steve van Sciver. He will consult on a regular basis with Al Zeller and John DeKamp from the NSCL to ensure the compatibility of the design and construction with the existing facilities at the NSCL.

The total project time will be 28 months. The proposed starting date is September 1, 1998, which will allow completion by December 31, 2000, in time for the completion 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 both Michigan State University and Florida State University. This project will include in addition to the magnet itself, the completion of a superconducting quadrupole magnet and a focal plane detector system which will be performed at MSU.

The total estimated cost is $996,625, of which we request $697,500 from the NSF. Matching funds from Michigan State University ($249,125) and Florida State University ($50,000) accounts

\(^1\)We received letters of support from J. R. Beene (Oak Ridge National Laboratory), G. Berg (Indiana University), R. Boyd (Ohio State University), D. Cebra (University of California at Davis), P. DeYoung and G. Peaslee (Hope College), J. Finck (Central Michigan University), J. Kolata (University of Notre Dame), W. Loveland (Oregon State University), A. Nadasen (University of Michigan at Dearborn), N. J. Stone and J. Rikovska Stone (University of Oxford), and R. Warner (Oberlin College)
for a total matching contribution of 30%.

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 Michael Thoennesen and he will report to the director of the NSCL. It is his responsibility to monitor the progress of the project and report the project cost and the status of the schedule to the director.

Upon completion the magnet will be maintained by the staff of the NSCL. It will be a users’ device at the laboratory which will be available free of charge to interested users of the NSCL. Beam-time is allocated by an external program advisory committee.