NUCLEAR STRUCTURE PHYSICS WITH MoNA-LISA

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Abstract

Interesting nuclear structure physics exists near the neutron dripline; extremely neutron-rich nuclei can even have different magic numbers than their more stable peers. Studies of these exotic nuclei at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University demand knowledge of the complete reaction kinematics and require high detector efficiency as well as the capability for multiple neutron detection and discrimination. The Modular Neutron Array (MoNA) [1] has been successful at meeting these demands and has led to furthering our understanding of the nuclear structure for a number of exotic nuclei such as ^{12}Li [2], ^{15}Be, ^{28}F, and ^{18}B [3]. The first decay energy spectrum for neutron unbound states in ^{24}O was observed by this array, and data suggest ^{24}O is a doubly magic nucleus [4]. This year MoNA will be used with LISA (Large multi-Institutional Scintillator Array) for a higher-resolution measurement of the first two excited states of ^{24}O with possible confirmation of a newly found excited state at 7.5 MeV. A MoNA-LISA study of ^{20}C in an effort to better understand how the *sd* shell evolves with neutron number is also in preparation.

Introduction

One only has to look at the experimental facilities being upgraded to see that studies of exotic nuclei at the neutron dripline play a key role in the international nuclear physics program. While the European Union continues to support CERN's ISOLDE (on-Line Isotope Mass Separator), Canada is upgrading the Isotope Separator and Accelerator (ISAC) to ISAC-II. In addition, France is upgrading the Systme de Production d'Ions Radioactifs en Ligne en Legne (SPIRAL) to SPRIRAL2 and Germany is upgrading their Heavy Ion Synchrotoron (SIS) to the Facility for Antiproton and Ion Research (FAIR) [5]. Japan

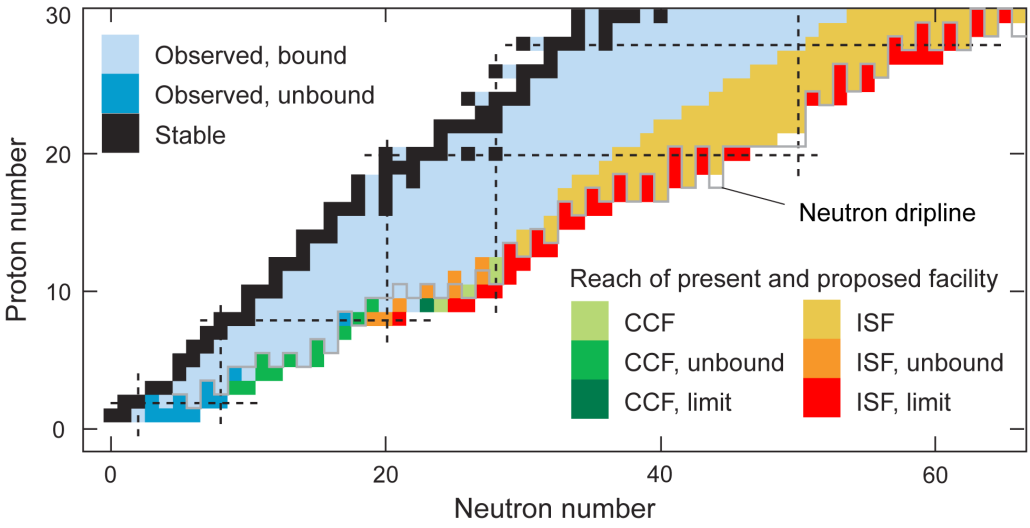

Figure 1: Expected reach of the FRIB and the present NSCL CCF (Coupled Cyclotron Facility) for light neutron-rich nuclei. Lightly shaded fields indicate nuclei predicted to be found and in reach of the CCF and FRIB (previously called the ISF). Darker fields show unbound nuclei where spectroscopy has been performed or can be done. The darkest fields at the dripline represent isotopes beyond the dripline which can be confirmed to be unbound with the FRIB, respectively [6].

plans to upgrade the RIKEN Accelerator Research Facility (RARF) to the Rare-Isotope Beam Factory (RIBF), and in the US the Facility for Rare Isotope Beams is currently under construction, supporting the US campaigns at both the Holifield Radioactive Ion Beam Facility and NSCL. This paper focuses on the current neutron dripline physics program supported by two detector arrays, the Modular Neutron Array (MoNA) and the Large multi-Institutional Scintillator Array (LISA), both currently in use at NSCL. MoNA-LISA has the appropriate energy resolution and efficiency for use at FRIB, and plans are underway to use the combined detector system at that facility.

Physics at the neutron dripline takes place on short time scales – the lifetimes of extremely neutron-rich nuclei beyond the dripline are on the order of 10^{-21} s. Bound nuclei close to the dripline usually lack bound excited states; γ-ray spectroscopy is therefore not feasible. Instead, these short-lived nuclei are studied indirectly by inferring structure based on their detected decay products (the neutrons and the charged-particle fragments are measured in coincidence). Both a highly efficient, position sensitive neutron detector array like the MoNA-LISA detector system, as well as a set of charged particle detectors, are necessary. For the experiments performed at the NSCL, the charged particles are "swept" out of the neutrons' flightpath by a large bending magnet, the "Sweeper."

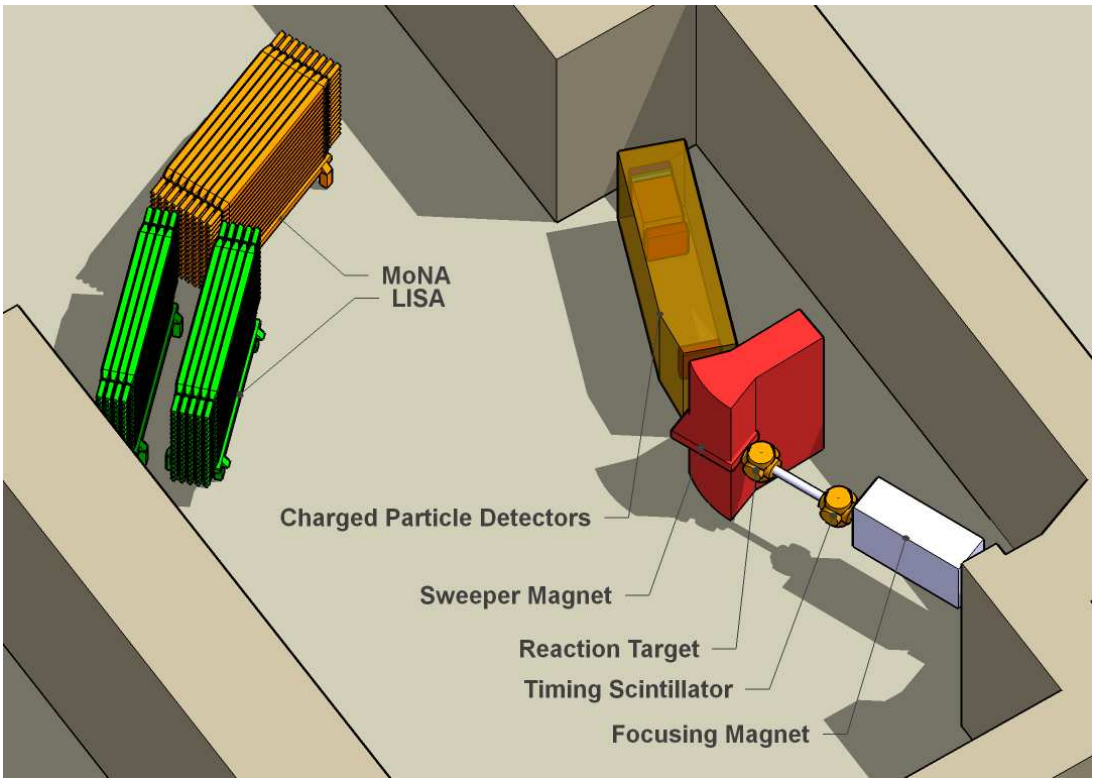

Figure 2: Typical layout of the MoNA-LISA in at the NSCL. The beam enters the vault from the bottom right.

Nuclear structure measurements with MoNA-LISA and the Sweeper

To create neutron-unbound states of oxygen, for example, as was previously done by the MoNA Collaboration [7], a beam of ^{26}F from the NSCL A1900 spectrometer was incident on a ^{9}Be target to create neutron-unbound excited states of ^{24}O as well as the ground state of ^{25}O. All charged fragments (including non-reacted beam) were deflected with a rigidity up to 4 Tm through the Sweeper [8, 9, 10, 11]. Neutrons are not deflected and a gap in the Sweeper magnet allows transmission of these neutrons; MoNA or LISA can therefore be at zero degrees relative to the ^{26}F beam. MoNA and now also LISA record both the neutron's position and time signature (with multiple-hit capability). The neutron energy is determined based on its time-of-flight (TOF) and the neutron position along each scintillator bar found from the time difference between photomultiplier signals at either end of each scintillator. The TOF spectra and the position of the neutron yield the neutron's momentum vector [1]. LISA was built and benchmarked in 2010 and installed in the N2 vault of the NSCL in the spring of 2011. Like MoNA, LISA consists of 144 plastic scintillators, each 2 m x 10 cm x 10 cm. A typical configuration of MoNA, LISA and the Sweeper with necessary charged particle detectors is shown in Figure 2.

All isotopes are identified by a set of charged-particle detectors that determine each frag-

ment's energy loss, position, time of flight, and total kinetic energy. Position information comes from cathode-readout drift chambers. The energy deposited for a particular fragment in an ion chamber and also in a thin plastic scintillator in conjunction with a measurement of the remaining kinetic energy with a thick plastic scintillator yields the proton number for each fragment since energy loss per unit thickness is proportional to the proton number Z. See the work by Frank et al. for more details about the charged particle detection system [12].

For isotope identification, however, we need not only Z but also A. Typically the resolution on the energy-loss information is not high enough to resolve specific isotopes. The MoNA collaboration uses TOF information that must be carefully analyzed in order to resolve isotopes. The t_{zero} for such a technique comes from a timing detector located immediately upstream from the reaction target (in this example of creating neutron-unbound states of oxygen, the reaction target is ^{9}Be). Raw TOF data is insufficient since the charged fragments are sensitive to the non-uniformities of the Sweeper magnet's field. Fragment energy and emission angle at the reaction target are determined using COSY INFINITY [13], based on an inverse transformation of the fragment's trajectory at the charged particle detectors using the measured Sweeper magnetic field map.

Once isotopes are correctly identified, then the decay energy for a particular isotope can be found via the invariant mass method, where the relativistic four-momentum vectors of the fragment and the neutron are determined from detector information and calculated at the point of the neutron-fragment state's breakup:

$$E_{decay} = \sqrt{m_{frag}^2 + m_n^2 + 2(E_{frag} \cdot E_n - p_{frag} \cdot p_n \cdot \cos(\theta))} - m_{frag} - m_n, \qquad (1)$$

where E_{decay} is the decay energy of the state, θ is the angle between the neutron and the fragment in the laboratory frame, E_{frag} is the fragment's total energy, m_{frag} is the fragment's rest mass, m_n is the neutron's rest mass, E_n is the neutron's total energy, p_{frag} is the fragment's momentum, and p_n is the neutron's momentum.

The structure of ^{24}O

An exotic nucleus of special interest, due to the strong possibility that it may be doubly magic, is ^{24}O [4]. In June of 2011 a commissioning experiment for LISA will remeasure the neutron-unbound excited states of ^{24}O. In the work by Hoffman et al. [7], the first two excited states of ^{24}O were measured at 4.7 and 5.3 MeV but with limited energy resolution. The June experiment will use a thinner ^{9}Be target to increase the energy resolution of the previous measurement and higher beam current for better statistics. See Figures 3 and 4.

Previous experiment shows that ^{24}O has an excited state at 7.5 MeV, beyond the S_{2n} level of 6.8 MeV [14, 15]. Analysis by Hoffman et al. [16] suggests a cascade through a resonance at 0.6 MeV with neutron decay to the unbound first excited state of ^{23}O and

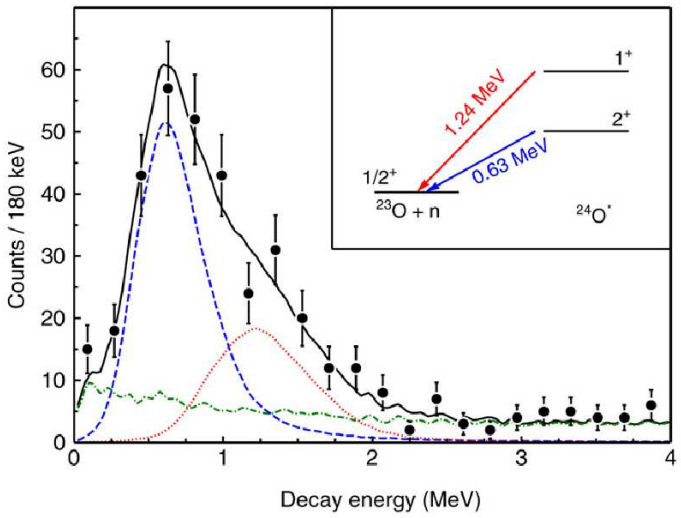

Figure 3: Decay energy spectrum for two excited states in ^{24}O [4]. Note that the states are not well resolved due to the thickness of the ^{9}Be target.

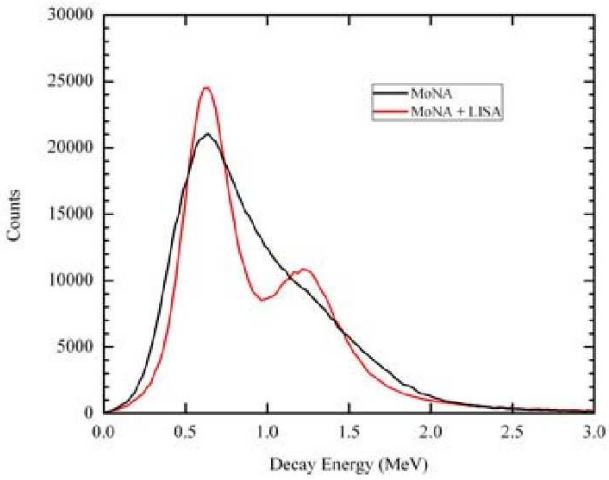

Figure 4: Simulated decay energy spectra for ^{24}O excited states. The single peak reproduces previous experimental data [4]. The two-peaked spectrum simulates a thinner ^{9}Be target (by a factor of two) but with increased beam current and the addition of LISA to MoNA.

then a 0.045 MeV resonance with neturon decay to the ground state of ^{22}O. An analysis technique called two-neutron coincidence spectroscopy is noteworthy, demonstrating where spectroscopy techniques can be used for highly excited unbound states.

The June commissioning experiment will also study the unbound excited state of ^{23}O, previously measured to be 4.0 MeV. This nucleus is of special interest to shell model theorists. Data suggest it has two sizable subshell gaps at N=14 and N=16 [17]. The shell model predicts this state to be a $\nu d_{3/2}$ single particle state [18]. A previous experiment used a (d, p) reaction to create the unbound excited state of ^{23}O. The June 2011 commissioning experiment will populate the unbound excited state of ^{23}O using the ^{26}F on a ^{9}Be reaction target through proton knockout followed by two-neutron decay.

Previous data suggests that ^{24}O has more to tell; excited states higher than the 7.5 MeV state may well exist. These possible states would likely decay through the 4.0 MeV neutron-unbound excited state of ^{23}O to the ^{22}O ground state. With both LISA and MoNA used together for the June 2011 experiment, the greater effective solid angle allows a better search for these higher energy excited states in ^{24}O.

The structure of ^{20}C

^{20}C is one of a number of heavy carbon isotopes of special interest to nuclear structure physics. Halo nuclei, deemed "one of the most spectacular phenomena that nuclear structure physicists have observed," include ^{22}C as the heaviest example to date [19]. And yet, it seems that ^{20}C is not a halo nucleus based on data and theory [20]. How the core nucleus couples to valence neutrons, in the nomenclature of halo nuclei, can be used to further our understanding of shell structure far from stability.

The N=14 magic number was first identified from a study of ^{22}O [21], and it raises questions about how the *sd* shell evolves with neutron (and proton) number. The MoNA Collaboration is preparing a study of ^{20}C in an effort to better understand how the *sd* shell evolves with neutron number. The proposed experiment will take place at the NSCL and use both MoNA and LISA as well as the Sweeper and charged particle detectors. ^{20}C will be created via (d, p) on ^{19}C using a deuterium target.

This campaign has two experimental differences from the oxygen campaign. Previous experiments to study oxygen, for example, have either used a ^{26}Ne beam on a ^{9}Be target (to produce neutron-unbound excited states in ^{24}O and ^{23}O) or a ^{26}F beam on a ^{9}Be target to produce neutron-unbound excited states of ^{24}O as well as the ground state of ^{25}O. The charged fragments of interest in the oxygen measurements can be differentiated from unreacted beam. However, in the ^{20}C measurement the unreacted beam of ^{19}C beam must be distinguished from the ^{19}C fragments. A new hodoscope, currently under development by Nathan Frank of Augustana College, will improve the kinetic energy resolution to the level where the beam can be distinguished from the ^{19}C fragments.

The second experimental difference from the oxygen campaign is the possible existence of neutron-*bound* excited states in ^{19}C, and therefore, gamma-ray spectroscopy should be utilized. The MoNA Collaboration proposes to use CEASAR (CAESium iodide ARray), a set of 192 CsI(Na) scintillators for in-beam gamma-ray spectroscopy [22].

Conclusion

The era of exotic beam facilities marks an exciting time in nuclear structure physics; improvements in beam development techniques, analysis, and magnetic spectrometer technology push measurements further up the neutron dripline. Experiments at the NSCL and future FRIB using neutron detector systems like MoNA-LISA will continue to inform our knowledge of nuclear structure. Halo nuclei and studies of nuclei like ^{24}O and ^{20}C demonstrate the high sensitivity nuclear structure has with regard to neutron (and proton) number.

Acknowledgments

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