TRIUMF SUB-ATOMIC PHYSICS EEC NEW RESEARCH PROPOSAL

Detailed Statement of Proposed Research for Experiment # S1158

Title: Precision mass spectrometry of halo nuclides

Spokespersons: D. Lunney and J. Dilling for the TITAN collaboration

Abstract: State-of-the art, three-body nuclear models that describe halo nuclides require the binding energy of the halo nucleon(s) as a critical input parameter, since the halo radius depends strongly on the binding energy. We propose precision mass measurements of the two-neutron halo nuclides ^{8}He and ^{14}Be as well as the contentious two-proton halo candidate ^{17}Ne. These measurements can presently be performed with the newly-commissioned TITAN mass spectrometer setup at TRIUMF-ISAC, given 28 shifts of beam time.

(a) **Scientific value of the experiment**: Describe the importance of the experiment and its relation to previous work and to theory. All competitive measurements at other laboratories should be mentioned. Include examples of the best available theoretical calculations with which the data will be compared.

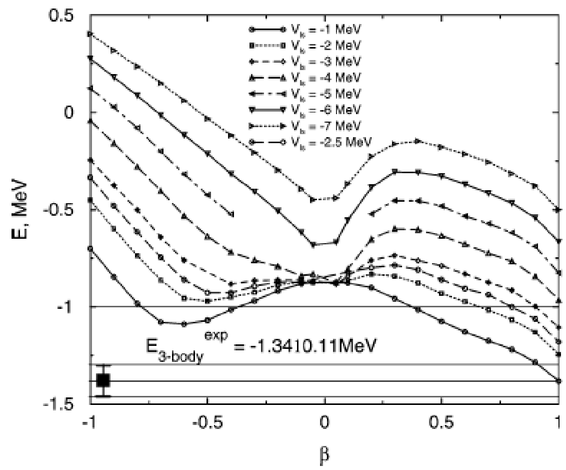
Halo nuclides rank as one of the most exotic nuclear phenomena yet discovered, as attested by the recent review articles of Jonson [JON04] and Jensen et al., [JEN04]. Halos are a dilute form of nuclear matter that dramatically illustrate the role of pairing in the quantum nuclear system. The discovery of the halo in ^{11}Li [TAN85] was all the more interesting given that two neutrons are necessary since adding only one to the ^{9}Li core results in the unbound ^{10}Li. The fact that the other subsystem (the di-neutron) was also unbound inspired M. Zhukov to describe such systems as Borromean, after the three-ring heraldic symbol used by that family in which removal of any ring causes the others to separate. Distinct from Borromean systems are: the Tango type [ROB99], having two unbound subsystems (suggested for the description of negatively-charged molecules) and the Samba type, with only one bound subsystem (e.g., ^{20}C), proposed by Yamashita, Tomio and Frederico [YAM04].♣ These descriptions are made in light of an attempted halo classification scheme using scaling laws based on the binding energies and virtual state energies.

The advent of radioactive beams has opened new experimental approaches for the elucidation of halo structure involving different types of reactions, such as electromagnetic dissociation (EMD). Accompanying such experiments are rigorous theoretical approaches based on *ab initio* two- and three-body formulations in an attempt to describe the properties of halo nuclides in a single, unified approach. Robust nuclear models are also required to disentangle the very effects of reactions themselves, to which halo nuclides are particularly sensitive (see, for example [ALK96]). Complementing reactions are precision measurements of global properties of halo nuclides such as the

♣ These apparently flippant terms do have coherent descriptions: the double unbound (Tango) systems are highly correlated and therefore move in step whereas the single unbound (Samba) system has more freedom to “shake”.

spin, charge radius, and the binding energy. These quantities serve as the building blocks for the elaboration of the theoretical description.

In addition to the archetypal halo nuclide ^{11}Li, another Borromean system of great importance is ^{14}Be. Considerable ambiguity persists concerning the ground-state structure of ^{14}Be, due to the large uncertainty of the binding energy. An EMD experiment on ^{14}Be was performed by Labiche *et al*. [LAB01] and studied by Forssén *et al*. [FOR02, FOR03], using an analytical cluster model with hyperspherical wave function expansions and a three-body mean-field potential. This model works well for the description of ^{6}He and ^{11}Li but fails to describe consistently the EMD observable, the radius and the binding energy of ^{14}Be. To help resolve this discrepancy, a precision mass measurement of this nuclide is necessary. Detailed theoretical analysis of ^{14}Be also requires knowledge of the unbound ^{13}Be and even, ^{12}Be, as explained in [TAR04] where the role of core excitation was explored. Shown (at right) is the calculated two-neutron separation energy versus deformation (from Fig. 6 in [TAR04]). This plot illustrates the role that experimental data play in constraining model parameters. As they were not able to reproduce the experimental data, the authors claimed that since "…the two measurements of the separation energy of ^{14}Be are quite different" (see next section) "our objective was to obtain a separation energy for ^{14}Be of at least 1 MeV." An earlier paper on ^{12}Be and ^{14}Be by the same group [THO96] concluded with: "An accurate measurement of the ^{14}Be binding energy would also be useful." Other theoretical work where the role of pairing and core-polarization in ^{12}Be has been addressed [GOR04] also requires reduced uncertainty on the one- and two-neutron separation energies.



In addition to halo physics, the very interesting question of shell quenching is of great importance for nuclear models. The first evidence for the disappearance of a magic number came at $N = 20$ from mass measurements of sodium isotopes [THI75]. A recent result on the first 2^+ state energy of ^{14}Be [SUG07] adds to growing experimental evidence that the $N = 8$ shell closure is also "opened" at the drip line. A precision mass measurement of the two-neutron separation energy for ^{14}Be would add important information for testing models, for example those exploring a tensor component of the spin-orbit interaction.

Efforts towards the measurement of the charge radius of halo nuclides are also continuing. It is important to distinguish the effects of the nuclear charge radius, including deformation effects, from the net matter radius. This was recently established for the case of ^{11}Li by a laser spectroscopy experiment performed at ISAC [SAN06]. Important complementary information can also be brought from nuclear moments, also determined via laser spectroscopy (see [NEU00] and the proposal of M. Pearson *et al*., for ^{11}Li). The nuclear charge radius is influenced by the two components of the measured isotope shift of the hyperfine structure: the field shift and the mass shift. For light nuclides, the mass shift dominates so much that the overall uncertainty is limited by the knowledge of the nuclear binding energy (see discussion in [SAN06] for ^{11}Li).

A new technique of laser spectroscopy using atom traps, developed to measure the charge radius of ^{6}He [WAN04] has now been performed on ^{8}He [MUE07]. The same problem of the enormous mass shift is present here, where the uncertainty of the ^{8}He charge radius will be limited by the uncertainty of the binding energy.

In the case of ^{11}Be, developmental efforts for a laser spectroscopy study are converging with a measurement planned for 2008 at ISOLDE [ZAK06]. Note that this is the same group who performed the laser spectroscopy study on ^{11}Li at TRIUMF [SAN06].

The case of a (two-)proton halo is more difficult to illustrate, due to the restraining effect of the Coulomb barrier. While there is evidence for the two-proton halo in ^{17}Ne from (high-energy) longitudinal momentum distribution measurements of the two-proton removal [KAN05], recent (high-energy) experimental attempts of proton-removal cross sections [WAR06] were unable to confirm it. A (low-energy) measurement of the magnetic moment of ^{17}Ne by laser-assisted β-NMR [GEI05] found "…no clear indication of an anomalous nuclear structure…". There is hope that (low-energy) laser spectroscopy [GEI00] will be able to clarify the question. In order to deduce the charge radius however, the dominating mass shift must, again, be measured as accurately as possible.

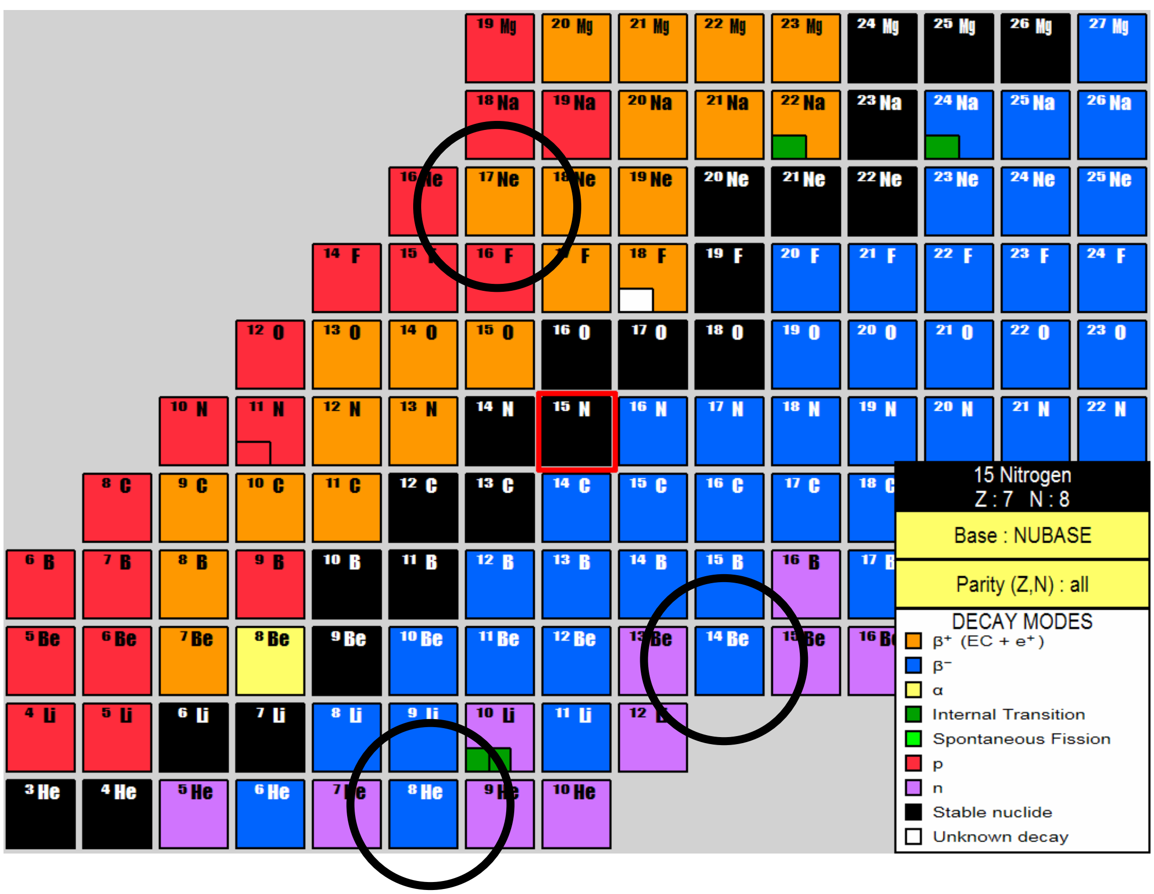
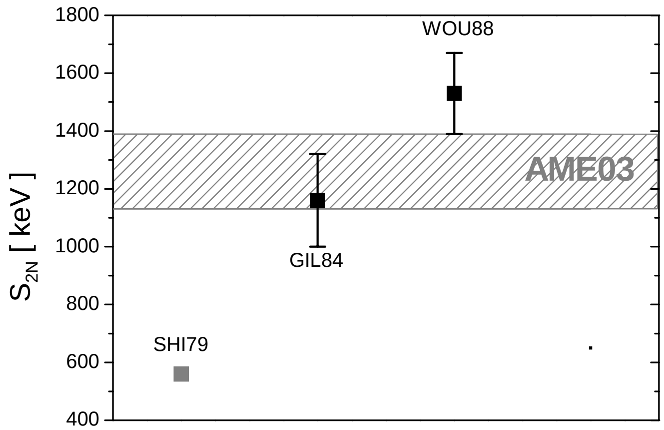


Chart of nuclides showing the light nuclides with color code for type of decay. The halo nuclides that are the subject of this proposal are circled.

The mass of ^{14}Be (and its two-neutron separation energy S_{2n}) is known with an uncertainty of 130 keV. Measurements and an extrapolation of the S_{2n} are shown left. Based on mass measurements of neighboring isotopes [THI74] the S_{2n} value of ^{14}Be was estimated to be 560 keV [SHI79]. R. Gilman *et al.*, deduced the value S_{2N} = 1160(160) keV from a Q-value measurement for the ^{14}Be production via pion double charge exchange $^{14}C(\pi^-,\pi^+)^{14}Be$ [GIL84]. The surprising result that ^{14}Be was 600 keV more bound than expected from systematics, was confirmed by J.M. Wouters and coworkers in 1988 [WOU88]. By using the Time-of-Flight Isochronous mass spectrometer (TOFI) at Los Alamos, the first direct mass measurement of ^{14}Be was accomplished and yielded S_{2n} = 1530(140) keV. Taking these measurements into account, the last atomic mass evaluation results in S_{2n} = 1260 (130) keV for ^{14}Be [AUD03].



In the AME2003, the mass excess of ^{8}He is determined predominantly by two $^{64}Ni(^{4}He,^{8}He)^{60}Ni$ reaction Q-value measurements yielding 31.613(16) keV [KOU75] and 31.693(8) keV [TRI77]. While these values are in good agreement, a TITAN mass measurement could reduce the uncertainty by up to a factor of fifty. It is also important to note that ^{8}He is involved in more than 20 different reactions in the mass table [AUD03] so that an improvement in the ^{8}He will improve all of those linked masses.

The mass excess of ^{17}Ne is determined by two $^{20}Ne(^{3}He,^{6}He)^{17}Ne$ reaction Q-value measurements yielding 16.479(50) keV [MEL70] and 16.453(32) keV [GUI98]. Again, while these values are in good agreement, a TITAN mass measurement could reduce the uncertainty by a factor of fifty.

The following table lists the relevant characteristics of the nuclides discussed in this proposal.

Nuclide	**Half life**	**uncertainty**	**Production rate (s^{-1})**	**No. shifts**
^{6}He	807 ms	1.3E-07	3E3; SiC-FEBIAD	1.5
^{8}He	119 ms	8.8E-07	5E4; SiC-FEBIAD	5
^{7}Li (reference)	stable	6.3E-10	(TITAN ion source)	0.5
^{10}Be	stable	4.0E-08	1E8; Ta-TRILIS	0.5
^{11}Be	13.8 s	6.4E-07	2E6; Ta-TRILIS	1.5
^{12}Be	24 ms	1.3E-06	3E3; Ta-TRILIS	5
^{14}Be	4 ms	1.0E-05	? ; Ta-TRILIS *	8
^{14}N (reference)	stable	4.3E-11	TITAN ion source	0.5
^{17}Ne	109 ms	1.7E-06**	1E5; SiC-FEBIAD	4
^{19}Ne	17 s	1.6E-08	7E7; SiC-FEBIAD	1
^{20}Ne (reference)	stable	1.0E-10	lots; SiC-FEBIAD	0.5

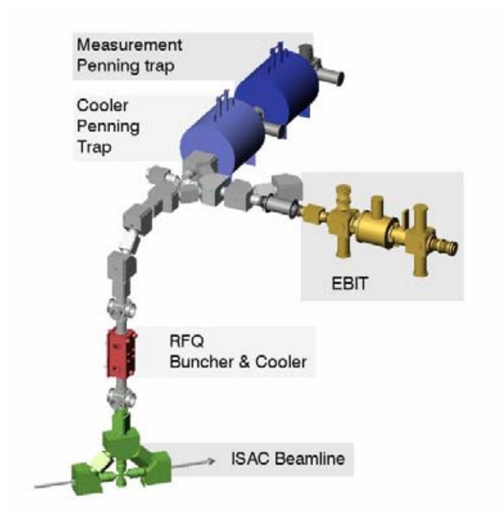
* a yield measurement is planned for December 2007

** a preliminary (unpublished) result from ISOLTRAP has an uncertainty of 4E-8

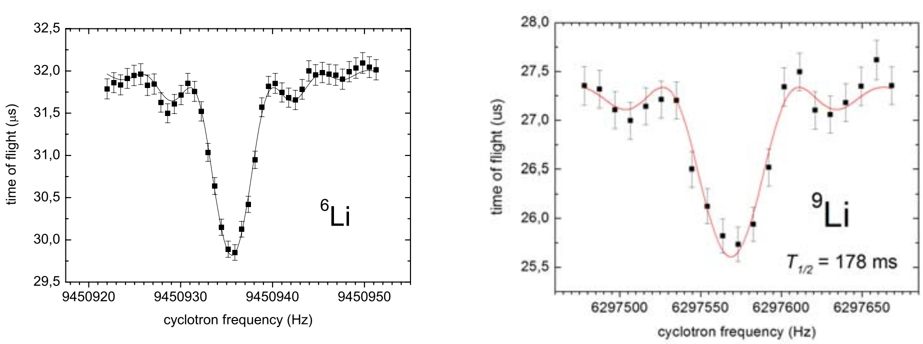
As seen in the above Table, there is not yet a yield measurement for ^{14}Be. While this is expected during a December 2007 run [M. Domsky, J. Lassen, priv. comm.], the physics case is compelling enough to warrant an attempt at the mass measurement. There are 15 shifts of beam time approved at ISOLDE for measurement of the ^{14}Be with the MISTRAL spectrometer. In a test measurement, the mass of ^{12}Be was measured (to a relative uncertainty of 10^{-6}). There are also approved shifts for ISOLTRAP to measure the mass of ^{8}He at ISOLDE in 2008. Note that the He and Ne nuclides are produced with the same target-ion-source and thus, can be measured during the same run.

(b) **Description of the experiment**: Techniques to be used, scale drawing of the apparatus, measurements to be made, data rates and background expected, sources of systematic error, results and precision anticipated. Compare this precision with that obtained in previous work and discuss its significance in regard to constraining theory. Give a precise list of targets to be used in order of their priority.

These measurements would be performed with the TITAN setup (left), requiring only the RFQ buncher and the measurement Penning trap [DIL06]. The laser ion source (TRILIS) is required for the Be isotopes. Particular to mass measurements is the need for a reference isotope. The relevant references are indicated in Table 1.



To make a mass measurement, an ion is injected into the homogeneous field of the TITAN Measurement Penning Trap (MPET) where its cyclotron frequency $f_c = qB/2\pi m$ is probed and determined using a time-of-flight detection of the ejected ions. The cyclotron frequency is compared to that of a well-known reference mass (generally, a stable species of similar mass) to provide a measurement. TITAN was commissioned in August, 2007 at which point the masses of the short-lived radioactive nuclides ^{8}Li and ^{9}Li were measured. Time-of-flight resonances of the reference mass ^{6}Li and ^{9}Li (having a half life of only 178 ms) are shown below.



Time-of-flight resonances recorded by the TITAN Penning trap for (left) stable ^{6}Li and (right) ^{9}Li, produced from an ISAC Ta target in August 2007. The excitation times were 400 ms (left) and 20 ms (right). The lines are a fit of the data to the theoretically-predicted distribution [Koen1995]. Note that the sidebands, due to time-gated RF excitation, play an important role in reducing the uncertainty of the center frequency.

From the measured yield of ^{9}Li during the August run and from subsequent off-line tests, the efficiency of TITAN is 0.1%, which is sufficient to measure all the nuclides in this proposal (given a ^{14}Be yield of 100/s). Preliminary analysis of the $^{6\text{-}9}$Li mass measurements indicate that the relative uncertainty is better than 5×10^{-8}.

(c) **Experimental equipment**: Describe the purpose of all major equipment to be used. Details of all equipment and services to be supplied by TRIUMF must be provided separately on the Technical Review Form available from the Science Division Office.

Aside from the TITAN setup itself, the only TRIUMF equipment necessary could be the yield station in order to map out the magnetic profile of some of the isobaric contamination. For example at $A = 8$, in addition to ^{8}He, there would be ^{8}Li and probably stable contamination ($^{16}O^{2+}$ and perhaps others). The mass difference of these isobars requires the ISAC separator to run with a resolving power of only 800. The case of $A = 17$ is more complicated although ^{17}Ne is sufficiently far in mass that the contaminations should be blocked by the slits of the separator. The case of ^{12,14}Be poses no problem due to the selective laser ionization used and the absence of any surface-ionized lithium isobars.

(d) **Readiness**: Provide a schedule for assembly, construction and testing of equipment. Include equipment to be provided by TRIUMF.

The TITAN setup is currently in running mode. The measurements of the He and Ne nuclides can be covered during the same run. The Be measurements would require changing the TITAN ion source from the surface ionizer to a discharge – a two-day job. **Since the proposed measurements can be made as of today, we request stage-two approval at this time.**

(e) **Beam time required**: State in terms of number of 12-hour shifts. Show details of the beam time estimates, indicate whether prime-user or parasitic time is involved, and distinguish time required for test and adjustment of apparatus.

We request a total of 32 shifts, as shown in Table 1. The shifts would be divided over two runs as follows:

He/Ne run (SiC target-FEBIAD source):	
^{7}Li pilot beam	**0.5**
^{6}He beam	**1.5**
^{8}He beam	**5.0**
^{20}Ne pilot beam	**0.5**
^{19}Ne beam	**1.0**
^{20}Ne beam	**4.0**
Total	**12.5 shifts**

Be run (Ta target-TRILIS source):	
^{10}Be ref beam	**0.5**
^{11}Be beam	**1.5**
^{12}Be beam	**5.0**
^{14}Be beam	**8.0**
^{14}N pilot beam	**0.5**
Total	**15.5 shifts**

with reference scans performed every 4-8 hours for both runs

(f) **Data analysis**: Give details and state what data processing facilities are to be provided by TRIUMF.

All the necessary software tools are now operational for analyzing TITAN data.

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