NSCL PAC 38 PROPOSAL ELEMENTS

Description of Experiment

I. Physics Justification

Introduction: The properties of extremely neutron-rich nuclei with N=7-8 reflect competition between the filling of the $1s_{1/2}$ and $0p_{1/2}$ orbitals which, for light neutron-rich systems, are close to each other in energy and inverted in comparison to nuclei closer to stability. We propose to study both ^{10}He and ^{10}Li following nucleon removal from ^{11}L, using HiRA. The properties of the ground states of ^{10}He and ^{10}Li depend on both the neutron single-particle energies and the nucleon-nucleon residual interaction in a region of large neutron excess where they are still poorly understood. The data from this experiment will inform theoretical calculations, especially “first-principles” approaches such as the Quantum Monte Carlo [1] and No-Core shell-model [2], at and beyond the limits of stability. The approach we propose here, direct single-nucleon pickup, is complementary to those used in earlier measurements of ^{10}He and ^{10}Li that have included two-nucleon stripping and one or multi-nucleon knockout. In addition to information about the structure of these unbound systems, the data can also be compared to those from nucleon knockout to provide information on the reaction mechanisms.

^{10}He: The main goal of the experiment is to study the low-energy structure of ^{10}He. This system, unbound with respect to decay to ^{8}He+2n, is still rather poorly understood [3-5]. In a simple picture, the neutron configuration in ^{10}He should be similar to that of the ground state of ^{11}Li. It has been known for some time that the ground state of ^{11}Li possesses both $(0p_{1/2})^2$ and $(1s_{1/2})^2$ amplitudes. Estimates of the s^2 magnitude vary widely, from about 25% to 50%. Both s^2 and p^2 configurations should thus be important in ^{10}He, leading to two configuration-mixed 0^+ states at low excitation energy. Neither a good candidate for an excited 0^+ state nor values of the s^2/p^2 amplitudes in ^{10}He exist from experiment. Theoretical estimates of *sd* to *p* ratios in ^{10}He of between 2 and 3 to 1 have been suggested [3,4], but these depend not only on the $1s_{1/2}$ and $0p$ single-particle energies, but also on the *nn* residual interaction, neither of which are well constrained. For instance, the ground-state spin-parity assignment for ^{9}He remains controversial. Neutron-transfer with the ^{8}He$(d,p)^{9}$He reaction [6-8] suggests that the parity inversion for N=7 observed in ^{11}Be persists in ^{9}He, with a $1/2^+$ ground state. Studies of ^{9}He following two-nucleon knockout from ^{11}Li have concluded, however, that this assignment is “doubtful,” that the ground-state $J^{\pi}=1/2^-$, and that the n-^{8}He *s*-wave interaction is “weak” [8].

A variety of results on ^{10}He are summarized in Fig. 1, and in Table I. Experimentally, the first claimed observation of ^{10}He is from Korsheninnikov in 1994 [9], from interactions of ^{11}Li+CD$_2$ (Fig. 1a). Due to the thick target used, ^{3}He particles from the (d,^{3}He) reaction were not observed, and the resolution of the ^{8}He-2n relative energy-spectra, as gauged from data for the ^{7}He ground state, was relatively poor. A number of other studies of ^{10}He followed, using different reaction mechanisms. Measurements of the ^{8}He(t,p)^{10}He reaction (Fig. 1c,d) [10,11] have attracted particular attention, and gave a higher ground-state energy than that of Ref. [9]. The most recent (t,p) data were interpreted as suggesting the presence of a 1^- excited state similar to a 1^-_1 state in ^{12}Be that has been suggested as further evidence of the reduction of the *p-sd* shell separation and a change in the neutron shell ordering in this region. Other analyses [3,12] disagree with that interpretation for ^{10}He and claim no such state is necessary to explain the data, and the question remains open. Furthermore, there exists a general discrepancy between results from nucleon knockout reactions and those from transfer reactions. Ref. [4] examined the question of why (t,p) and proton removal different should give different results, suggesting sensitivity to the extended size of ^{11}Li, however very recent results from a study of ^{14}Be-2p2n multi-nucleon removal (Fig. 1b, Ref. [5]) which agreed with those from ^{11}Li-p knockout discounted that solution and according to the authors the question remains “unresolved.”

We will also start from ^{11}Li, but instead of reconstructing the ^{10}He energy from ^{8}He+2n correlations, we will use the (d,^{3}He) reaction in inverse kinematics with a thin target and observe the ^{3}He particles as was done in E10011. One possible explanation for the discrepancies between different results from different reactions is the possibility of two nearby overlapping 0^+ states consisting of orthogonal combinations of $(1s_{1/2})^2_{0+}$ and $(0p_{1/2})^2_{0+}$ amplitudes. Depending on the reaction mechanism and configuration mixing, either one or both of these 0^+ states might be populated in different prior measurements, thus changing the apparent “ground-state” energy and width. Only one of these, with the neutron configuration similar to that of the ground state of ^{11}Li, should be populated in (d,^{3}He). *One more summative thought here*.

^{10}Li: Just as an understanding of ^{10}He relies on knowledge of the single-particle properties of ^{9}He, calculations for ^{11}Li rely on data for ^{10}Li. Simultaneously with the (d,^{3}He) measurement, we will collect data for the ^{11}Li(d,t)^{10}Li reaction. The low-energy spectrum of ^{10}Li is generally described as possessing a virtual s-wave neutron ground state, with a nearby p-wave excitation at E_X~0.5 MeV. This picture has emerged from both neutron-knockout from ^{11}Li [16,17], as well as neutron stripping with (d,p) on ^{9}Li [18]; Table 2 and Fig. 2 summarize some of the information available on ^{10}Li. In fact, the prevailing description is too simple, as the neutron single-particle strengths must be split due to coupling with the angular momentum of the $0p_{3/2}$ proton. In ^{12}B, the splitting between the J=1 and 2 members of the positive- and negative-parity doublets is approximately 1 MeV each, an amount comparable to the splitting of the effective $s_{1/2}$ and $p_{1/2}$ single-particle strength in ^{10}Li expected based on extrapolations from ^{13}C, ^{12}B, and ^{11}Be. While this detail has been overlooked in the analysis of many (but not all, see Ref. [20]) data on ^{10}Li, some clarification can be obtained from a study of the selective ^{11}Li(d,t)^{10}Li reaction. At the energies we will use, even at quite forward angles the triton angular distribution can distinguish l=0 and 1 transitions and will help determine the locations of the s-wave and p-wave strengths in ^{10}Li.

^{8}He Calibration: In past experiments it has proved extremely useful to have a good calibration reaction. We will characterize the performance of HiRA with the ^{9}Li(d,^{3}He/^{3}H)^{8}He/^{8}Li reactions in inverse kinematics. ^{9}Li is a prolific beam and as both ^{8}He and ^{8}Li ground states are bound the ^{9}Li(d,^{3}He/^{3}H) reactions will provide a good calibration. Furthermore, although the ground-state transitions will be strongest, due to configuration mixing information about excited states in ^{8}He may also be obtained from this reaction. There is also uncertainty about the spectrum of excited states in ^{8}He, where recent data show rather different results. Figure 4 shows data from the ^{6}He(t,p)^{8}He reaction [12] which claims several narrow excited states, one of which is possibly 1^{+} even though direct transitions to unnatural parity states via (t,p) here are forbidden. The possibility of a 1^{-} state was also mentioned in [12], although both suggested observations remain controversial. For instance, very recent data from ^{8}He breakup [21] (Fig. 4b) show a rather different picture, claiming two broad excitations but no narrow excited states. Data for the unbound states in ^{8}He may help resolve some of these questions.

II. Goals of the proposed experiment

1. Observe the ^{11}Li(d,^{3}He)^{10}He$_{\text{g.s.}}$ reaction and study the properties of ^{10}He$_{\text{g.s.}}$.
2. Study the ^{10}Li low-energy structure with the ^{11}Li(d,t)^{10}Li reaction.
3. Calibrate HiRA with the ^{9}Li(d,^{3}He/^{3}H)^{8}He/^{8}Li reactions and study nucleon-removal to states in ^{8}He and ^{8}Li.

III. Experimental Details

The experiment will be performed using ^{9,11}Li secondary beams produced by fragmentation of an ^{18}O primary beam at 120 MeV. Target and wedge thicknesses are provided in the attached

LISE++ files. The A1900 I2 slits will be set for $\delta p/p=2\%$, and the ^{11}Li energy will be 85 MeV/u. With these parameters, LISE++ predicts a ^{11}Li focal plane rate of 75 pps/pnA, corresponding to a total focal-plane rate of $1.2\text{x}10^4$ pps. Assuming a transport efficiency of 80% to the S2 vault in accordance with prior experience, this corresponds to a rate of approximately 10^4 pps on target. The ^{3}He/^{3}H reaction products will be detected using HiRA, which will be installed in the large scattering chamber in the S2 vault (See Fig. 5) in the same position as for experiment E10011, and for the experiment proposed by the Washington University at St. Louis group on ^{11}O submitted to PAC38, although the target will be in the center of the chamber as indicated in Fig. 5. The method will be the same as used in the successful E10011: ^{3}He/^{3}H reaction products with low energies will be detected and identified using the ΔE and E silicon-detector layers of the HiRA telescopes. In E10011, the coincident detection of the high-energy recoiling decay products permitted the clean isolation of the reactions of interest (see Fig. 6). Here, the angles of the high-energy beam-like ^{8}He/^{9}Li recoils do not exceed 2.5 degrees, and these nuclei will not be observed in the normal HiRA telescopes. To detect these fragments, we will include an additional silicon-scintillator telescope at 0 degrees with scintillator thick enough to stop the high-energy ^{8}He particles. This telescope will have only a single silicon layer, segmented so as to be able to accept the full expected incident beam of 10^4 pps. For the E scintillator, we will use either a segmented CsI(Tl) or plastic-scintillator detector to accommodate the full beam rate. For the ^{9}Li calibration, the beam is much more intense ($>10^5$ pps), but the beam-like recoils extend to larger laboratory angles. We will block the center-most part of the 0 degree detector and limit the beam intensity to 10^5 pps for the calibration run. Additional calibration data will be obtained from alpha-particle source measurements.

Our count rates for the ^{11}Li portion of the experiment are based on the following estimates: A ^{11}Li intensity of 10^4 pps, a HiRA solid angle of 0.45 sr, and target thickness of 2.5mg/cm^2. This corresponds to a count rate of approximately 0.6 counts/hour/mb/sr; DWBA calculations predict cross sections of several mb/sr for unit spectroscopic factor. If the average cross section is as small as 1 mb/sr, we would still obtain a ground-state yield of approximately 100 counts in one week of running, which will be sufficient to characterize the energy and width of the state and provide information about the angular dependence of the cross section. We have performed Monte-Carlo simulations of the reactions to determine the HiRA acceptance and the effects of target thickness and beam-spot size. With this setup, HiRA will cover angles between 5 and 35 degrees in the laboratory. The expected beam-spot size of 5mm X 10mm and 2% momentum acceptance have little effect on the resolution. The energy loss of ^{3}He in target will broaden and shift the ^{10}He ground-state peak, however the effects are straightforward to correct and we will still be able to extract determinations of energies and widths for populated states. We request 12 h for development of the 120 MeV ^{18}O beam, 5h each for development and delivery to the S2 vault of the ^{9,11}Li beams, 24 h for debugging and setup of HiRA with ^{9}Li, 24h for the ^{9}Li calibration measurement, and 168h for the ^{11}Li measurement, for a total request of 238 hours.

IV. Supplemental Information (Figures, Tables, References, etc., including one figure that depicts the layout of the experimental apparatus)

References:

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[12] K. Hagino, N. Takahashi, and H. Sagawa, Phys. Rev. C 77, 054317 (2008)

Table 1. Different values of the energy and width of the ^{10}He ground state. Table reproduced from Reference [3].

Reaction	E_{2n} (MeV)	Γ (MeV)	Ref.
^{1}H(^{11}Li,2*p*)	1.7(3)(3)		10
^{2}H(^{11}Li,^{3}He)	1.2(3)	<1.2	9
^{10}Be(^{14}C,^{14}O)	1.07(7)	0.3(2)	11
^{14}B-2*p*2*n*	1.60(25)	1.8(4)	5
^{3}H(^{8}He,*p*)	2.1(3)	~2	13
^{3}H(^{8}He,*p*)	~3		12
^{11}Li-*p* knockout	1.42(10)/1.54(11)	1.11(76)/1.91(41)	14

Table 2. Resonance parameters for states in ^{10}Li, reproduced from Reference [17]. ^{a}Scattering length for a virtual s-wave ground-state, ^{b}Excited-state resonance parameters

Reaction	E_{n}	Γ (MeV)	Ref.
^{11}Li-*n* knockout	-22.4±4.8^{a}	0.352±0.022	16
^{11}Li-*n* knockout	~30^{a}	0.3	18
^{9}Li(*d,p*)^{10}Li	$-24<a<-13^{a}$		19
^{9}Li(*d,p*)^{10}Li^{b}	~0.4	~0.2	19
^{11}Li-*n* knockout^{b}	0.566±0.014		16
^{11}Li-*n* knockout^{b}	0.510±0.044		18
^{14}C(π^{-},*pt*)^{b}	0.70±0.05	<0.2	17
^{14}C(π^{-},*dd*)^{b}	0.78±0.15	~0.5	17
^{9,10}Be(^{12,13}C,^{12,13}N)^{b}	2.35±0.10		20
^{11}Li-*n* knockout^{b}	~5.2		10
^{15}C(π^{-},*dd*)^{b}	6.12±0.09		17

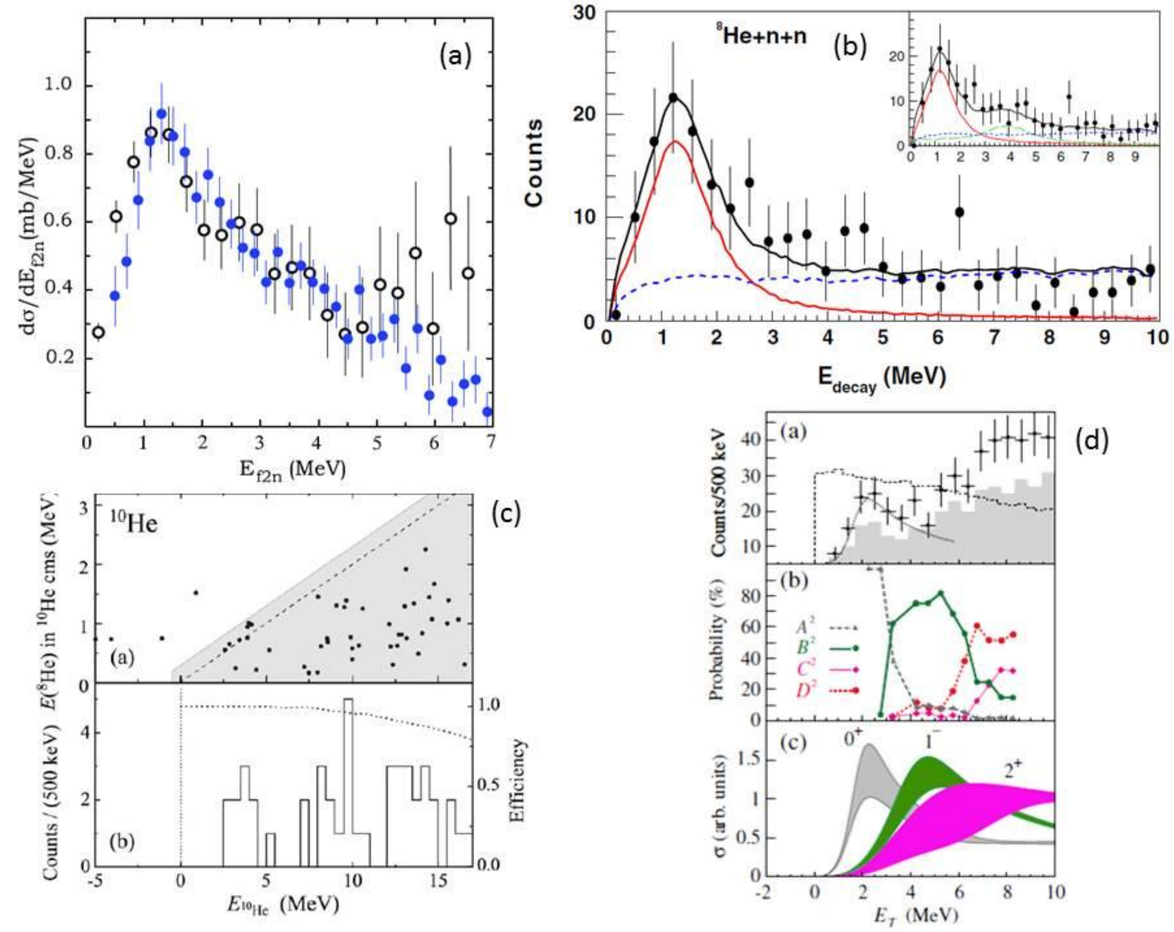

Figure 1. ^{10}He excitation spectra deduced from: (a) ^{8}He-2*n* events from ^{11}Li+CD$_2$ interactions from [9] (open symbols) and [8] filled symbols. (b) ^{8}He-2*n* events from ^{14}Be-2*p*2*n* knockout [5], ^{8}He(*t,p*)^{10}He from (c) Ref. [12] and (d) Ref [13].

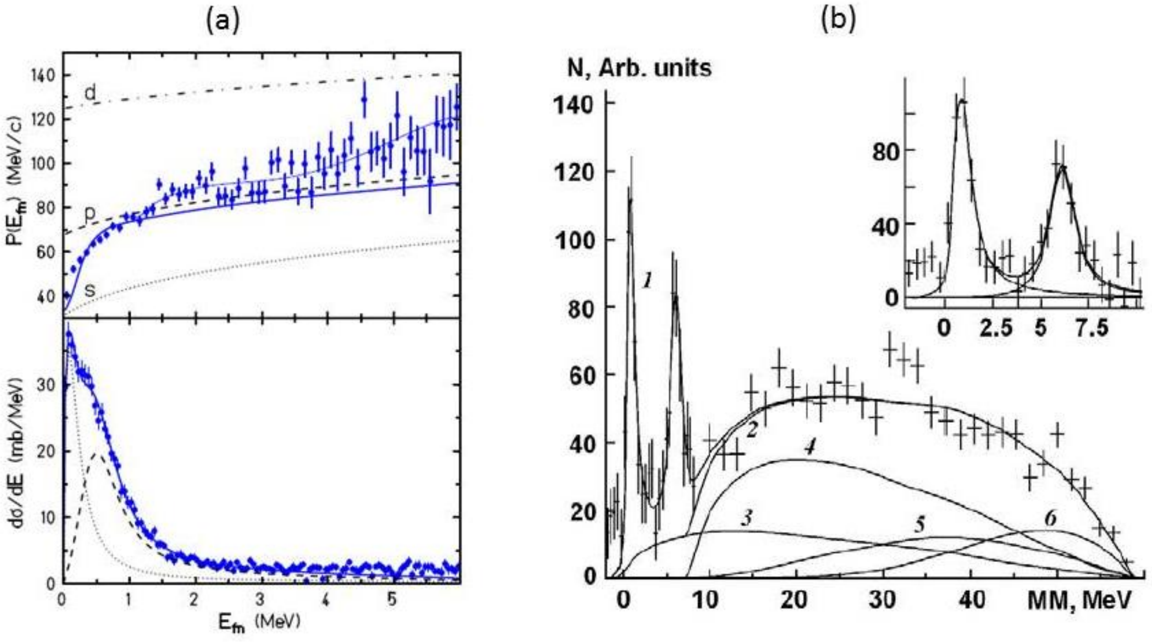

Figure 2. ^{10}Li spectra from (a) ^{11}Li-n knockout (Ref. [16]) and (b) a recent report of pion absorption (Ref. [17]).

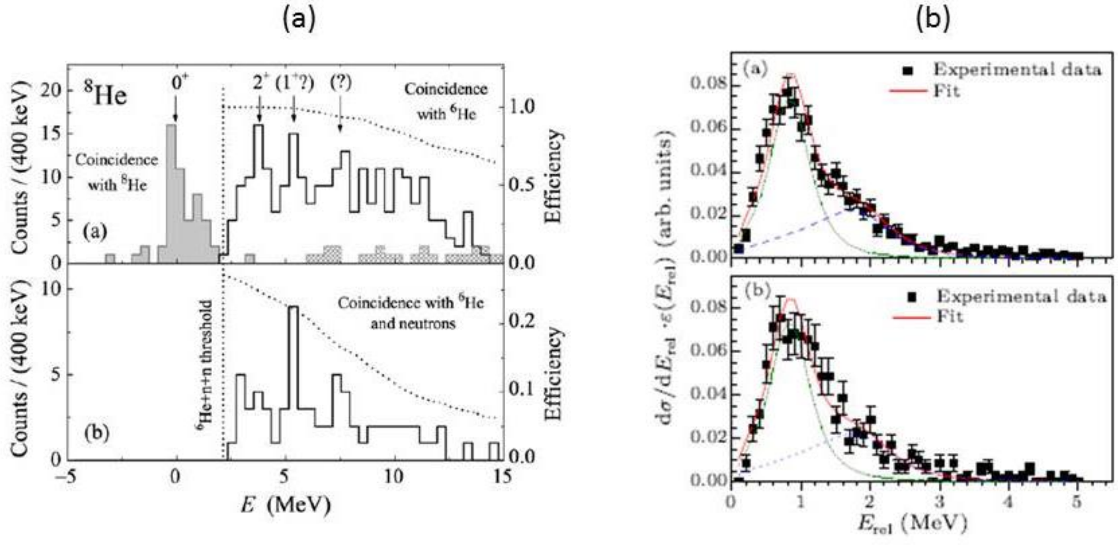

Figure 3. ^{8}He spectra from (a) the ^{6}He(t,p)^{8}He reaction (Ref. [12]) and (b) ^{6}He-2n correlations following ^{8}He breakup (Ref. [21]).

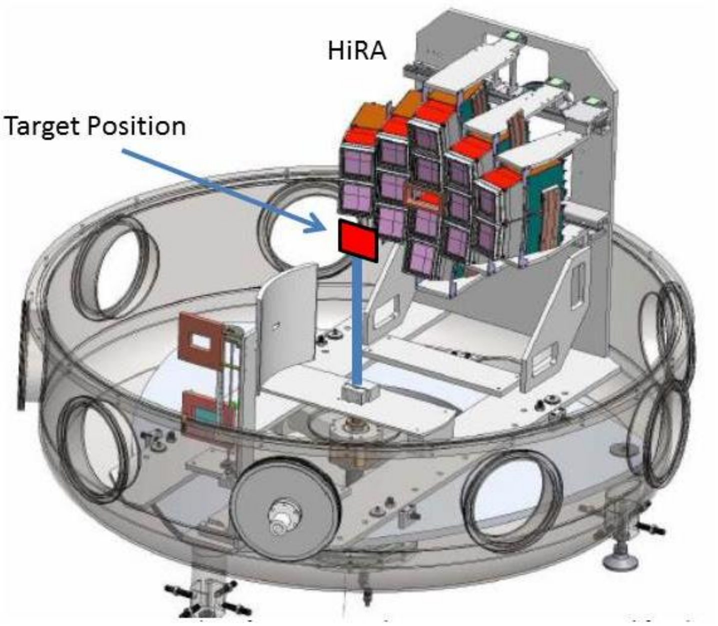

Figure 4. Experimental setup showing HiRA in the S2-vault large scattering chamber.

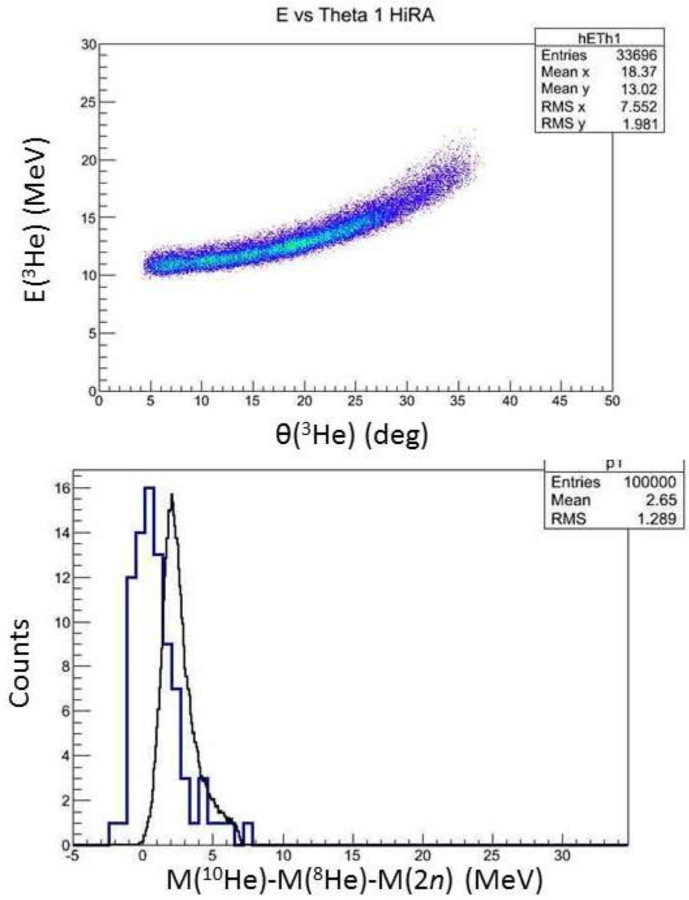

Figure 5. Monte-Carlo simulations of the ^{11}Li(*d*,^{3}He)^{10}He reaction in inverse kinematics measure with HiRA. (a) ^{3}He energy-angle correlation. (b) ^{10}He missing-mass spectra with source spectrum (thin histogram) and reconstructed expected ^{10}He signal for a 1mb/sr average cross section (thick histogram).

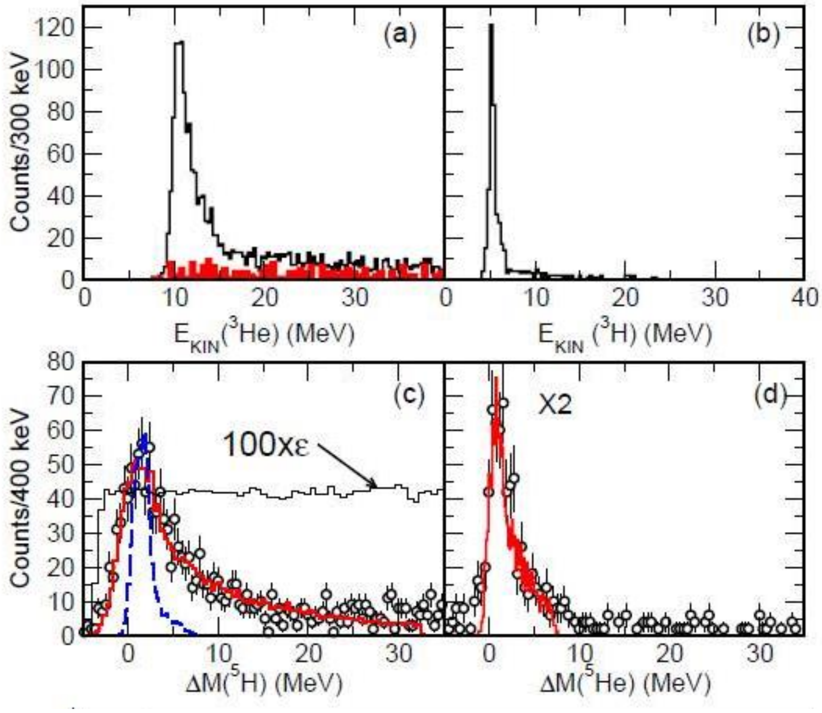

Figure 6. Results from the recent study (E10011) of the ^{6}He(d,^{3}He/^{3}H)^{5}H/^{5}He reactions using HiRA. (a,b) ^{3}He and ^{3}H kinetic-energy spectra obtained in coincidence with ^{3}H/^{4}He from the decay of ^{5}H/^{5}He; (c,d) ^{5}H and ^{5}He missing-mass spectra. The dashed histogram in Fig. 1c illustrates the resolution from that measurement.

Status of Previous Experiments

Results from, or status of analysis of, previous experiments at the CCF listed by experiment number. Please indicate publications, invited talks, Ph.D.s awarded, Master's degrees awarded, undergraduate theses completed.

E10011: The first analysis of the results from E10011, run in August 2013, is complete, and a manuscript describing the results has been submitted to Physical Review Letters. (See figure 6).

Educational Impact of Proposed Experiment

If the experiment will be part of a thesis project, please include the total number of years the student has been in graduate school, what other experiments the student has participated in at the NSCL and elsewhere (explicitly identify the experiments done as part of thesis work), and what part the proposed measurement plays in the complete thesis project.