NATIONAL SUPERCONDUCTING CYCLOTRON LABORATORY
PROPOSAL FOR EXPERIMENT
(submit original only - unpunched/unstapled)

Date Submitted: April 12, 2001 Experiment # ____________ (Assigned by NSCL)

TITLE: Rare Isotope Production

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Is this a thesis experiment? May Be If yes, for whom? In coming student

OTHER EXPERIMENTERS: (please spell out first name) Check, if applicable

Name	Organization	Grad	Sr. Grad
D. Bazin	NSCL		
M. J .van Goethem	NSCL		
X. Liu	NSCL		X
W. Lynch	NSCL		
M. Steiner	NSCL		
W. Trautmann	GSI		
G. Verde	NSCL		
M. Wallace	NSCL		X

REQUEST FOR CURRENT PERIOD: BEAM ON TARGET (either primary or rare-isotope)

	Particle	E/A(MeV)	Current (pps)	Desired beam purity (%)	Hours on target
a)	^{86}Kr	140	7 pna	100%	28
b)	^{78}Kr	140	7 pna	100%	24
c)	^{48}Ca	140	15 pna	100%	24
d)	^{40}Ca	140	15 pna	100%	24

TOTAL REQUESTED HOURS: 172 (Calculated per note on beam list. Include time for test runs, for calibration of beams, and for particle/energy changes)

Will further time be requested for a subsequent PAC? If so, estimate additional hours: ____________

HOURS APPROVED: ____________

HOURS RESERVED: ____________

SET UP TIME: (before start of beam):

Access to:	Experimental Apparatus	8	hrs
	Electronics Set-up Area	8	hrs (Be realistic--affects scheduling)
	Data Acquisition Computer	100	hrs *does not need to be immediately before the experiment.

TAKE DOWN TIME: (After beam, include all calibrations, etc.):

Access to:	Experimental Apparatus	____	hrs
	Electronics Set-up Area	____	hrs (Be realistic--affects scheduling)
	Data Acquisition Computer	____	hrs

WHEN WILL YOUR EXPERIMENT BE READY TO RUN? 6 / 1 / 2001

DATES EXCLUDED: ____

EXPERIMENTAL EQUIPMENT (CHECK WHICH OF THESE DEVICES WILL BE USED):

X	A1900	____	Ge Array
____	4pi Array	____	NaI Array
____	92" Chamber	____	Beta-Decay Station
____	RPMS*	____	Neutron Walls
____	S800 Spectrograph	____	SuperBall
____	Irradiation Station	____	Other (give details)

*The RPMS is being refurbished and is not expected to be available for experiments till the beginning of 2002.

TARGETS:
9Be, Ta

SPECIAL REQUIREMENTS: (e.g., shipping RADIOACTIVE targets or sources, toxic gases, etc.)

NOTE: Shipping radioactive materials requires permission of both your institution and MSU. For information, contact Kristin Erickson (517)355-5008, ERICKS30@MSU.EDU.

SUMMARY (no more than 200 words)

We propose to measure projectile fragmentation at E/A=140 MeV with two heavy beams (^{78}Kr, ^{86}Kr), two light beams (^{40}Ca, ^{48}Ca) and two targets (^{9}Be, ^{181}Ta). Both heavy and light beams are chosen so as to explore the dependence of the fragmentation process on projectile size and on the overall Coulomb interaction. Two different values for N/Z are chosen for each mass in order to understand the dependence of isotopic yields on the isospin asymmetry of the projectile. Two targets with different N/Z were chosen in order to understand to role of the target asymmetry. This data will greatly assist in the development of a theoretical understanding of this fundamental decay mode of highly excited nuclei. It will also assist in the technical development of intense rare isotope beams.

DESCRIPTION OF EXPERIMENT

Physics justification

Fragmentation is the fundamental decay mode of highly excited nuclear systems [1]. While there are many puzzling aspects to this phenomenon, it does display some simplifying characteristics at high incident energies. For example, many of the experimental observables in peripheral collisions at high incident energies ($E/A > 200$ MeV), such as charge or multiplicity distributions, approach “limiting fragmentation” values that vary little with incident energy and target mass [2].

This “limiting fragmentation” behavior forms the basis for the EPAX2 parameterization [3] used to calculate the rates for the proposals for this PAC cycle, the rates at other rare isotope facilities, and even the rates for the RIA facility [4]. This parameterization assumes that the isotopic distributions and their dependence on the isospin of the projectile and target are also consistent with limiting fragmentation. Very little data exists to examine whether isotopic distributions are independent of target and beam energy, consistent with the limiting fragmentation assumption; EPAX2 assumes its validity and derives its results from a careful empirical fit to a limited data set of production cross sections measured under a wide variety of experimental conditions. The parameterization is not based upon a specific theory for projectile fragmentation; EPAX2 is known to be better at interpolating between measured data points taken under similar conditions than it is at predicting the best way to produce an isotope further away from the valley of stability [4, 5].

Some indication of the internal consistency of the procedure can be obtained by examining the data used in the EPAX2 fit. For this examination, we employ an isotopic ratio

$$R_{21}(N,Z) = Y_2(N,Z) / Y_1(N,Z) \qquad (1)$$

where $Y_i(N,Z)$ is the yield of an isotope with N neutrons and Z protons emitted in a specific reaction labeled “i”. This ratio displays a scaling behavior [6]

$$R_{21}(N,Z)=C\cdot \exp(aN+bZ) \qquad (2)$$

where C, a and b are fitting constants. This scaling applies to a wide range of statistical mechanisms ranging from multifragmentation to deeply inelastic scattering and compound nuclear evaporation [7].

Adopting the convention that the initial system of reaction 2 is more neutron-rich than that of reaction 1, we plot $R_{21}(N,Z)$ as a function of N in the left panel of Figure 1, where reactions 1 and 2 correspond to the projectile fragmentation of ^{78}Kr and ^{86}Kr, respectively. To provide a clearer representation of the data, all even-Z isotopes are shown as solid points while the odd-Z isotopes are shown as the open points. The corresponding solid and dashed lines in the left panels are drawn to guide the eyes. There is a substantial rise in the value of R_{21} as one goes toward very neutron-rich isotopes, reflecting increases in the yields of neutron-rich isotopes with increases in the N/Z of the beam. For example, there is an order of magnitude increase in isotope yield for each extra neutron in isotopes of elements, Z=28-31, demonstrating the real benefits of using neutron-rich beams to make neutron-rich isotopes. In the data for Z<25, the measured R_{21} exhibits a V-shape suggesting that production of the lighter proton-rich isotopes is also enhanced if one uses the neutron-rich projectile instead of the proton-rich projectile. This observation is counter-intuitive and may indicate problems with the limiting fragmentation assumption, which assumes the fragmentation of ^{78}Kr projectiles which was performed with a ^{58}Ni target at E/A=75 MeV [8] is fundamentally the same process as the fragmentation of ^{86}Kr projectiles which was performed with a ^{9}Be target at E/A=500 MeV[9]. Bolstering this concern, the predictions of EPAX2 for R_{21} shown in the right panel do not reproduce the experimental trends. even though the ^{86}Kr data represent a large fraction of the data used in obtaining the fitting parameters in EPAX2.

A better test of this assumption would be a detailed comparison of the fragmentation yields for two different isotopes as projectiles at the same incident energy impinging on the same or different target. Unfortunately, the comparison of Kr isotopes in the left panel of Figure 1 is the most complete set of isotopically resolved fragmentation data available for such comparisons. The fragmentation yields of Xe and other isotopes obtained at GSI, for example, do not span a large mass range in the measured isotopes. Moreover, the isotopic distributions are seldom measured with a uniform target thickness. Instead, thinner targets were generally used for the measurements of the production of abundant isotopes around the valley of stability and thicker targets were used for the more n-rich isotopes. As the thicker targets are typically 25% or more of an interaction length in thickness, the role of multiple interactions in the target cannot be neglected.

In an effort to understand the production of neutron rich isotopes, we employed a microscopic, Abrasion-Ablation, (A-A) model [5]. The abrasion stage assumes a non-equilibrium process (Abrasion) wherein nucleons are rapidly removed from the projectile during an encounter with a stationary target. The remaining portion of the projectile is then left in an excited state that decays by an evaporative quasi-equilibrium second stage (Ablation) to reach the final products. Both the non-equilibrium process and the evaporative stages, play important roles in populating the most neutron rich final isotopes from a given system. Figure 2 shows the paths of producing different Ni isotopes (solid points) from the fragmentation of ^{86}Kr which is denoted by the symbol in the upper right corner of the figure at Z=36 and N=50. The open circles locate the average charge and neutron number of the excited nuclei, produced after the abrasion stage and the solid circles locate the final nuclei after subsequent evaporation. The production of the most neutron rich isotopes (N>39) in these calculations can be traced to the intermediate systems where the abrasion (non-equilibrium) stage removes nearly all the charge, while additional loss of neutrons to reach the final product occurs in the second stage (ablation). If, instead, only equilibrium processes at high temperature were involved, the average yields would move strongly towards the valley of stability; the population of the most neutron rich nuclides would rely entirely on statistical fluctuations about the average process. However, such statistical fluctuations under-predict the yields of neutron rich isotopes. To reproduce the observed yields it is necessary that the non-equilibrium abrasion stage produces intermediate systems at very low excitation energy with significant probability. Such "cold fragmentation" processes allow for the minimum evaporation of additional neutrons

This apparent sensitivity to details of the initial stage is contrary to the “limiting fragmentation” assumption and provides a strong motivation for new measurements in which both the projectile and target N/Z are varied. As the neutron-proton cross section is up to three times the neutron-neutron cross section in this energy domain, one expects enhancements in cold proton knock-out relative to cold neutron knock-out for neutron-rich targets like Ta relative to symmetric targets like Be. This would lead to higher yields of cold intermediate and subsequently final neutron-rich projectile remnants with neutron-rich Ta targets than is the case with our current symmetric targets like Be. The asymmetry term of the EOS may also play a significant role in the dynamical transport of nucleons between projectile and target, in their non-equilibrium emission during the collision and therefore, in the isotopic composition of the fragments produced at the end of the non-equilibrium initial stage.

Our calculations also show that multiple interactions in the target are important to describe thick target data and could be the dominant contribution in the limit of very thick targets. For example, the dashed line in Figure 3 shows the EPAX2 prediction of Sulphur isotopes from fragmentation of ^{82}Ge beams using a 10 g/cm^{2} ^{9}Be target, which corresponds 1.2 interaction lengths. Assuming for the purposes of argument that the EPAX predictions are the correct description for the contribution from single interactions, one can make the prediction for the two-step contribution given by the solid line. Clearly, the production of the extremely n-rich S isotopes with A>49 would be dominated by the 2-step processes in such a thick target; in fact, two step contributions dominate many of the predictions for RIA beams at extreme neutron excess. The understanding the relative importance of single and multiple interactions *is extremely important from the technological point of view because it provides important guidance to the relevant parameters for rare isotope beam production. We stress that the confrontation of good quality data with theory, not a blind fitting of a random assortment of data, is essential to disentangling the various effects.*

Goals of proposed experiment

We propose to measure projectile fragmentation at E/A=140 MeV with two heavy beams (^{78}Kr, ^{86}Kr), two light beams (^{40}Ca, ^{48}Ca) and two targets (^{9}Be, ^{181}Ta). Both heavy and light beams are chosen so as to explore the dependence of the fragmentation process on projectile size and on the overall Coulomb interaction. Two different values for N/Z are chosen for each mass in order to understand the dependence of isotopic yields on the isospin asymmetry of the projectile. Two targets with different N/Z were chosen in order to understand to role of the target asymmetry. The focus of these investigations will be on fragments with $A>A_{beam}/2$. Such fragments have smaller decay cones and are detected with higher efficiency $\varepsilon>50\%$. The cross sections will be used to develop and test models of the fragmentation mechanism to understand better this fundamental decay mode of highly excited nuclei.

Experimental details

The experiment will be performed with the A1900 separator running in stand-alone mode. The acceptance of the separator was calculated with LISE assuming no additional degraders after the production target. These calculations showed that in this mode the A1900 selected a range of isotope with similar charge to mass ratio, but that the acceptance as a function of Z/A was limited to about one isotope of a given element per setting. Isotopes for which the acceptance was optimized were transmitted with acceptances of the order of 70-80% but the neighboring isotopes of the same element were much smaller (of order 20-30%).

As the acquisition rate will limit our data rate for most settings, we believe that it would be better to optimize the A1900 setting so that each isotope is measured with good efficiency. This requires of the order 20-30 settings per beam target combination. We believe that we can complete one of these settings in the order of 10-12 minutes and an entire beam-target combination in the order of 8 hours, after allowing some longer runs on the extreme tails of the isotopic distributions.

Allowing, on the average, 4 hours for setup of the A1900 for each beam-target combination, and an additional 4 hours for measuring the charge state distributions of elements produced in Kr fragmentation, we estimate that we could conclude our data taking in about 100 hours. As we are requesting 4 beams, we need to include 72 additional hours for the three additional primary beams. The total then is 172 hours.

Before this experiment can run effectively, the initial commission runs with the A1900, including the acceptance measurements, need to be completed.

References:

1. W.G. Lynch, Ann. Rev. Nucl. Part. Sci. 37, 493 (1987).

2. A. Schuttauf, et al., Nucl. Phys. A607, 457 (1996).

3. K. Sümmerer and B. Blank, Phys. Rev. C 61, 034607 (2000)

4. http://www.phy.anl.gov/ria/ria_yields/yields_home.html

5. W. A. Friedman et. al. Phys. Rev. C 62, 064609 (2000).

6. H. Xu et al., Phys. Rev. Lett. 85, 716 (2000).

7. M.B. Tsang et. al., Phys. Rev. Lett. (in press). http://xxx.lanl.gov/abs/nucl-ex/0103010

8. R. Pfaff, et. al. Phys. Rev. C53, 1753 (1996).

9. M. Weber et al., Z. Phys. A 343, 67 (1992); Nucl. Phys. A578, 659 (1994).

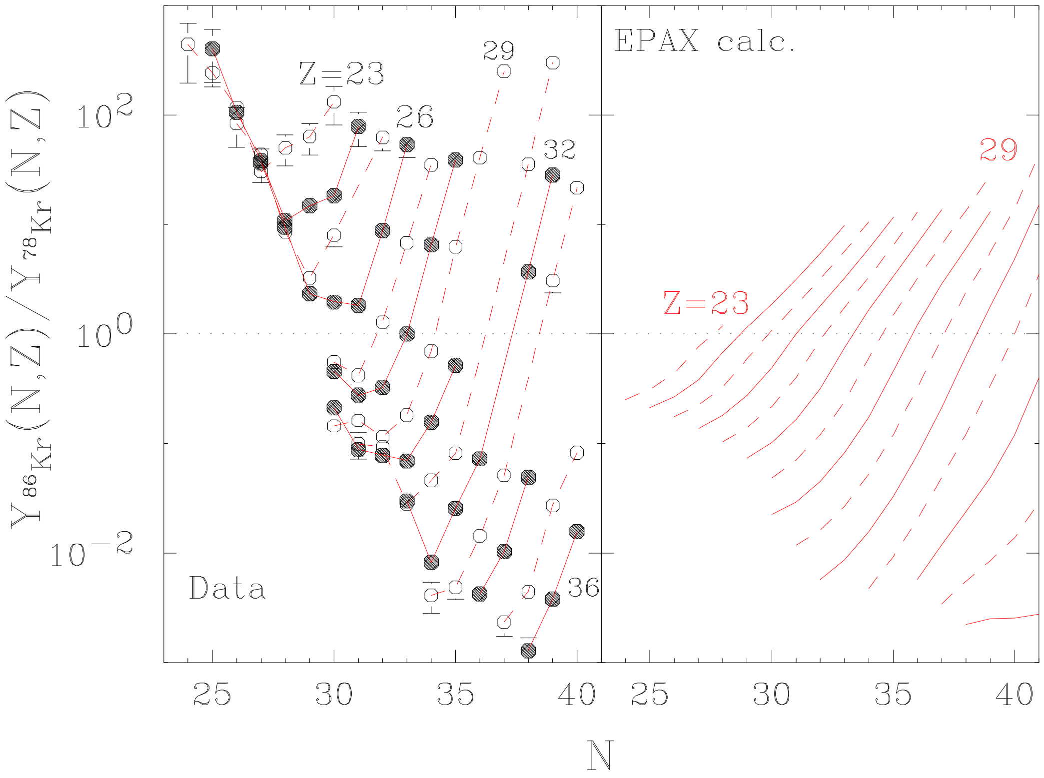
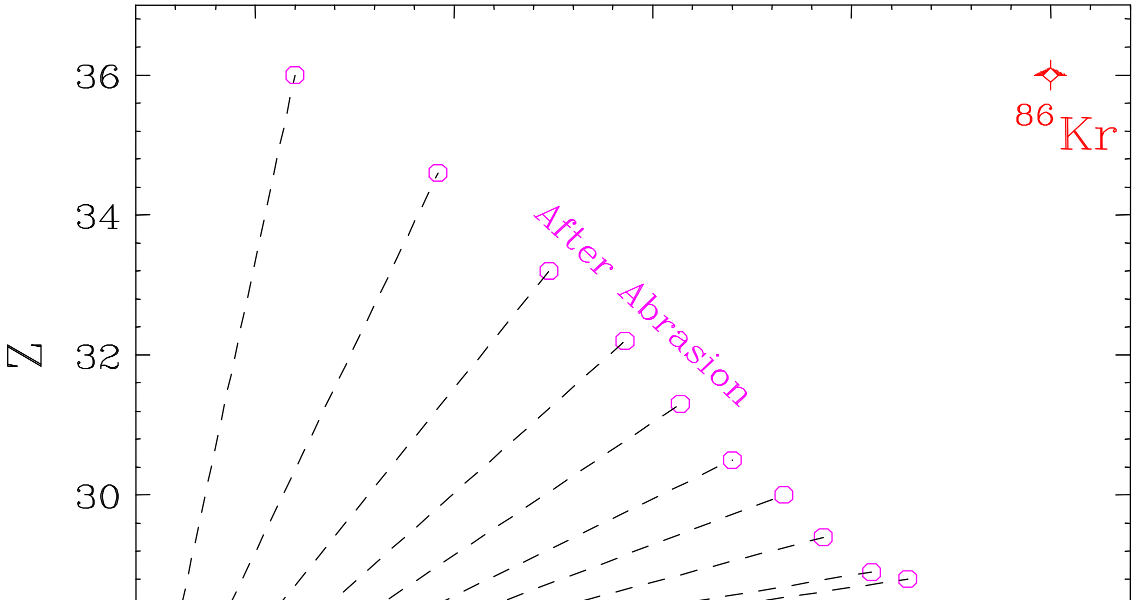


Fig. 1: Left panel: Experimental values for R_{21}(N,Z).
Right panel: EPAX2 predictions for R_{21}(N,Z).



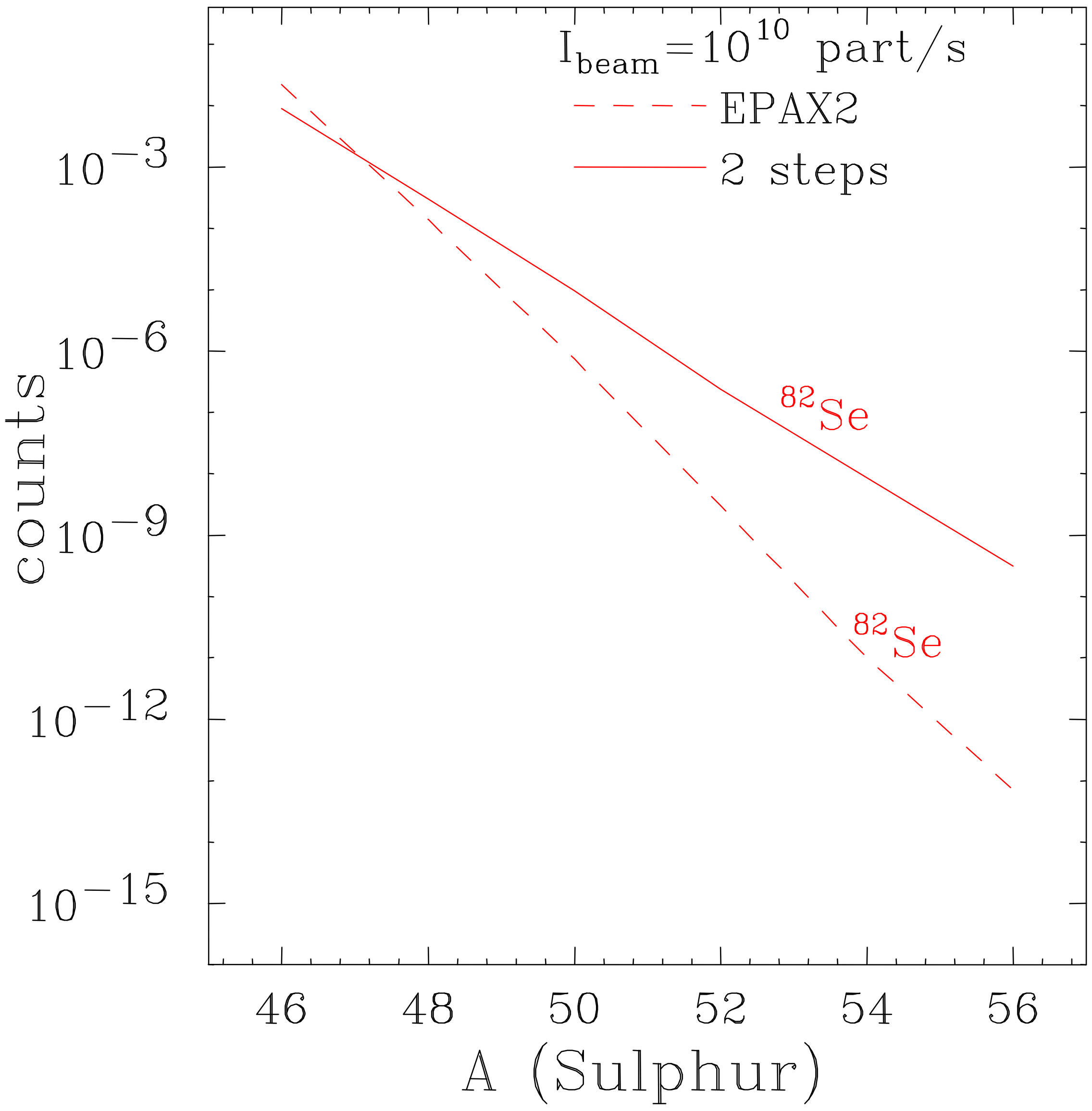


Fig. 3: Comparison of single interaction (dashed line) and double interaction (solid line) predictions using the EPAX2 parameterization.

LIST OF EQUIPMENT REQUIRING NSCL DEVELOPMENT AND DIAGRAM OF EXPERIMENTAL APPARATUS (include for all experiments)