National Superconducting Cyclotron Laboratory
Proposal Form - PAC 38

By submitting this proposal, the spokesperson certifies that all collaborators listed have read the Description of Experiment and have agreed to participate in the experiment.

Title

The structure of 11O

Spokespeople

	Primary Spokesperson	**Backup Spokesperson**
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Position	Senior Researcher	Senior Researcher

Experimenters

Name	**Organization**	**Position**
Cole Pruitt	Washington University	Graduate
Kyle Brown	Washington University	Graduate
Jon Elson	Washington University	Senior Researcher
Kim Suho	Washington University	Undergraduate
John Bromell	Carelton College	Undergraduate
Kouicki Hagino	Tohoku University, Japan	Senior Researcher
Alan Wuosmaa	University of Connecticut	Senior Researcher
Zbigniew Chajecki	NSCL	Postdoctoral Associate
Juan Manfredi	NCSL	Graduate
Betty Tsang	NSCL	Senior Researcher
Bill Lynch	NSCL	Senior Researcher
Rebecca Shane	NSCL	Postdoctoral Associate

Location & Equipment Details

Location	S3 Vault
Equipment	High Resolution Array Radio Frequency Fragment Separator

	Setup Time (Days)	Take Down Time (Days)
Experimental Vault	28	14
Data Acquisition	28	14
Electronics	28	14

Preferred Experiment Start Date	9/19/2014
Dates Excluded	

Summary

The nucleus ^{11}O and its isobaric analog state in ^{11}N are part of an isospin sextet containing the neutron-halo nucleus ^{11}Li. We propose to produce and identity the particle-unstable ground state of ^{11}O following two-neutron knockout reactions with a ^{13}O beam. The $2p+^{9}$C exit channel produced in the decay of ^{11}O will be detected with the HiRA array and the mass of ^{11}O will be inferred with the invariant mass method. We will also use the invariant mass method to search for its isobaric analog state in ^{11}N. Together with the masses of the other three known members of this sextet, we will search for deviations from the Isospin Multiplet Mass Equation which is a signature of isospin violation. In addition, the $(s_{1/2})^2$ contribution to the ground-state wavefunction can be inferred from the difference in ^{11}O and ^{11}Li masses (Thomas-Ehrman shift) and independently from the correlations between the momenta of the three bodies in the exit channel of ^{11}O.

Special Requirements

Detail any modifications needed to the standard configuration of the device used:

Requirements that are outside the current NSCL operating envelope:

Reaction targets at the experimental station:

Breaks required in the schedule of the experiment:

Non-standard resources:

Other special requirements:

Proposal Elements

PAC38_11O.doc

LISE++ Files

13O_Be2900_Al600_RFFS_13O.lpp
13O_Be2900_Al600_p.lpp
13O_Be2900_Al600_NZ.lpp
13O_Be2900_Al600_9C.lpp

Fast Beam Worksheet 1

Primary Beam

Beam Type	Developed
Isotope	16O
Energy	150 MeV/nucleon
Intensity	175 pnA
Tuning Time	12 hrs

Beam-On-Target

Isotope	13O
Energy	70 MeV/nucleon
Rate at Experiment	1500 pps/pnA
Total A1900 Momentum Acceptance	1 %
Purity at Experiment	90 %
Rare-Isotope Delivery Time Per Table	2 hrs
Tuning Time to Vault	3 hrs
Total beam preparation time	17 hrs
Is a plastic timing scintillator required at the A1900 focal plane for providing a timing start signal?	No
Is event-by-event momentum correction from position measured at the A1900 Image 2 position required?	No
Experimental Device	Other - RF-kicker with 1 mm scint and HirA The beam rate given above is after the RF-kicker AND scaled down by 0.4 to account for recent experience. The RF-kicker is ONLY used for this the data runs.
Experimental Device Tuning Time	4 hrs
On-Target Time Excluding Device Tuning	108 hrs
Total On-Target Time	112 hrs
Total Beam Preparation Time	129 hrs

Fast Beam Worksheet 2

Primary Beam

Beam Type	Developed
Isotope	16O
Energy	150 MeV/nucleon
Intensity	175 pnA
Tuning Time	0 hrs

Beam-On-Target

Isotope	proton
Energy	80 MeV/nucleon
Rate at Experiment	662 pps/pnA
Total A1900 Momentum Acceptance	1 %
Purity at Experiment	25 %
Rare-Isotope Delivery Time Per Table	2 hrs
Tuning Time to Vault	3 hrs
Total beam preparation time	5 hrs
Is a plastic timing scintillator required at the A1900 focal plane for providing a timing start signal?	No
Is event-by-event momentum correction from position measured at the A1900 Image 2 position required?	No
Experimental Device	Other - Hira in S3 Scattering Chamber
Experimental Device Tuning Time	0 hrs
On-Target Time Excluding Device Tuning	3 hrs
Total On-Target Time	3 hrs
Total Beam Preparation Time	8 hrs

Fast Beam Worksheet 3

Primary Beam

Beam Type	Developed
Isotope	16O
Energy	150 MeV/nucleon
Intensity	175 pnA
Tuning Time	0 hrs

Beam-On-Target

Isotope	4He
Energy	80 MeV/nucleon
Rate at Experiment	12000 pps/pnA
Total A1900 Momentum Acceptance	1 %
Purity at Experiment	2 %
Rare-Isotope Delivery Time Per Table	2 hrs
Tuning Time to Vault	3 hrs
Total beam preparation time	5 hrs
Is a plastic timing scintillator required at the A1900 focal plane for providing a timing start signal?	No
Is event-by-event momentum correction from position measured at the A1900 Image 2 position required?	No
Experimental Device	Other - Hira in S3 scattering Chamber with RF chopper.
Experimental Device Tuning Time	0 hrs
On-Target Time Excluding Device Tuning	5 hrs
Total On-Target Time	5 hrs
Total Beam Preparation Time	10 hrs

Fast Beam Worksheet 4

Primary Beam

Beam Type	Developed
Isotope	16O
Energy	150 MeV/nucleon
Intensity	175 pnA
Tuning Time	0 hrs

Beam-On-Target

Isotope	9C
Energy	81.4 MeV/nucleon
Rate at Experiment	2000 pps/pnA
Total A1900 Momentum Acceptance	1 %
Purity at Experiment	10 %
Rare-Isotope Delivery Time Per Table	2 hrs
Tuning Time to Vault	0 hrs
Total beam preparation time	2 hrs
Is a plastic timing scintillator required at the A1900 focal plane for providing a timing start signal?	No
Is event-by-event momentum correction from position measured at the A1900 Image 2 position required?	No
Experimental Device	Other - HiRa
Experimental Device Tuning Time	0 hrs
On-Target Time Excluding Device Tuning	5 hrs
Total On-Target Time	5 hrs
Total Beam Preparation Time	7 hrs

Spectrograph Worksheet

No Spectrograph Worksheet is required.

Sweeper Worksheet

No Sweeper Magnet Worksheet is required.

Safety Information Worksheet

Contact: Betty Tsang

Yes	**Radioactive sources required for checks or calibrations**	Th alpha source required calibration of Si detectors
No	**Transport or send radioactive materials to or from the NSCL**	
No	**Transport or send? to or from the NSCL?chemicals or materials that may be considered hazardous or toxic**	
No	**Generate or dispose of chemicals or materials that may be considered hazardous or toxic**	
No	**Mixed Waste (RCRA) will be generated and/or will need disposal**	
No	**Flammable compressed gases needed**	
No	**High-Voltage equipment (Non-standard equipment with > 30 Volts)**	
No	**User-supplied pressure or vacuum vessels, gas detectors**	
No	**Non-ionizing radiation sources (microwave, class III or IV lasers, etc.)**	
No	**Biohazardous materials**	
No	**Lifting or manipulating heavy equipment (>500 lbs)**	

NSCL PAC 38 PROPOSAL ELEMENTS

Description of Experiment

I. Physics Justification

The exotic nucleus ^{11}Li is the textbook example of a halo nucleus, with the two-neutron halo extending well out into space giving it an outer radius similar to that of a ^{208}Pb nucleus. This nucleus has an isopin of T=5/2 and thus must be part of an isospin sextet (2T+1). All members of the sextet are expected to have a similar structure, i.e. a two-nucleon halo [1]. However apart from ^{11}Li, this halo is not bound and the members of the sextet will decay by two-nucleon emission. The second member of this sextet is the isobaric analog state in ^{11}Be (T_Z=3/2) which was observed in RIKEN in 1997 [2]. We have recently found [3] the next member of the sextet, the double isobaric analog state in ^{11}B (T_Z=1/2), from data we collected in a HiRA experiment at MSU in 2007.

Most sextets have only one known member (T=T_Z), and only a couple have two. Thus the A=11 sextet in the most complete at present and we are proposing to add ^{11}O (T_Z=-5/2, the mirror of ^{11}Li) and possibly its isobaric analog state in ^{11}N (T_Z=-3/2). To the extent that isospin is a good quantum number and thus ignoring the Coulomb energy, the mass of each member of a multiplet should be identical. However, Wigner found that if two-body forces are responsible for the charge-dependent effects, then the masses are expected to follow a quadratic dependence $M(T,T_Z)= a + bT_Z + cT_Z^2$ [4] called the isospin multiplet mass equation (IMME).

This dependence has been verified for a large number of isospin quartets and quintets and only a few cases are known where there are deviations indicating higher-order isospin violations [5]. Some cases like the A=32 quintet where the deviation is small (~1 keV), have been explained by isospin mixing between levels [6]. But the largest known deviations (~100 keV) are for the A=8 quintet which is still unexplained [7], see Fig 1. Given the A=8 quintet contains ^{8}He and thus also has a halo structure, it would be interesting to see if the A=11 sextet follows the IMME or not. In principle sextets should be more sensitive probes of this physics as they cover a larger range of T_Z and can probe for higher-order deviations. A least one more member of the A=11 sextet is needs to be measured in order to explore deviations from the quadratic IMME.

It is well known that a theoretical understanding of the properties of ^{11}Li requires considerable inclusion of $(s_{1/2})^2$ configuration in addition to the expected $(p_{1/2})^2$ component [8,9]. In addition, the valence nucleons are predicted to have two well separated components; A dinucleon component, where the halo nucleons are mostly on the same side of the core, and a cigar component where they are more on opposite sides (Fig. 2). It is the long tail of the dineutron component that gives rise to the halo structure [8]. Fig.2 also shows that the relative contribution of dinucleon to cigar configurations is predicted to be very sensitive to P(s^2), the relative s^2 contribution.

The difference in the mass between ^{11}O and ^{11}Li can be related to the coulomb energy between the two-proton halo in ^{11}O and its core and the halo self coulomb energy [3]. This will depend on the extent of the halo and thus on P(s^2). Based on the IMME extrapolation of the known T_Z=5/2,3/2,1/2 masses, the decay energy of $^{11}O_{g.s.}$ is E_T=3.21(84) MeV [3]. The IMME results were found consistent with the calculations of halo wavefunction of Ref [10] with P(s^2) = 23%. More recently, Fortune has suggested a value of E_T=5.41(11) MeV based on an extrapolation using mirror-energy-differences [11], but this would signify an extreme violation of the IMME. Subsequently, Fortune and Sherr [12] proposed that lower E_T values could be obtained with very significant s^2 contributions to the halo [P(s^2)>0.59 see Fig. 3] . The physics being probes here is basically the same as for Thomas-Ehrman shifts [13].

The momentum correlations between the decay products can be used to determine the prompt or sequential nature of the decay and to constrain structure-model calculations [14]. For example, Fig. 4 shows the measured distribution of E_x/E_T obtained in the two-proton decay of the $^{45}Fe_{g.s}$. where E_x is the relative kinetic energy between the two protons [15]. The low and high E_x/E_T peaks are preferentially populated by diproton and cigar configurations respectively. In this case, the relative strength of these components is sensitive to the p^2 contribution. Figure 5 shows our results for $^6Be_{g.s.}$ and here the two components are still discernable, but the effect of barrier penetration acts to smears them out to some extent [14,16].

Therefore the relative contributions of cigar to dinucleon component can be inferred from the E_x/E_T distribution and for the ^{11}O, this can be used to constrained the s^2 contribution. Thus measurement of the ^{11}O mass and its decay correlations can give independent measures of the s^2 components of the sextet. Of course it is possible that P(s^2) might change along the sextet, for example P(s^2) was predicted to change by 10% between the mirror pairs ^{12}O and ^{12}Be[17].

With the E_T value from the IMME extrapolation, the 2*p* decay would be considered a prompt democratic decay because the widths of the possible intermediate states in ^{10}N are of similar magnitude to the decay energy to these states [18]. However, for the higher value of E_T=5.4 MeV from [11] which we think is unlikely, the decay may have a more sequential nature and, using the R-matrix formalism [19], we estimate a decay width of Γ=1-2 MeV depending of the assumed structure of $^{11}O_{g.s.}$. These estimates drop below 1 MeV for the lower decay energies, but the application of the R-matrix for democratic decay maybe questionable [7], in any case we expect it to be no smaller than the value of 306(182) keV measured for its analog in ^{11}B [3].

II. Goals of the proposed experiment

We propose to use a secondary ^{13}O beam and create $^{11}O_{g.s.}$ and possibly its analog state in ^{11}N via 2*n* and *n*+*p* knockout reactions. The goals of the experiment are

a) To measure the mass and decay width of the ^{11}O ground state from its detected $2p+{}^{9}C$ decay products using the invariant-mass method.

b) To measure the momentum correlations between the $2p+{}^{9}C$ decay product (in particular the E_x/E_T distributions).

c) Use this mass to look for deviations from the IMME and thus indications of higher-order isospin violation. In addition, use the measured mass and correlations to constrain nuclear models and thus infer the $P(s^2)$ contribution of the sextet and look for evidence of variation of $P(s^2)$ along the sextet.

d) To search for the isobaric analog state of ^{11}O in ^{11}N using the invariant-mass method from its $2\alpha+3p$ exit channel. If this is found, it will add further sensitivity when looking at deviations from the quadratic IMME.

In addition to these major goals we note that via one nucleon knockout reactions we will also produce $^{12}O_{g.s.}$ and its isobaric analog in ^{12}N [20]. Although we have studied their two-proton decay recently in a Texas A&M experiment, there were not enough statistics to define the two-dimensional correlations. The proposed experiment, with ~1000 times the beam intensity would remedy this.

III. Experimental Details

The decay fragments from the states of interest will be detected in the HiRA array [21] which has been used successfully for similar invariant-mass measurements in the past. Fig. 6 shows the detector arrangement used for most of these measurements and which is proposed in this work. With a secondary beam of ^{13}O at 70 MeV/*A*, the correlated two-nucleon stripping model of Tostevin et al. [22] predicts a 0.5 mb cross section for producing ^{11}O in its ground state. In the *sd*-shell, the limited experimental data indicates that this model overestimates the cross section by roughly a factor of two [23]. However, these other experiments studies have not probed the usefulness of these reactions to produce nuclei beyond the proton drip line. In fact for *single*-nucleon knockout cross sections, this model overestimates the removal from deeply-bound states by up to a factor of 4 [24]. As we are attempting to remove two deeply-bound neutrons, for a conservative estimate (ignoring the possible correlated nature of the knockout neutrons) we have assumed a factor of 4^2 reduction from the estimate of Tostevin's model. This experiment will provide an experimental measure of this reduction factor which can be used to better plan future experiments on the proton drip line. A number of possible 4*p* decaying states are reachable via 2*n* knockout reactions.

In our most recent experiment (11001), the desired secondary beam was ^{17}O produced with a ^{20}Ne primary. The secondary beam intensity was 0.4 of that predicted by LISE++ and the (-αn) product (^{15}O) was much more intense than predicted. To remove this problem in the present case we propose using the RF-Kicker to remove the expected ^{11}C contaminate from the ^{13}O beam. With less than a 20% loss of ^{13}O, the ^{11}C is removed by more than two orders of magnitude. The larger beam size produced with the FR-kicker optics does not significantly influence our reconstructed resolution. The expected rate of ^{13}O of 1700 /s/pna (300k/s total) is taken from LISE with the RF-kicker in and a further factor of 0.4 reduction to scale to our recent experience. (The A1900 staff made this suggestion.) The addition of a scintillator after the FR-kicker ensures a timing detector run at a usable low rate and facilitates cross-section measurements. With a 1mm Be target and a simulated efficiency of detecting the 2*p*+^{9}Li exit channel of 8%, we get 800 detected ^{11}O events per day. The simulations also indicate an experimental resolution of 350 keV (FWHM) which is the same order or smaller than the expected decay width.

The detection of the isobaric analog state in ^{11}N is much more difficult. The state will two-proton decay to the isobaric analog state in ^{9}B, which itself undergoes particle decay leading eventually to a final exit channel of 3*p*+2α. Although we have detected 5-particle correlations in the past [7], the detection efficiency will be low around 1%. Measurement of the $^{11}\text{N}_{\text{IAS}}$ mass is not critical to major aims of the experiments, but will add further sensitivity in looking for to deviations from the IMME if we find it.

Precision measurements of the mass of the ^{11}O and its isobaric analog state in ^{11}N require accurate energy calibrations of the CsI(Tl) detectors in each HiRA module which are specific for each particle type. We ask for 80MeV/A beams of protons and an N=Z cocktail containing alpha particles. We also expect an 81 MeV/A ^{9}C beam to be a contaminant of the desired ^{13}O beam. Lower-energy calibration points with be obtained with degrader foils. We need 12 hours of beam time for the setup of HiRA and 4 days of data taking. The latter should give ~5600 detected ^{11}O events which would provide a statistical error on the ^{11}O mass of 26 keV for Γ=2 MeV or less for smaller more reasonable values of Γ .

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

References:

[1] Suzki and Yabana, Phys. Lett. B **272**, 173 (1991)
[2] Teranishi et al. Phys. Lett. B **407**, 110 (1997)
[3] Charity et al., Phys Rev C**86**, 041307 (2012).
[4] Benenson and Kashy, Rev. Mod. Phys. **51**, 527 (1979).
[5] MacCormick and Audi, http://arxiv.org/abs/1312.152
[6] Signoracci and Brown, Phys. Rev C **84**, 031301 (2011).
[7] Charity et al., Phys. Rev. C**84**, 051308 (2011)
[8] Esbensen et al, Phys. Rev. C76, 024302 (2007)
[9] Shulgina et al, Nucl. Phys. A825, 175 (2009)
[10] Hagino and Sagawa, Phys. Rev. C 72, 044321 (2005)
[11] Fortune, Phys. Rev. C**87**, 067306 (2013)
[12] Fortune and Sherr, Phys. Rev. C**88**, 034326 (2013)
[13]Auerbach, Phys. Rep. 98, 273 (1983)
[14] Grigorenko et al., Phys. Rev. C**80**, 034602 (2009)
[15] Miernik et al, Phys. Rev. Lett, 99, 192501 (2007)
[16] Egorova, Phys. Rev. Lett, 202502 (2012)
[17] Grigorenko et al, Phys. Rev. Lett, 88, 042502 (2002)
[18] Charity, Phys. Rev. C**84**, 014320(2011)
[19] Barker, Phys. Rev C **66**, 047603(2002)
[20] Jager et al., Phys. Rev. C **86**, 011304 (2012)
[21] Wallace et al., Nucl. Instrum. Methods A**583**, 302 (2007)
[22]Tostevin et al., Phys. Rev. C**70**, 064602 (2004)
[23] Yoneda et al., Phys. Rev. C**74**, 021303 (2006)
[24] Gade et al., Phys. Rev. Lett. **93** 042501 (2004)

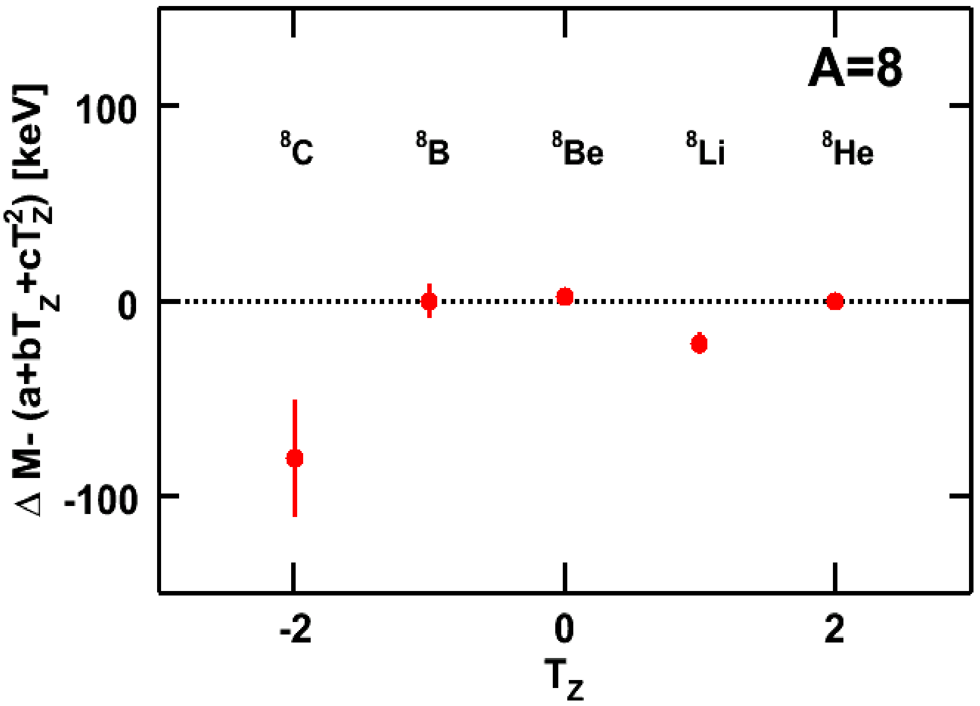

Figure 1 deviations of the experimental masses of the *A*=8 quintet from the fitted quadratic isobaric multiplet mass equation [7].

the preferred s^2 fraction for ^{11}Li [12].

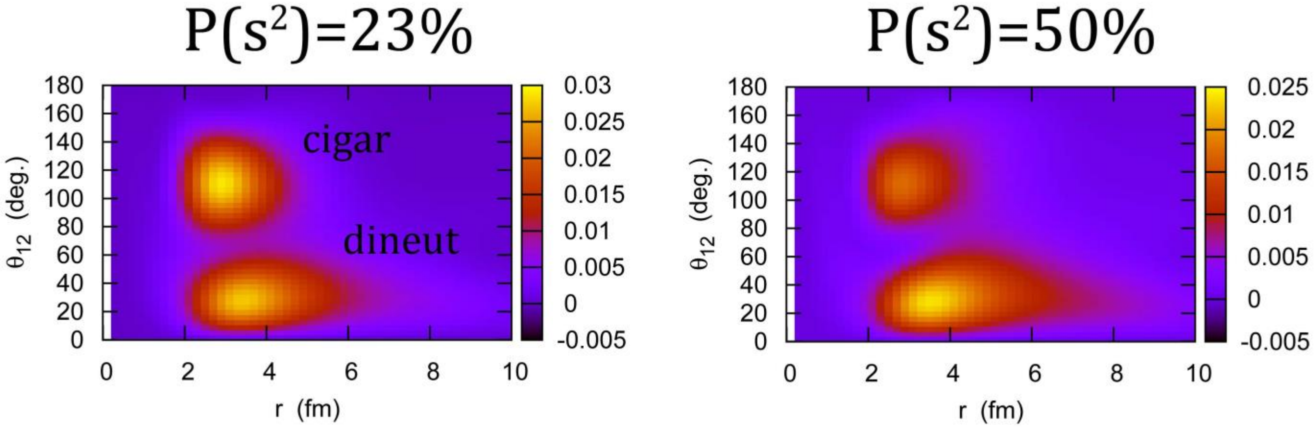

Figure 2 Two-neutron density for the halo of ^{11}Li for r_1=r_2=r (Core-neutron distance) and the angle between the neutrons. Results are shown for calculations with P(s^2)=23% and 50%. From the calculations of Ref. [8]

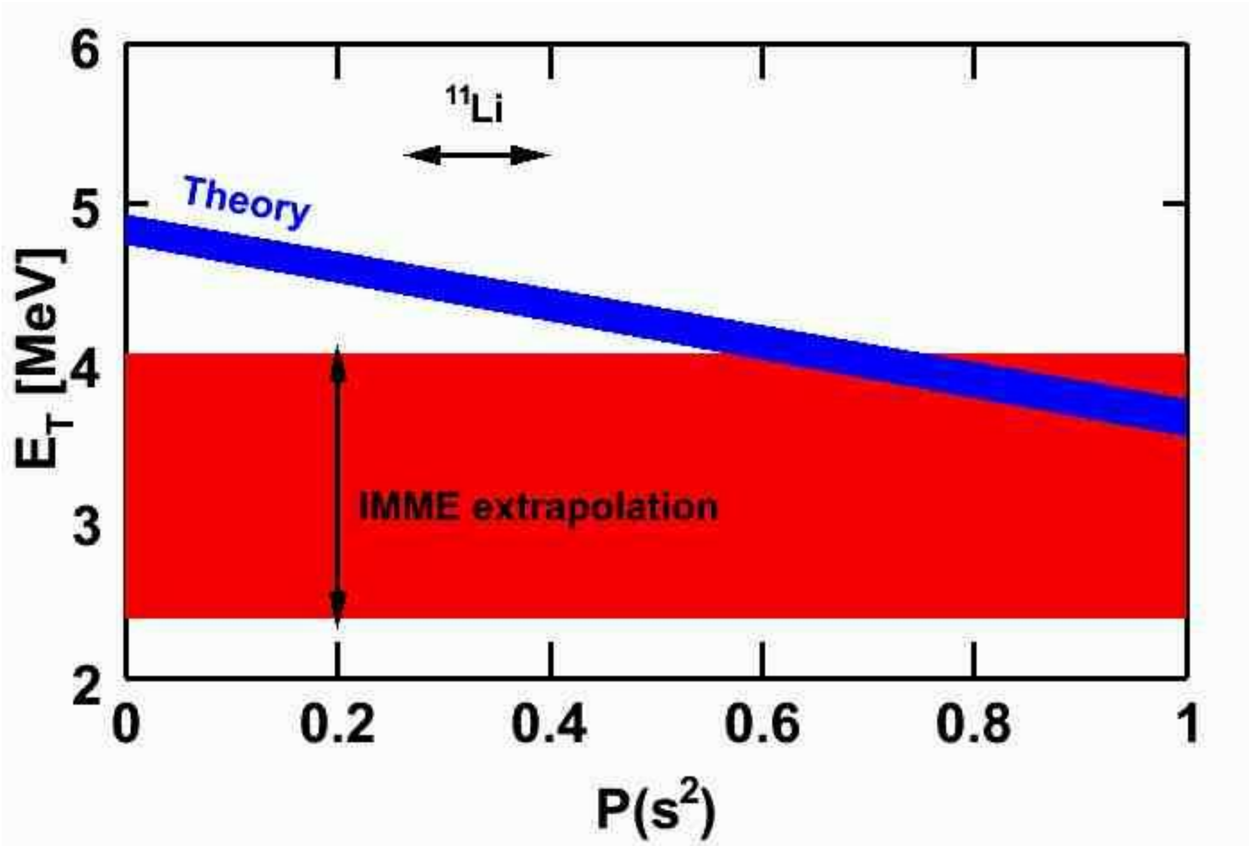

Figure 3 Predicted ^{11}O decay energy by Fortune and Sherr as a function of the relative s^2 component. The value of the IMME extrapolation is shown in addition to the s^2 fraction for ^{11}Li from Ref. [12]

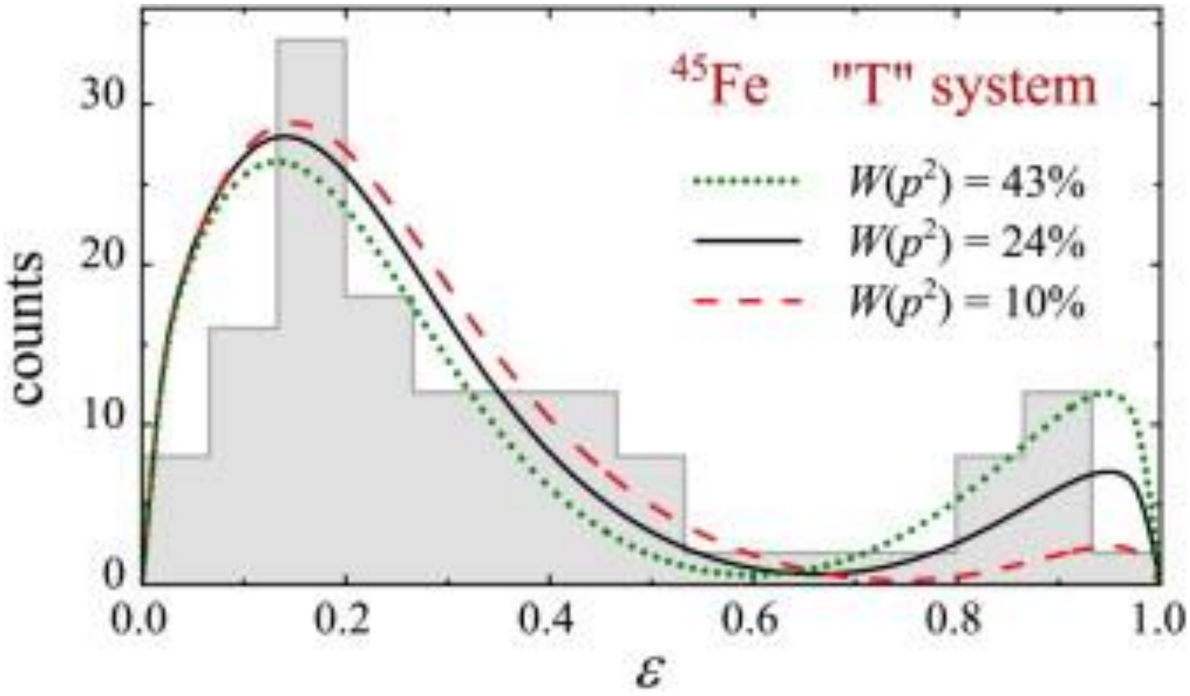

Figure 4 Experimental and theoretical distributions of the fraction of the decay energy in p-p relative motion for the two-proton decay of

^{45}Fe[14]

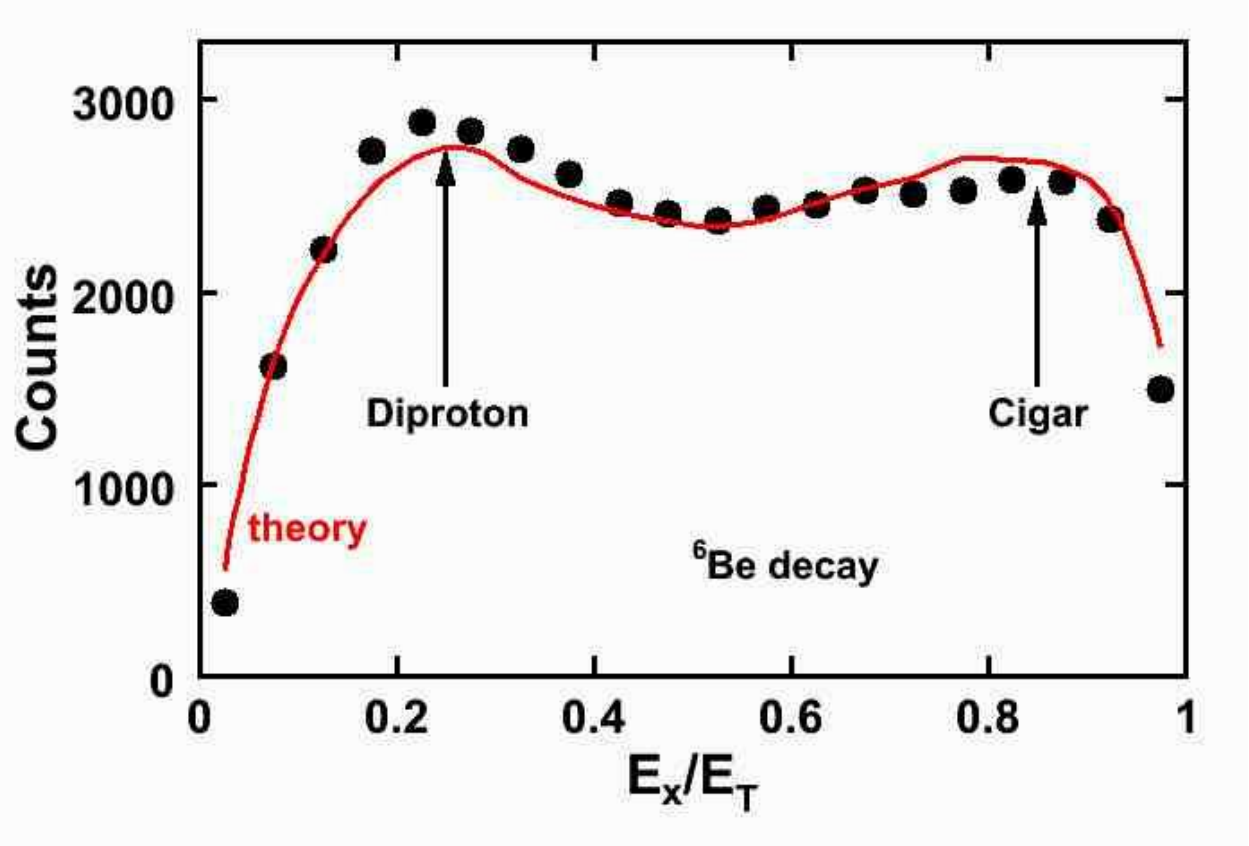

Figure 5 Experimental and theoretical distribution of distributions of the fraction of the decay energy in p-p relative motion for the two-proton decay of ^{6}Be [16].

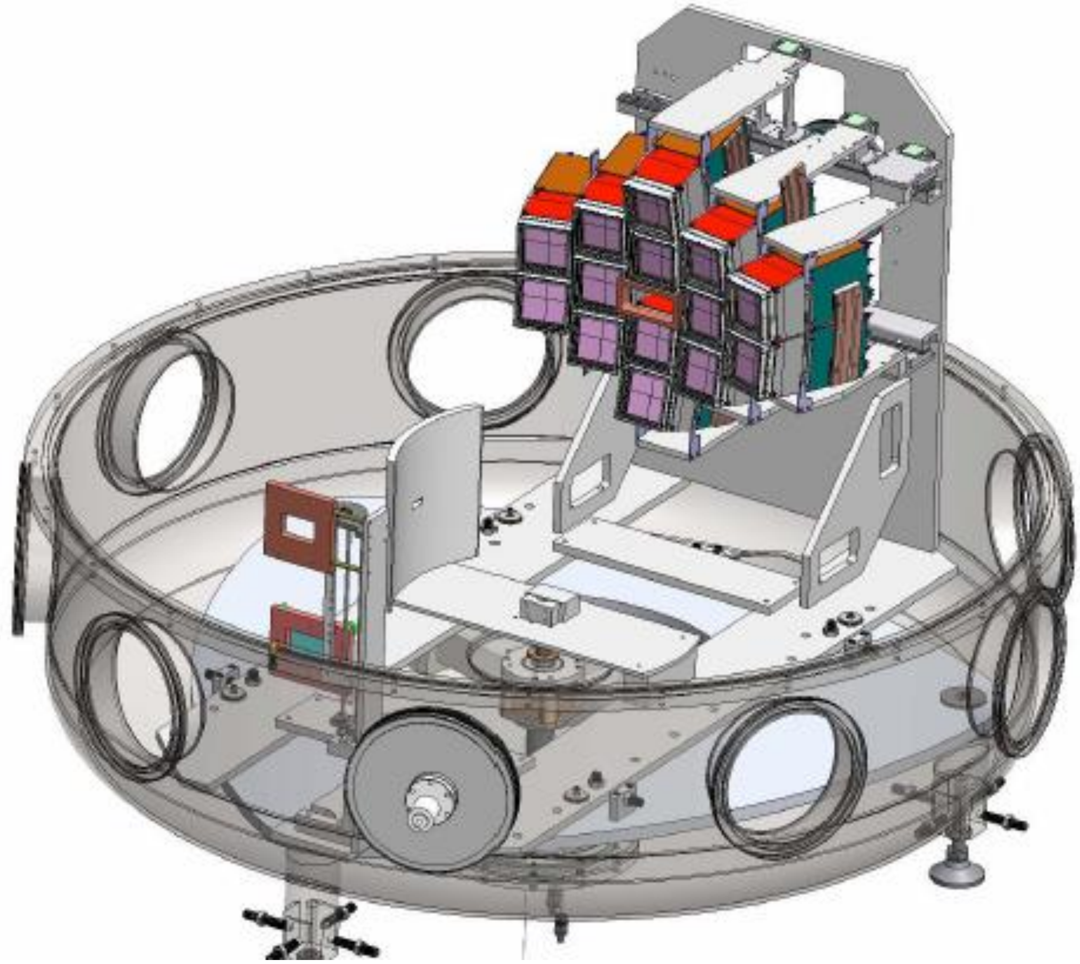

Figure 6 Experimental configuration used in experiment 08001 and for the proposed experiment showing the HiRA array and the Be target.

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.

E02019
Charity et al, Phys. Rev. C 86, 041307 (2012) Rapid communication
Charity et al., Phys. Rev. C 78, 054307 (2008)
Charity et al., Phys. Rev. C 76, 064314 (2007)

E07009
Shane et al., Phys. Rev. 85, 064612 (2012), Phd thesis of R. Shane

E08001
Egorova et al, Phy. Rev. Lett 109, 202502 (2012), Phd Thesis of I. Egorova
Charity et al., Phys. Rev. C 84, 014320 (2011)
Charity et al, Phys. Rev. C 84, 051308 (2011) Rapid Communications
Charity et al, Phys. Rev. C 82, 041304 (2010) Rapid Communications

E10001, E11001
Under analysis. Phd Thesis of K. Brown

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.

This experiment will be the major part of Cole Pruitt thesis. Cole is a first year graduate student at Washington University.