EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and N-ToF Experiments Committee (INTC)

HIGH ACCURACY MASS MEASUREMENT OF THE VERY SHORT-LIVED HALO NUCLIDE [11]Li

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Abstract. The archetypal halo nuclide [11]Li has now attracted a wealth of experimental and theoretical attention. The most outstanding property of this nuclide, its extended radius that makes it as big as [48]Ca, is highly dependent on the binding energy of the two neutrons forming the halo. New generation experiments using radioactive beams with elastic proton scattering, knock-out and transfer reactions, together with *ab initio* calculations require the tightening of the constraint on the binding energy. Good metrology also requires confirmation of the sole existing precision result to guard against a possible systematic deviation (or mistake). We propose a high accuracy mass determination of [11]Li, a particularly challenging task due to its very short half-life of 8.6 ms, but one perfectly suiting the MISTRAL spectrometer, now commissioned at ISOLDE. We request 15 shifts of beam time.

1. Introduction and Motivation

The halo phenomenon in exotic nuclei continues to be a subject of intense interest. The term: halo, somewhat displaced in sober science, comes from the quantum mechanical tunneling effect of very weakly bound neutrons straying far beyond the immediate confines of the core. Thus, the very light ^{11}Li takes on the proportions of the much heavier ^{48}Ca.

Since this first halo manifestation of ^{11}Li [TAN85], experimental visions of other halos have since occurred and attracted intense attention of nuclear theory as well as a rash of experiments for which the reader is referred to reviews [HAN95, TAN96, RII00].

While the ^{11}Li nucleus is itself particle stable, each of its three, two-body components are unstable, placing it into a class of systems now called "Borromean" since it resembles the three interlocking rings in the heraldic symbol of an Italian noble family of similar name (see [VAA00] for a somewhat philosophical treatment of the subject and description of this term, coined by M.V. Zhukov). An established, universal dictum concerning such systems is that the extent of the halo is very sensitive to the two-neutron separation energy S_{2n}, which itself, is much smaller that that of more stable nuclides. In the case of ^{11}Li, the S_{2n} value is only about 300 keV (compared to over 10 MeV for the stable Li isotopes). In the simple, illustrative model of Hansen and Jonson [HAN87], the radius decays with a length equal to $\hbar/(2\mu S_{2n})^{1/2}$ where μ is the reduced mass of the core and halo. We know now that this interpretation is an over-simplification but the sensitive dependence of the halo properties on the separation energy remains. In fact, all of the modern and more elaborate models (see below) require the binding energy as essential input.

The ground state properties of ^{11}Li are now fairly well known, thanks to nuclear spectroscopy studies performed at ISOLDE (IS-320) [Bor97] and elsewhere [AOI97, MOR97] as well as ISOLDE laser spectroscopy results [ARN92]. Halos have now become the targets (so to speak) of high energy elastic proton scattering [EGE01] and knock-out reactions (see the reviews [SHE01, HAN01, OZA01]). Accompanying these new generation experiments are more rigorous theoretical approaches based on *ab initio* two- and three-body formulations in an attempt to describe all the properties of this nuclide in a single, unified approach (discussed below). This is also due to the fact that a very robust nuclear model is required to disentangle the very effects of these high energy reactions themselves. In fact, according to [HAN01]: "it has become customary to calculate the radial wave functions in potential-well models that are adjusted to the experimental separation energy." Hence the interest in constraining this important quantity.

1A. Models

It is instructive to examine what theory might predict for this important binding energy. It is well known that the absolute differences of mass models can diverge enormously when extrapolated far from stability. However since the two-neutron separation energy is a mass *difference*, one could hope that the errors might not be so dramatic.

Models for predicting masses span a large spectrum, from rather phenomenological algebraic (or local) relations such as those of Comay, Kelson and Zidon [COM88] and Janecke and Masson [JAN88], to more or less fully microscopic techniques such as Hartree-Fock [GOR01] and the Relativistic Mean Field (RMF) [MEN97] approaches, both of which use a selected nucleon-nucleon force - though the force itself is constructed using adjusted parameters. Between these lies a hybrid type of model that consists of a gross, macroscopic (e.g. liquid drop) part that is sculpted by (parameterized) microscopic corrections (shell effects, pairing, deformation etc.). The most famous version of a macro-micro model is the Finite Range Droplet Model [MOL95] making use of some 30 parameters. As the FRDM has produced no values for Li isotopes, we have included two others here: a very old, 50-parameter version by von Groote, Hilf and Takahashi [GRO76] and a new, 18-parameter version of the Tachibana model by Koura et al. [KOU00]. The different S_{2n} predictions using these various approaches as compared to experiment are plotted in figure 1.
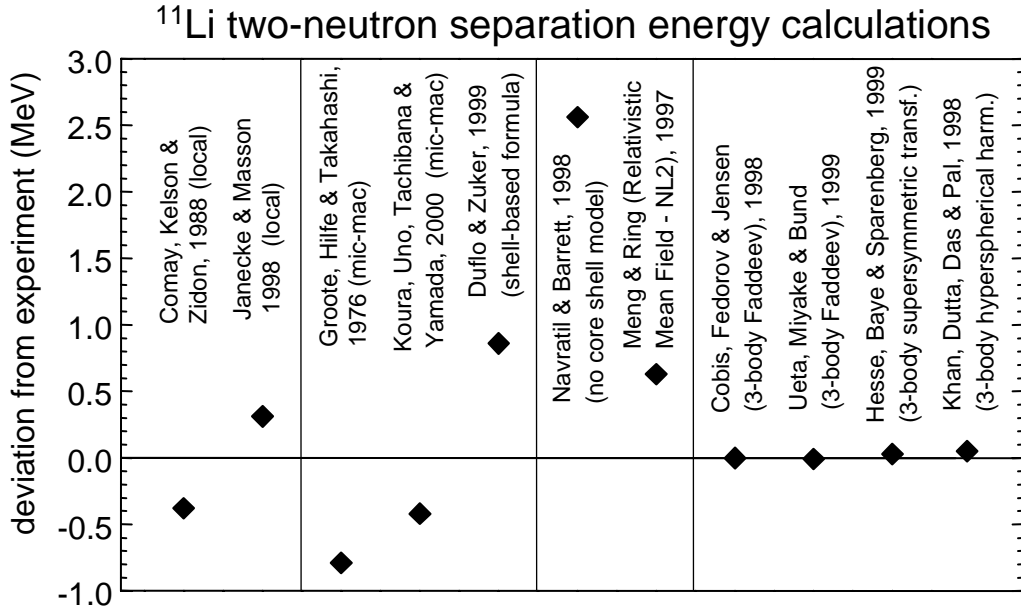
FIGURE 1. Difference in mass predictions (or calculations) of various models for the ^{11}Li two-neutron separation energy. See text for a discussion of (and reference for) the various models.

Model differences tend to favor local models when known masses are not far away. The first however, predicts ^{11}Li as being unbound - as do the two macro-micro models! Microscopic models tend to produce masses rather poorly since they have much less room to maneuver parameter-wise. The microscopic shell model approach of Duflo and Zuker [DUF99] manages an excellent overall mass fit with only seven parameters however it would seem that the two masses involved here have conspired to give a rather large deviation in the S_{2n}. The most striking deviation is the full-basis shell model result of Navrátil and Barrett [NAV98]. For light nuclides, the basis is large enough not to require resorting to a core approximation but despite their claim of "...easily obtaining a reasonable binding energy" for ^{11}Li, the resulting S_{2n} leaves a lot to be desired.

The comparisons on the right panel in figure 1 are made with modern and powerful, three-body (Falddeev) separable potential calculations [KHA98, COB98, UET99, HES99]. These have been developed especially for studying halo nuclides. While they might seem to do the best job of calculating the S_{2n} values, they are in fact used as (iterative) input for adjusting the model potentials. In particular, Hesse et al. [HES99] claim to adjust their parameterization to the experimental value and (re)produce the binding energy with an error of about 10 keV. One could naively assume that an input mass value with less than 10 keV uncertainty would help constrain this type of calculation.

1B. Measurements

The mass of ^{11}Li is, of course, already known. The question is not only to what precision it can be determined, but also with what accuracy. In mass spectrometry there is a clear distinction between these two terms. Precision refers to the reproducibility of repeated measurements whereas accuracy means the correct value. Precision is necessary but not sufficient for accuracy. One of the best ways to ensure accuracy is to determine the mass using two separate techniques having comparable precision. This uncovers any systematic error that may have been lurking undetected.

The experimental situation is shown in figure 2 for the S_{2n} value of ^{11}Li. Since the mass of ^{9}Li is known to within 2 keV, the error is completely governed by that of ^{11}Li. There are four values more or less in agreement but only one of which has an uncertainty approaching what could be termed "high precision". One of the measurements in figure 2 was determined using a mass spectrometer [THI75], one by the time-of-flight installation TOFI at Los Alamos [WOU88]. The other

two were measured by reactions: an unpublished result from the *Q*-value of the double pion exchange reaction on ^{11}B [KOB91] and a more recent ^{14}C(^{11}B,^{11}Li)^{14}O reaction *Q*-value from MSU's NSCL [YOU93] which has reported the smallest error bar of 35 keV. This state of affairs could clearly benefit from a higher precision, independent measurement.
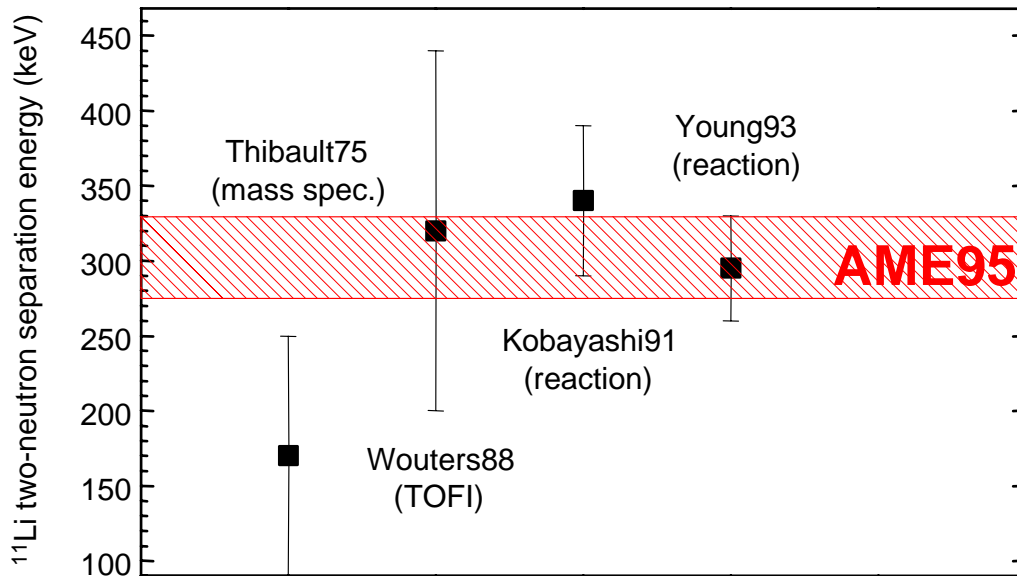

FIGURE 2. Two-neutron separation energy values for ^{11}Li determined from previous experiments. From left to right: Thibault et al. [THI75] using a mass spectrometer, Wouters et al. [WOU88] using a fragmentation-time-of-flight technique; Kobayashi et al. [KOB91] from the ^{11}Be(π^+,π^-)^{11}Li reaction (unpublished) and Young et al. [YOU93] using the ^{14}C(^{11}B,^{11}Li)^{14}O reaction. The hatched area is from the 1995 atomic mass evaluation [AME95] and corresponds to the weighted error of 27 keV. The expected uncertainty of the proposed MISTRAL measurement would be 5 keV (error bars within the points on this figure).

Generally speaking, there are two axes along which we can improve our knowledge of a given phenomenon. New experimental techniques at higher energies can expose new observables and hence new handles to grapple with the problem theoretically. The complementary approach is to refine existing data and squeeze the theory a little harder. One example is particle physics' quest to dethrone the vaunted standard model by building larger and larger machines while complementary nuclear and mass spectroscopy studies (such as those performed by the IS-384 collaboration [Ays00]) may allow us to tighten the noose by refining the data used by the unitarity test. A similar situation exists for ^{11}Li where refinement might not only pressure existing models but help in diagnosing the problems of newer formulations that rely on tuning the potentials. A very plausible one-sigma deviation from the MSU result would already change the S_{2n} value to the extent that structural changes in the three-body potentials would be noticeable. Though this will not solve theoretical problems related to these models, it will eliminate a potential source of uncertainty. Improving the mass value for ^{11}Li is important simply because the S_{2n} value is so small. The current uncertainty is about 10% of the total S_{2n} which is far from sufficient. The measurement proposed here should allow us to reduce this figure closer to 1%.

2. *MISTRAL*

MISTRAL is one of several programs dedicated to the accurate mass measurement of radioactive isotopes (for reviews see [BOL97, MIT97]). These programs are all complementary in technique and/or applicability. The *MISTRAL* spectrometer at *ISOLDE* uses a rather special technique of radiofrequency modulation of the cyclotron motion at the full beam transport energy (for details see [LUN01A, AUD99, STS95]. This allows very rapid measurements of excellent precision thus ren-

dering it particularly suitable for short-lived nuclides such as [11]Li. *MISTRAL* has now produced several results, mostly in the light, neutron-rich region near the island of inversion at *N*=20. Isotopes of Na [TOA99, LU01A], Ne and Mg [MON00, LU01B, MIS01] and the drip line nuclide [74]Rb [VIE01,VIE02] have been measured. As with all techniques, results on the most exotic nuclides are limited by statistical error but where statistics are sufficient, a measurement precision of better than 5×10^{-7} has been reached, even for nuclides with half-lives as short as 30 ms.

A schematic diagram of the *MISTRAL* spectrometer with its nominal trajectory is shown in fig.3. Ions injected at the full *ISOLDE* beam energy (60 kV) follow a two-turn helicoidal isochronous trajectory inside the homogeneous magnetic field (fig.3, inset right) and are counted. To obtain high mass resolving power, a longitudinal kinetic energy modulation is effected using two symmetric electrode structures located at the one-half and three-half turn positions inside the magnetic field. This way the ions make one cyclotron orbit between the two modulators. A radiofrequency voltage is applied to the central modulator electrodes and the ions are transmitted through the 0.4 mm exit slit only when the net effect of the two modulations is zero. This happens when the radiofrequency voltage is an integer-plus-one-half multiple of the cyclotron frequency which means that during the second modulation the ions feel exactly the opposite of what they felt during the first. For high harmonic numbers (e.g. larger than 1000) and a radiofrequency voltage of about 200 V, the ion signal over a radiofrequency scan shows narrow transmission peaks having resolutions of about 50,000 (over 100,000 is possible) evenly spaced at the cyclotron frequency (fig.3, inset left).
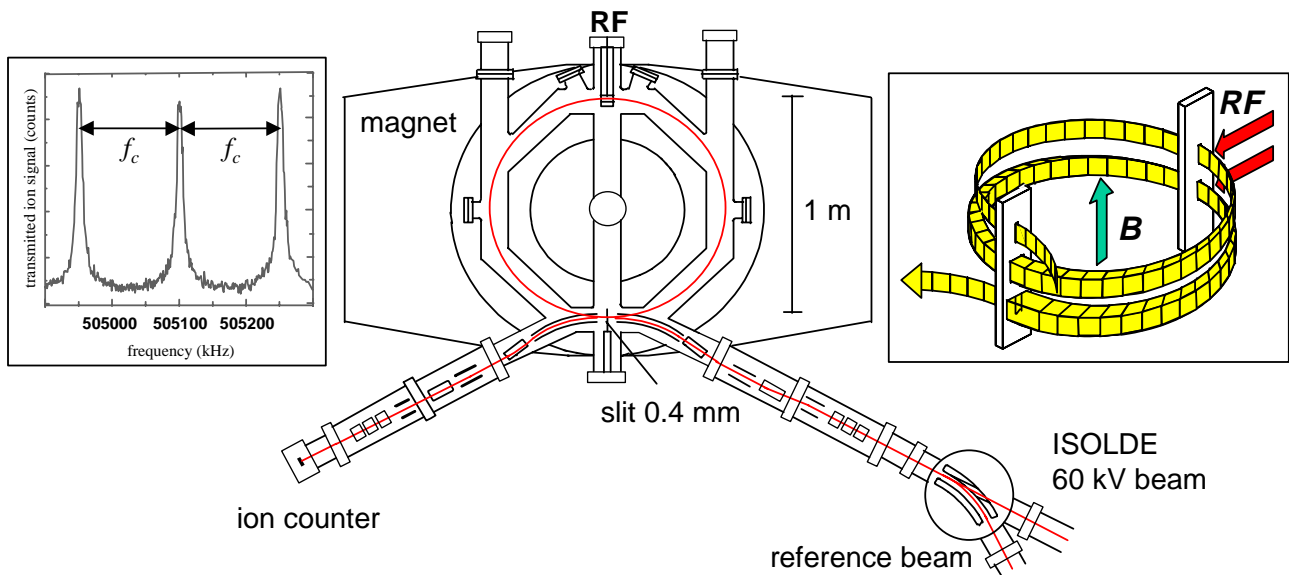

FIGURE 3. Layout of the *MISTRAL* spectrometer showing the nominal ion trajectory. Ions are injected from the *ISOLDE* beam line at the full transport voltage of 60 kV while the reference mass is alternately injected (without changing the magnetic field) at its corresponding energy. Inset (right) shows an isometric view of the trajectory envelope with the 0.4 mm injection slit followed by the first modulator at one-half turn, the second modulator at three-half turns and finally the exit slit. Inset (left) shows a transmitted [39]K ion signal frequency scan spanning three harmonic numbers (around 3400). The mass resolution here is about 50,000 but can easily exceed 100,000.

A mass measurement is made when an unknown mass is alternately injected with a reference mass *without* changing the magnetic field. Comparing masses in this way requires changing not only the transport energy of the reference beam but the voltages of all electrostatic elements in the spectrometer. These comparisons are done once every PS supercycle in order to eliminate short-term drift in the magnetic field.

In the case of short-lived nuclides it is impossible to scan the entire required frequency range in time after the impact of the proton pulse. For each radioactive beam pulse, the ion transmission signal is recorded for only one radiofrequency point (determined randomly) and the transmission peak is reconstructed at the end. This point-by-point mode not only allows us to increase statistics

in the peak but for each point, the ion signal may also be recorded with the radiofrequency switched off so that not just the intensity but the true transmission is measured in order to correctly normalize the peak. Moreover, since we count the number of ions that have been separated with high resolution, we can produce very clean release curves to verify isobaric contamination via the half-life.

The previous measurements have revealed that a calibration is necessary due to the slightly differing trajectories of the measured and reference ions. This is accomplished by first measuring masses known to sufficient accuracy and using isobaric doublets wherever possible. In the recent case of ^{74}Rb we accomplished this using ^{74}Ge as a reference and also measuring the well-known ^{76}Rb using ^{76}Ge as a reference [VIE01].

3. Beam time request

This mass measurement will enhance the now already extensive ISOLDE physics program built around the ^{11}Li nuclide. In addition to the nuclear (IS-320) and laser spectroscopy (IS-304) already performed, there is a planned REX-ISOLDE experiment [AND00] and a recently accepted proposal for further laser spectroscopy to study the charge radius [DAX00]. The interest of the present proposal to the latter is that the precision of mean-square charge radius variation in light nuclides is limited by the dominating effect of the mass shift.

Based on our experience of over 50 shifts of radioactive beam, we are confident that we can reach a precision on the mass value of ^{11}Li of 5 keV, given a minimum yield of 1500 ions/pulse. This would be an improvement of more than five over the current mass table value (27 keV) and a factor of seven over the only precision datum (35 keV), from MSU. In addition to this potential improvement, it is extremely important from a metrological point of view to confirm the MSU value using a completely different technique to ensure that no systematic error was present. This way, precision measurements are transformed into accurate ones.

The mass measurement of ^{11}Li would be performed using ^{10,11}B and ^{12}C as reference masses from our own ion source. These beams have already been transported through the spectrometer. We will also measure the mass of ^{9}Li for calibration purposes.

We would expect to use the Ta (2 μm foil) target with surface ioniser. The record (short-term) yield for this target is listed as 14,000 ions/pulse however the ISOLDE coordinator has informed us that the more conservative yield of 2000-6000 ions/pulse over a period of a few days could certainly be delivered. The experiment could be performed with either the GPS or the HRS.

Given a yield of 2000/pulse, one independent measurement with sufficient statistics could be performed in one shift of beam time. We would require a minimum of five independent measurements, each of which accompanied by a calibrating mass measurement of ^{9}Li requiring a few hours. Our experience shows that due to target outgasing and changing beam emittance, the spectrometer needs to be readjusted after the first one-two days of running.

We therefore ask for a total of 15 shifts of beam time to provide a mass measurement of highest possible accuracy with this experiment.

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