A PROPOSED FACILITY UPGRADE
FOR THE
TEXAS A&M UNIVERSITY CYCLOTRON INSTITUTE
(31 August 2001)

I. Introduction

This document discusses a facility upgrade for the Texas A&M University Cyclotron Institute. This project would significantly extend our research capabilities as a stable beam facility with moderate rare beam capabilities. This would be achieved by re-activating our 88" Cyclotron to deliver high intensity light particle and heavy ion beams, to be used for production of rare isotopes for acceleration in the K500 Cyclotron and as precursor beams to produce significantly higher intensity stripping and fragmentation beams in our MARS spectrometer. In addition to greatly extending the reach of the present TAMU research program, this facility could play a much wider role in support of the national accelerator based scientific research effort. This facility could also prove to be very useful for early testing of techniques to be employed in the Rare Isotope Accelerator, RIA, and in educating younger scientists for the RIA era.

The Cyclotron Institute

The Cyclotron Institute is a major accelerator facility which encompasses a broad range of technical and scientific capabilities. The original experimental program of the Institute began in 1967 with the commissioning of the 88" Cyclotron. Operation of the new, locally constructed, K500 cyclotron with an ECR source began in 1989. Since 1989 a series of new experimental devices have been constructed and brought on line. Jointly funded by the State of Texas and the Department of Energy, the Institute carries out a program of basic research and education in both nuclear physics and nuclear chemistry. This program encompasses experimental and theoretical work in nuclear structure, nuclear astrophysics, fundamental interactions, nuclear dynamics, and atomic physics. Figure 1 presents a schematic layout of the present facility.

At present the research program takes advantage of a wide variety of stable beams delivered from the K500 Cyclotron. Figure 2 presents a representation of all such beams which have been run for the experimental program to date. Other beams have been developed and, in principle, useful beams of any stable isotope can be delivered. Heavier beams of higher energy can be delivered if lower intensities are acceptable for the intended use.

Lower mass stable beams from the K500 are also used to produce a limited range of secondary radioactive beams in the MARS spectrometer. Beams such as ^{7}Be, ^{11}C, ^{21}Na with intensities ~ 10^{5} pps are being used for nuclear astrophysics, fundamental interaction and isospin equilibration studies.

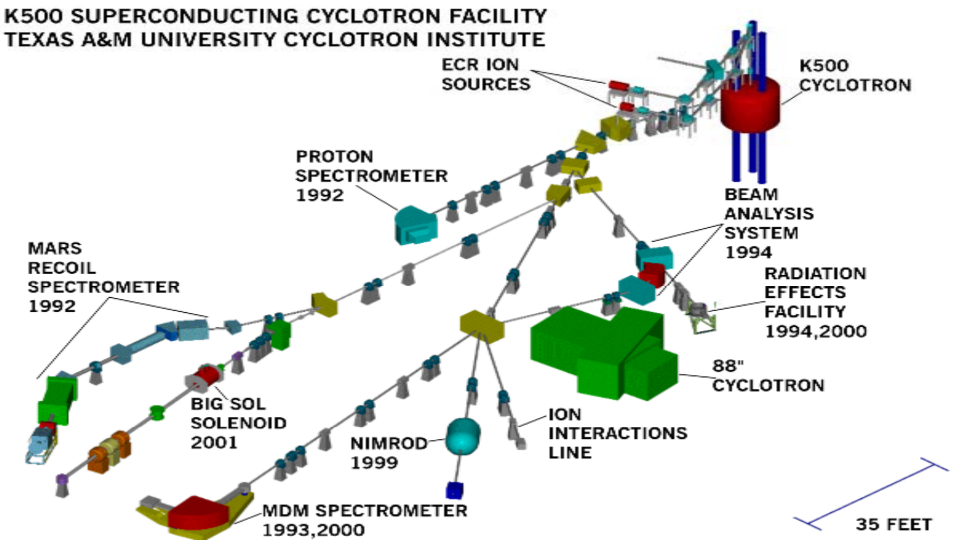

Figure 1. K500 accelerator and experimental equipment, August, 2001

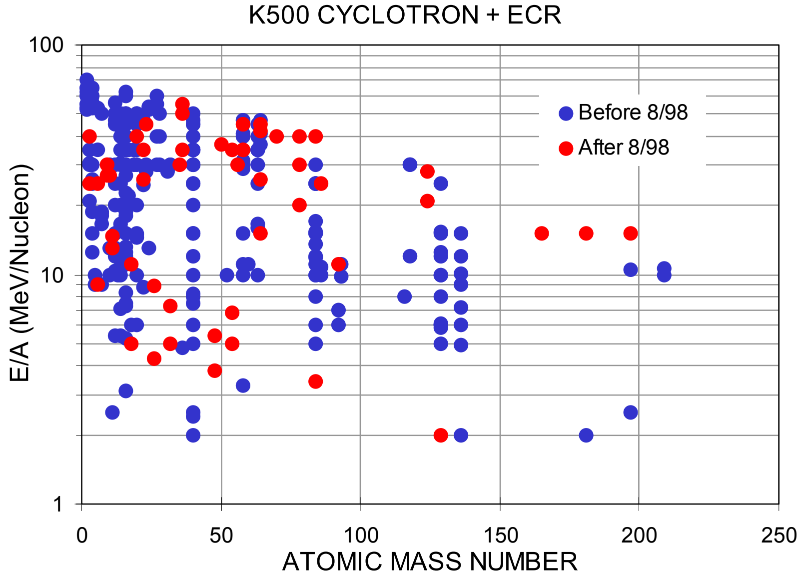

Figure 2. A summary of all beams run for experiments using the combined ECR- K500 Cyclotron Facility

II. Proposed Facility Upgrade

Over the past 2.5 years Cyclotron Institute personnel have devoted considerable effort to exploring future directions for the TAMU Cyclotron Institute. This has included extensive in-house discussions by a "Futures Committee", a number of seminars by outside experts, a workshop in which we extended the discussions to include a broader community of experts in various aspects of nuclear research and technical evaluation of various possible facility upgrades by our accelerator physics and operations staff. Discussions were focused on projects which could be realized in a timely fashion and would significantly extend our research capabilities as a stable beam facility with moderate rare beam capabilities. We believe that an important enhancement of our program and of the national capabilities could be realized by an upgrade project which would involve re-activating our 88" Cyclotron to deliver high intensity light particle and heavy ion beams. These would be used for production of rare isotopes for acceleration in the K500 Cyclotron and as precursor beams to produce significantly higher intensity stripping and fragmentation beams in MARS. High quality accelerated rare beams of both neutron deficient and neutron rich isotopes could be provided in the 5 to 50 MeV/u range. The upgraded facility is depicted schematically in Figure 3.

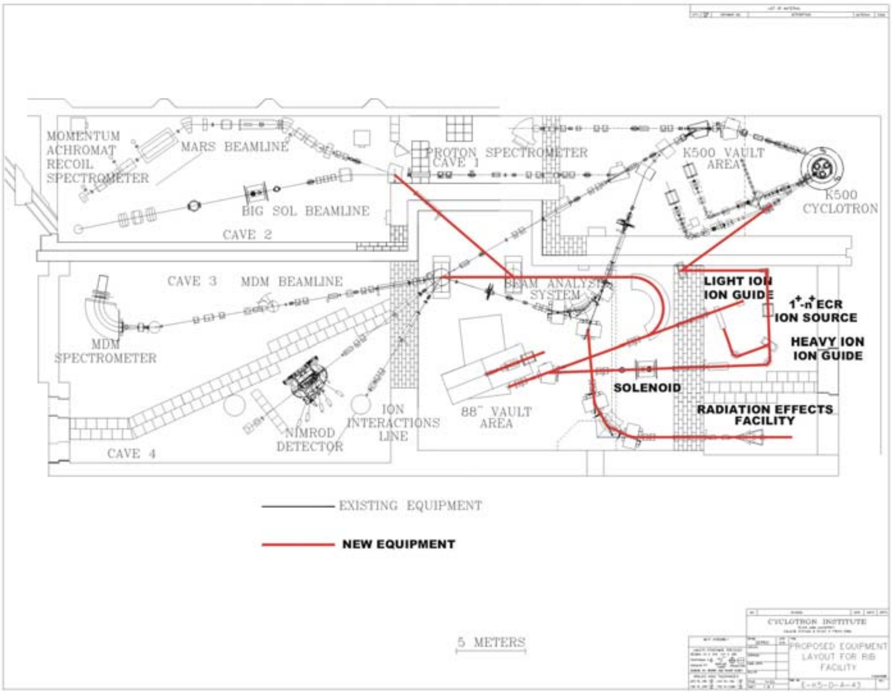

Figure 3. Upgraded TAMU Facility. New additions are drawn in darker lines. High intensity light stable beams from the re-commissioned 88" Cyclotron will be used with ion guide techniques to produce high quality re-accelerated rare ion beams from the K500 Cyclotron and fragmentation beams in MARS. Direct delivery of these beams to existing lines is also possible.

The niche which this facility would fill is not well covered in current or planned facilities. The broad range of stable beams and expanded range of rare beams possible from these accelerators would create an exceptionally versatile facility for low and medium energy research.

III. New Beam Capabilities Expected

A. 88" Cyclotron High Intensity Stable Beams

At a main-coil current of 2800 A, the Texas A&M 88" Cyclotron is capable of a bending factor of K=140, where $E/A = K(Q/A)^2$ gives the upper limit on energy for heavy-ion beams. Some high intensity beams that can be extracted from the 88" Cyclotron coupled to an ECR ion source such as our ECR2 source are listed in Table 1. These intensities are similar to those produced by the LBNL 88" Cyclotron.

Table 1. – Expected 88" beam intensities and energies assuming ECR2 type source, K=140 and 25% transmission.

Isotope	*Energy*	*Intensity*		*Isotope*	*Energy*	*Intensity*
	MeV/u	*pμA*			*MeV/u*	*pμA*
p	*55*	*27*		^{20}*Ne*	*28*	*3.0*
d	*35*	*21*		^{22}*Ne*	*29*	*0.5*
^{3}*He*	*45*	*11*		^{34}*S*	*20*	*0.7*
^{4}*He*	*35*	*10*		^{40}*Ar*	*17*	*1.4*
^{6}*Li*	*35*	*7*		^{40}*Ca*	*17*	*1.5*
^{7}*Li*	*25*	*8*		^{59}*Co*	*11*	*0.9*
^{10}*B*	*35*	*4*		^{78}*Kr*	*10*	*0.6*
^{11}*B*	*29*	*4.7*		^{86}*Kr*	*8.3*	*0.6*
^{16}*O*	*35*	*2.3*		^{129}*Xe*	*5.6*	*0.5*

B. Re-Accelerated Rare Beams with Ion Guide Techniques

Using beams from the 88" Cyclotron, we plan to produce radioactive species for acceleration by the K500 Cyclotron. Intense beams from the 88" Cyclotron would impinge on various targets. An ion guide system [1,2] coupled to a 1^+-n^+ ECR ion source would then be used to slow down, accumulate and re-ionize product isotopes which would then be accelerated in the K500 Cyclotron.

Ion guide systems rely on the slowing down of reaction products in helium gas where, due to the large ionization potential of helium, many of the captured products remain in the 1^+ charge state. These captured 1^+ ions are then extracted from the helium cell to form a beam which is injected into the ECR source. The ECR plasma captures injected ions if they can be slowed to close to zero velocity. Captured ions behave the same as 1+ ions formed from neutrals, and for a given element the extracted charge-state distributions should be the same. The total efficiency for conversion into high-charge states has been shown to be high, >65% [3]. The beam transport system will provide some initial analysis for the reaction products, and the K500 Cyclotron will provide approximately one-part-in 5000 mass analysis for the accelerated beam.

The ion guide system would have at least three different configurations depending upon the reactions chosen for production: light ions impinging on light to heavy targets yielding fusion-evaporation products that have small forward momenta; light ions impinging on very heavy targets yielding fission fragments that have large momenta at large-angle; heavier ions impinging on targets yielding deep inelastic, transfer and fragmentation products that have large forward momenta. Given the different kinematic conditions for these three cases different ion guide efficiencies are expected.

1. Light-ion induced reactions

Extensive IGISOL (ion guide with a separator on line) studies for light ion reactions such as (p,n), (d,p) and (α,n) have been done at the Cyclotron lab at the University of Jyväskylä in Finland (JYFL) where the IGISOL technique originated [1,2]. For proton beams on a variety of targets, the geometry of the IGISOL cell employed was relatively simple. The beam entered the small (~1 cc) IGISOL cell through the production target and exited through a foil or the other side of the cell. Helium gas flowed through the cell. Recoil ions thermalized in the helium and trapped in the gas flow exited through a hole at 90° to the beam. These ions were guided by an electric field through a hole in a skimmer plate. Once past the plate, the ions were in a region of much lower gas pressure, and their final acceleration occurred.

Table 2. Estimated Beam Intensities for Products of Light Ion Induced Reactions

(p,n)	**Energy Range**	**Intensity**
product	**MeV/u**	**pps**
^{20}Na	31-63	0.9-1.9 X 10^4
^{27}Si	22-57	0.5-1.1 X 10^4
^{50}Mn	17-45	0.3-0.7 X 10^4
^{54}Co	19-46	0.9-1.8 X 10^4
^{64}Ga	14-45	2.1-4.3 X 10^4
^{92}Tc	11-35	1.6-3.2 X 10^4
^{106}In	9-28	0.4-0.8 X 10^4
^{108}In	9-28	0.6-1.2 X 10^4
^{110}In	9-26	0.9-1.9 X 10^4
(d,p)		
product		
^{12}B	7-46	1.0-2.0 X 10^4

The light ion reactions utilized in Jyväskylä had 15-20A MeV beam energies. The highest measured ion guide efficiency at JYFL, where the products were stopped in the cell, was 10%. Higher efficiencies are expected to result from higher incident-beam energy, higher gas pressure, larger cell dimensions and recent innovations in cell design and modeling. For Table 2 the minimum operating K for the K500 Cyclotron is assumed to be 250 to assure good extraction efficiency from the accelerator.

2. Light-ion induced fission

The IGISOL technique has also been employed for light ion induced fission. Reactions of protons with ^{238}U have been examined at JYFL [2]. The fission fragments were slowed by a foil before entering the helium cell. Because they are emitted isotropically the target could be at a large angle to the beam to increase its effective thickness. The typical efficiency in the Jyvaskala experiments was quite low, reflecting the particular demands of the experiments and size of the stopping cell (many fragments were not stopped). Based on recent ion guide developments we believe that higher efficiencies can be realized and provide estimates below for two different projected ion guide efficiencies.

Table 3. Estimated beam intensities for re-accelerated fission fragments produced in proton induced reactions at 20 MeV.

		Intensity	Intensity
Fission	Energy Range	2% IG efficiency	20% IG efficiency
Fragment	MeV/ u	pps	pps
^{96}Sr	9.8 - 31	4.3 x 10^4	4.3 x 10^5
^{98}Y	9.4 - 30	3.9 x 10^4	3.9 x 10^5
^{100}Zr	9.0 - 29	3.6 x 10^4	3.6 x 10^5
^{103}Nb	8.5 - 27	3.2 x 10^4	3.2 x 10^5
^{105}Mo	8.2 - 26	2.6 x 10^4	2.6 x 10^5
^{107}Tc	7.9-25	1.1 x 10^4	1.1 x 10^5
^{110}Ru	7.5 - 24	1.1 x 10^4	1.1 x 10^5
^{112}Rh	7.1 – 23	0.9 x 10^3	0.9 x 10^4
^{115}Pd	6.8 - 22	1.4 x 10^4	1.4 x 10^5
^{117}Ag	6.6 - 21	1.1 x 10^4	1.1 x 10^5
^{120}Cd	6.3 - 20	1.0 x 10^4	1.0 x 10^5

3. Heavy-ion deep-inelastic reactions and fragmentation

Some work on ion guides for heavy ion induced reactions has been done at Leuven [4], at RIKEN [5] and at Grenoble [6]. Recently a major ion guide development effort has begun at ANL ATLAS in conjunction with developing systems prototypes for the RIA project [7]. At ATLAS the cell is about 25 cm long and 5 cm in diameter. Inside there is a series of electrodes with both dc and rf potentials applied. The recoils first pass through a cylindrical space formed by wide electrodes and then through a narrowing conical space formed by thin electrodes. The helium flow (P=250 torr) and the dc potential serve to push the recoils through the cell as well as focus them into the extraction aperture at the apex of the cone. The rf field serves to prevent the recoils from diffusing to the wall. After exiting the cell the recoils enter an RFQ device that is used at ANL for eventual trapping, but could be used for simple acceleration. The RFQ goes through two skimmer chambers; each separately pumped by a Roots blower, and finally through a high vacuum chamber pumped by a turbo pump. The efficiency of the ion guide has been reported to be as high as 45%[7]. Presently, there are active studies proceeding at other laboratories that should lead to important improvements in efficiency. Only recently JYFL has reported that they have achieved 50% efficiencies in cells with α-recoil ions [8]. Careful modeling of the ion guide transport efficiencies, as is also being done at ANL has helped to accomplish this. In addition, up to now the emphasis at JYFL had been on very short-lived radio-nuclei, so the target cells have been small and unable to stop the more energetic recoils. Higher energies and larger target cells with higher gas pressures should raise the total production for a significant number of reactions. The development of these techniques at TAMU will contribute to the community effort to prepare an optimized system for RIA.

For heavy ions, experiments indicate that allowing the beam to enter the ion guide cell seriously degrades the collection efficiency. At RIKEN a gas filled spectrometer was used to separate products from the beam. The reaction products then entered the cell through a foil. Our intention is to use a large bore superconducting solenoid with an on axis beam blocker as a high efficiency first stage collector. We are presently installing such a device, the University of Michigan 7T “BigSol” solenoid on a beam line at TAMU to carry out development tests.

Intensities for re-accelerated beams reported in Table 4 were obtained using reaction models that simulate the product kinematics [9] and simulations of ion transport through BigSol [10] together with the 45% ion guide efficiency reported by ANL [7]. For comparison, a few intensities expected at the NSCL are also shown. NSCL A1900 rate estimates are given at the full momentum acceptance (~5%) of the A1900 separator [11]. Typical fragment energies are 80-100 MeV/u. We estimate that requiring a precise energy definition of RIBs comparable to that of our K500 re-accelerated beams (e.g.~0.1-0.2%), would lower those A1900 intensities by a factor of ~10. Demanding an angular divergence which would match that of the re-accelerated beams would result in a further reduction factor of 20 to 50.

Table 4. **Estimated Beam Intensities-Ion Guide System and Heavy Ion Reactions.**

RIBs produced by 88" Cyclotron primary beams, are filtered via a Superconducting Solenoid and stopped in a gas cell. RIB ions in a 1+ charge state will be extracted and led to an ECR ion source. Re-accelerated RIBs will then be produced with the K500 Cyclotron. The combined efficiency of the Ion Guide/IonSource and re-acceleration stages is 1 to 2 %. Intensities and energies of RIBs out of the K500 are indicated. *Optimum beam-target combinations have been used in each case.*

a) Neutron Rich Products

Isotope	Energy Range	Intensity	NSCL Intensity**
	MeV/u	pps	A1900, pps
^{9}Li	13-45	$1.7-3.4\times10^{6}$	
^{11}Li (8.6ms)	9-35	$0.4-0.8\times10^{4}$	5.8×10^{5}
^{12}Be	16-45	$2.7-5.5\times10^{6}$	
^{14}Be(4ms)	12-40	$0.4-0.8\times10^{4}$	
^{38}S	9-36	$2.5-5.0\times10^{5}$	2.4×10^{7}
^{40}S	8-32	$0.5-1.0\times10^{5}$	
^{42}S	7-29	$1.8-3.6\times10^{3}$	
^{44}S	7-26	$0.9-1.8\times10^{2}$	
^{42}Ar	9-39	$3.3-6.6\times10^{5}$	
^{44}Ar	7-38	$0.9-1.8\times10^{5}$	
^{46}Ar	6-35	$1.8-3.6\times10^{4}$	
^{48}Ar	6-32	$0.9-1.8\times10^{2}$	
^{62}Fe	13-38	$1.9-3.8\times10^{4}$	
^{60}Cr	10-32	$0.5-1.0\times10^{3}$	

b) Proton Rich Products

Isotope	Energy Range	Intensity	NSCL Intensity**
	MeV/u	pps	A1900, pps
^{7}Be	21-60	$0.5-1.0\times10^{6}$	
^{8}B	16-70	$1.2-2.4\times10^{6}$	
^{11}C	19-63	$1.3-2.6\times10^{6}$	
^{14}O	21-70	$0.7-1.4\times10^{5}$	
^{22}Mg	19-57	$3.1-6.3\times10^{4}$	
^{23}Al	24-60	$1.2-2.4\times10^{3}$	3.8×10^{5}
^{27}P	28-62	$1.0-2.0\times10^{3}$	
^{62}Ga	15-47	$2.1-4.3\times10^{2}$	1.0×10^{5}
^{64}Ga	14-45	$0.9-1.9\times10^{4}$	

** Note: NSCL A1900 rate estimates are given at the full momentum acceptance (~5%) of the A1900 separator. Requiring beam quality comparable to that of re-accelerated K500 beams would reduce those intensities significantly. (See text.)

Figure 4 presents a schematic summary of the rare beams listed in the tables above. **We emphasize that this is only a representative sampling of possible beams and is only indicative of the added capabilities.**

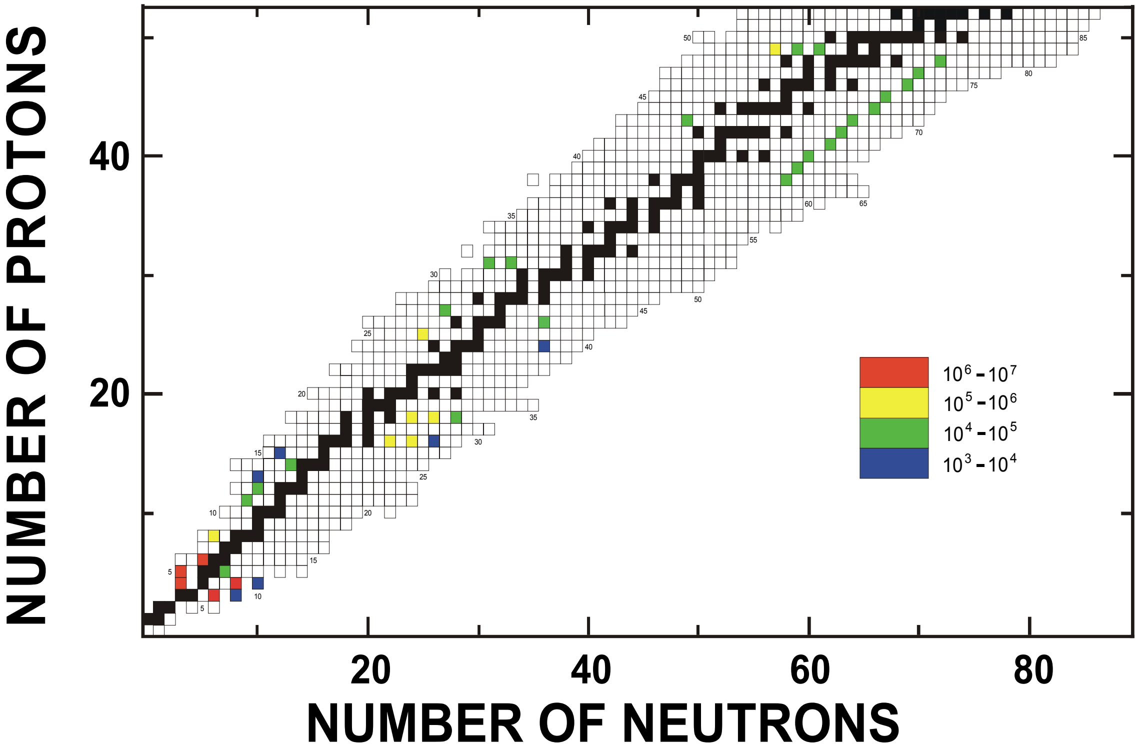

Figure 4. Anticipated intensities for a sampling of the re-accelerated rare beams expected from the K500 Cyclotron are indicated by colored squares. The isotopes are produced in (p,n) reactions, proton induced fission of ^{238}U (at 19.8 MeV) and heavy ion induced deep inelastic reactions. The colors of the squares indicate the calculated intensity range.(See text.) Stable isotopes are depicted as black squares.

IV. Effect on Institute Programs

Eloquent overviews of the important scientific questions which can be addressed with radioactive beams have been presented in a number of recent documents[12-15]. We do not repeat those discussions here. Rather we focus on the particular impact the proposed upgrade will have on the TAMU scientific program. Though not a user facility, per se, TAMU has always welcomed outside users and collaborators who can make effective use of the accelerator facilities and that policy will continue. With appropriate funding levels the facility could undertake an extended role in support of outside user programs.

A. Nuclear Astrophysics

Over the past five years, we have developed a new technique for determining reaction rates at stellar energies. This new approach involves measuring asymptotic normalization coefficients (ANC) by conventional transfer reactions. Extracting ANCs requires that we have a very peripheral transfer reaction. The optimal energy to carry out peripheral transfer reactions is around 10 MeV/A. We have used stable heavy ion beams from the K500 Cyclotron and ^{3}He beams (in collaboration with a group from the Czech Republic) in this energy range to measure ANCs. We have also used secondary radioactive beams, obtained with our recoil spectrometer MARS, for several experiments. Our group has applied the ANC technique to several (p,() capture reactions – ^{7}Be(p,()^{8}B, ^{9}Be(p,()^{10}B, ^{16}O(p,()^{17}F, and recently ^{13}C(p,()^{14}N and ^{11}C(p,()^{12}N. The proposed upgrade would allow us to extend this work in several ways.

1. Radioactive beams from the K500

As a driver, the 88" Cyclotron would be used to provide radioactive beams that would then be re-accelerated by the K500 Cyclotron. This combination would be ideal to supply secondary beams at around 10 MeV/A. Using the accelerated secondary beams and the MDM spectrometer, we would be able to measure transfer reaction cross sections at and around 0E, where the extraction of ANCs is most reliable. We have already made measurements at 0E for the ^{9}Be(^{10}B,^{9}Be)^{10}B and ^{13}C(^{14}N,^{13}C)^{14}N reactions using stable beams and the MDM. In those cases, we were able to measure ANCs for both ground state and excited state transitions. Accelerated secondary beams would provide the same beam quality as stable beams, so that it would be feasible to measure ANCs for excited states. Typically this is the information that is needed in (p,() reactions involving nuclei in the s-d shell. To date, we have been restricted to measurements of ground state ANCs for radioactive systems due to the energy spread in our secondary beams. Furthermore, the excellent angular resolution provided by the K500+MDM makes it straightforward to use the angular distribution at small angles to separate the different j transfers, even when one is much weaker than the other. For example, we found surprising results for the relative strength of $p_{1/2}$ vs. $p_{3/2}$, which had only been hinted in previous ^{13}C(^{3}He,d)^{14}N analyzing power measurements, when populating excited states in ^{13}C(^{14}N,^{13}C)^{14}N. To date, with radioactive beams we have been forced to utilize theoretical predictions for the ANCs populating different orbitals because the angular spread in our secondary beams has precluded direct measurements.

2. Stable beams from the 88"

We have developed a collaboration with a group in the Czech Republic to measure ANCs using the (^{3}He,d) reaction. The group at Rez has access to a U120M Cyclotron and can produce ^{3}He beams at energies up to about 10 MeV/A. They do not have access to a good magnetic spectrometer, and thus, measurements to date have been done using Si solid-state detectors. The intense flux of elastically scattered ^{3}He severely limits the quality of the data that can be obtained at small angles (<10E). During the analysis of

^{16}O(^{3}He,d)^{17}F data taken at Rez to determine the ANCs for ^{16}O(p,()^{17}F, it became clear that the lack of small angle data introduced significant systematic uncertainties. This ^{3}He beam energy is not in the range directly accessible with the K500 Cyclotron. Ultimately, we obtained complementary data at Texas A&M with a (^{3}He-d)$^{+}$ molecular ion beam from the K500 and the MDM. This permitted us to reduce the systematic uncertainties in the corresponding ANCs substantially. But the molecular ion beam was very unreliable and of low intensity, and the deuterons present in the beam precluded measurements at lab angles below 1E. The 88" Cyclotron would be able to provide ^{3}He beams in the energy range that we need for carrying out the (^{3}He,d) reactions. Once again, the MDM spectrometer would be used to make measurements in to 0E.

3. Beams from the 88" Cyclotron to MARS

Much of the ANC work that has been carried out and that which is proposed in the near future with radioactive beams from MARS is better suited to using precursor stable beams from the 88" Cyclotron than from the K500 Cyclotron. The stable beam energies are in a range appropriate to the 88" Cyclotron, and the intensities available from the 88" would be much higher than we have achieved from the K500 Cyclotron. For example, based on the primary beam intensities of Table 1 above we expect improvements of approximately one order of magnitude in rare beam intensity,e.g.,^{7}Be beams of 1 X 10^{6} and ^{11}C beams of 5 x 10^{6} pps. The energy spread and phase space of the 88” Cyclotron beams is inferior to those from the K500, but this is not an issue for secondary beam production. A long list of secondary beams could be made available by combining MARS and the 88". Some examples of proton rich beams that would be straightforward to produce include ^{17}F, ^{18}F, ^{19}Ne, ^{21}Na, ^{22}Na, ^{22}Mg and ^{24}Al.

B. Nuclear Structure

1. Giant Monopole Resonance and Compressibility

The energy of the giant monopole resonance(GMR) is directly related [16] to the compressibility of the nucleus K_A by $E_{GMR} = (K_A/m<r^2>)^{1/2}$. The behavior of the GMR in neutron rich nuclei could provide clues to the compressibility as one moves toward neutron matter. In stable nuclei, measurements from ^{112}Sn to ^{124}Sn provide about as large a range of asymmetry as available[17]. Extending GMR measurements to unstable nuclei will both allow the study of this giant resonance as a nuclear structure effect and provide information on compressibility in nuclei with much higher asymmetry than available in stable nuclei. The GMR peaks strongly at 0^{o} in inelastic scattering whereas other multipolarities provide almost flat angular distributions. In inelastic scattering above 25 MeV/A, the GMR dominates the spectrum at 0^{o} [18] and the GMR strength can be obtained by subtracting a spectrum taken at a larger angle from the one taken at 0^{o}, so that relatively little data is required to obtain a GMR strength distribution [19]. We have carried out the d(^{28}Si,d’)^{28}Si* reaction (inverse kinematic inelastic deuteron scattering) at 40 MeV/A detecting the d with silicon detectors in coincidence with the particle decay products from ^{28}Si* (detected in the MDM spectrometer at 0^{o}) using a deuterated polyethylene target. A preliminary analysis of data taken at d angles of 10^{o} and 20^{o}

shows a peak at the position expected for the ^{28}Si GMR at both angles with approximately the correct relative cross section. This peak is not visible in the singles deuteron spectra, but only in coincidence with heavy particles near 0^o. While this technique is certainly not fully explored or proven, this result would indicate that usable information on the GMR in unstable nuclei could be obtained in 1 week run time if a deuteron detector covering the angles of interest ($10^o<\theta<45^o$, with complete ϕ coverage) and beams exceeding a few times 10^5/s were available. This technique can be developed with stable beams at TAMU, including carrying out (d,d') experiments to obtain energy dependence of the cross section and to obtain optical parameters. With the upgraded facility, the GMR in nuclei in the sd shell could be studied up to 4n above stability, and using beams from fission fragments, the GMR in nuclei with 38#Z#48 can be studied from 5n to 10n above stability. Once the techniques are developed, the GMR in nuclei from proton to neutron rich such as $^{12-22}$O and $^{106-132}$Sn could be identified using beams from the new MSU Coupled Cyclotron Facility. Beams from the proposed RIA facility would extend this further to more neutron rich and heavier nuclei.

2. Cluster Structure

Recently measurements of the level structure of ^{8}He in the ^{8}He + p reaction at Dubna and investigations of α-cluster structure of ^{22}Ne and ^{22}Mg in ^{18}O + ^{4}He and ^{18}Ne + ^{4}He reactions at Louvain la Neuve were carried out by a collaboration of scientists from TAMU, Notre Dame University, the Dubna Joint Institute for Nuclear Research and the Kurchatov Institute in Russia, the University of Jyväskkylä and the Åbo Akademi in Finland and the Université Catholique de Louvain in Belgium. Both experiments used a new resonance scattering method employing inverse kinematics and a very thick target. This technique is well suited to conventional as well as to radioactive beams [20,21] even at relatively low (10^3-10^4 pps) intensities. For the experiments in Dubna the TAMU group constructed a special, high pressure (up to 6 atm of methane) reaction chamber, and a time of flight system based on position-sensitive multiwire avalanche counters. This series of measurements is continuing. The next experiment at Dubna is scheduled as the first one on their new RIB U400M-U400 complex. Similar experiments could be successfully realized with our proposed facility. There is particular interest in pursuing investigations of cluster structures in proton rich nuclei. Experimental investigations of the cluster structures in neutron rich nuclei using radioactive beams have found evidence for cluster states in ^{12}Be with a possible α + 4n + α structure [22]. Freer et al. have identified other cluster structures in ^{12}Be [23] and in ^{10}Be [24]. Little is known about possible cluster structure in nuclei with proton excesses. Do molecular type structures, found in ^{10}Be ($\alpha + \alpha$ + 2n) survive in ^{10}C ($\alpha + \alpha$ + 2p)? Study of non-self-conjugate nuclei also allows investigation of isobaric analog states in mirror systems. Comparison of the results for both proton rich and neutron rich systems can bring new spectroscopic information and shed light on such properties as the radii of the cluster states.

C. Fundamental Interactions

The availability of beams such as those to be realized in the upgrade will allow us to carry out important structure studies directly pertinent to the interpretation of superallowed \$-decay measurements. We are presently using such measurements to determine the vector weak-current coupling constant, which is a key component to a demanding test of CKM unitarity, a basic tenet of the Standard Model. Current world data lead to a failure of unitarity by more than two standard deviations, a provocative but not yet definitive result. An important question that remains before this test can be sharpened is the accuracy of the small calculated correction terms, *$_C$, which depend upon the details of local nuclear structure. These *$_C$ calculations can be tested by measurements of the \$-decay of odd-odd superallowed emitters with A \$ 62. However, for the test to be meaningful we will need to know many of the other properties of nuclei in this region. Many of these properties will become accessible through transfer reactions, which can be studied in inverse kinematics using the appropriate radioactive beams. The location of T=1 multiplets, particularly of 0^+ states, will yield information on charge-dependent mixing via the *c* coefficient of the IMME. The location of 0^+ and 1^+ states in the daughter nuclei will make it possible to locate weak \$-decay transitions that could otherwise be missed. Finally, determining the energies of single-particle states near closed shells and sub-shells in the same region will improve the reliability of shell-model calculations, which are needed to calculate *$_C$.

D. Nuclear Dynamics and Nuclear Thermodynamics

The addition of a variety of new unstable isotopes to our beam capabilities would significantly expand the ability of the reaction dynamics and hot nucleus groups. Measurements of the isospin dependence of nuclear transparency, equilibration, the nuclear specific heat and critical behavior would extend the study of the nuclear equation of state in heated nuclei to much more asymmetric nuclear matter. Our NIMROD detector, a 4π charged particle array with isotope identification for species up to Z=10 inside a 4π neutron calorimeter, and FAUST, a compact highly segmented forward array for peripheral collisions and inverse kinematics reactions, provide the high total efficiencies needed for such studies. Recent experimental results indicate that techniques are now in place to map the limiting temperatures and critical energies over a range of isospins. Recent theoretical calculations indicate that measurements of early particle emission, of nucleon transfer and of differential neutron and proton flow for different combinations of total entrance channel isospin will provide new information on the equation of state including the density dependence of the symmetry energy [25]. The importance of this information extends beyond understanding the nuclear EOS and has a significant impact on important topics in astrophysics. In a recent review Lattimer and Prakash [26] have pointed out that the nuclear EOS at sub-nuclear density plays an important role in the collapse rates of supernovae. They identify the nuclear specific heat and symmetry energy as being the crucial properties. At near nuclear density the symmetry energy is particularly important in determining structural aspects of neutron stars.

While this facility would not reach as far into the asymmetric matter domain as the NSCL, it would satisfy the needs of a number of experiments, particularly since greater time could probably be accorded to individual experiments at this facility than could ordinarily be programmed at the NSCL. A mode of operation in which many experiments requiring low to intermediate energy stable beams or rare beams not far from beta stability were carried out at TAMU and experiments requiring beams farther from stability were done at NSCL could be a very efficient way to meet national program needs.

E. Radiation Line Activities

The Institute is now one of the primary US facilities for testing of microchips. Qualification of commercially produced microelectronic devices for use in communications satellites, space shuttles and the space station continues to be the major activity. Currently 20% of our beam time is devoted to the facility radiation effects line. The wide variety of beams of intermediate energy which the facility can provide covers a range of energy loss and penetration depth particularly well suited to the single event upset testing which is being carried out by a variety of government and industrial groups. Given the general growth of the communications industry, the pursuit of space exploration and the continued efforts to design new and more powerful micro-circuitry, we expect the pressure for beam time for such testing to remain high.

The radiation line program is making a very important contribution to achieving some significant national priorities. At the same time it is providing critical support for the other Institute programs, in manpower, in enhanced technical capabilities, and in general facility operation costs. In particular a number of researchers and technical staff personnel are now supported from radiation line receipts. The flexibility associated with the new capabilities would allow for increased beam time for SEU testing.

V. Plans and Upgrade Schedule

A schematic time-line for the project is presented in Figure 5. The project could be completed in three years from time of funding. For Figure 5 this is assumed to occur near the end of Year 1. The time estimates assume normal running of the K500 research program except for short targeted shutdowns required to carry out specific tasks which could not be otherwise accomplished. In this mode reactivation of the 88” Cyclotron, including installation of all new power supplies and utilities, cooling tower capacity upgrade, new control system compatible with the K500 system, new RF system, ECR source injection line, turn on and field mapping will take two years. This would begin at time of funding. Ion guide development studies will begin soon. This will include collection tests with BigSol and 1^+- n^+ source tests using a commercial 1+ source with ECR1. Following development studies the ion guide system will be designed and constructed. At the beginning of the third year after funding ECR2 will be moved to the 88” and tests with internal beam will begin while the ion guide system and new injection line are being installed. Stable beams will then be delivered to MARS. Re-accelerated beams will be delivered at the end of that year.

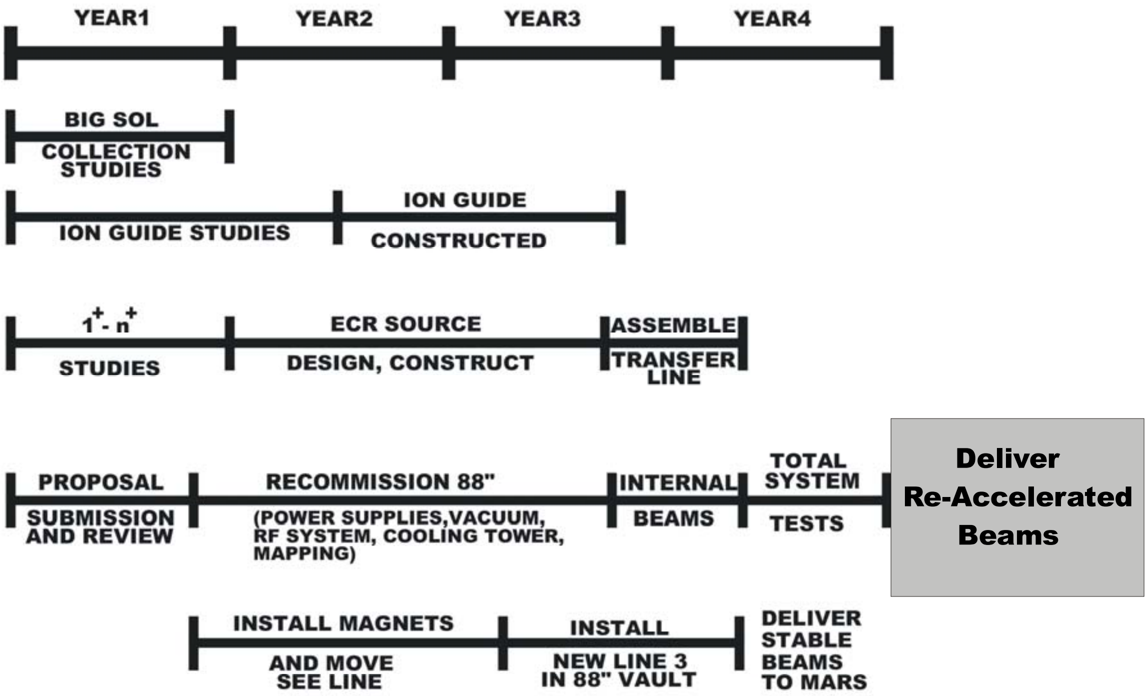

Figure 5. Anticipated timeline for the upgrade. Year 1 focuses upon development studies for ion collection and re-ionization. The project could deliver re-accelerated rare beams three years after it is formally funded. For this diagram that is assumed to occur near the end of year 1.

VI. Summary

A strategy for an upgrade of the TAMU Cyclotron Institute accelerator capabilities which would significantly extend the reach of this facility, providing high intensity lighter beams, a wide range of heavy ion beams and modest fragmentation and re-accelerated rare beams from low to intermediate energies has been presented. The upgraded facility would provide a particularly versatile and cost effective resource for the low energy program in the pre-RIA years and offer important complementary capabilities to other heavily subscribed national facilities such as NSCL, supporting investigations with stable beams, as well as experimental programs requiring less exotic rare beams.

Such an upgrade is well within our technical capabilities and could be realized within three years of being funded. Many details regarding this upgrade, including the possible availability of surplus magnets, new power supply requirements, changes and additions to the beam line system, possible increased requirements for total building power, renovated cooling tower capacity and liquid He capacity etc. are still being investigated. At the present time the cost estimate for this project is $6,000,000. A significant matching contribution from TAMU, ~ 20-25%, is anticipated.

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