Eur. Phys. J. A **25**, s01, 31–32 (2005)
DOI: 10.1140/epjad/i2005-06-005-5

EPJ A direct
electronic only

Mass measurement of short-lived halo nuclides

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Received: 23 November 2004 /
Published online: 12 April 2005 –

Abstract. A direct mass measurement of the very-short-lived halo nuclide ^{11}Li ($T_{1/2} = 8.7$ ms) has been performed with the transmission mass spectrometer MISTRAL. The preliminary result for the two-neutron separation energy is $S_{2n} = 376 \pm 5$ keV, improving the precision seven times with an increase of 20% compared to the previous value. In order to confirm this value, the mass excess of ^{11}Be has also been measured, $ME = 20171 \pm 4$ keV, in good agreement with the previous value.

PACS. 21.10.Dr Binding energies and masses – 21.45.+v Few-body systems

The ^{11}Li is a two-neutron halo nuclide, consisting of a ^{9}Li core and two neutrons with a large spatial extension. The nuclide has a radius far beyond the droplet approximation [1], and has a very weak binding energy [2]. It is a Borromean three-body system, since the constituents cannot form bound two-body systems (*i.e.* ^{10}Li or the dineutron). This particular configuration represents a good test for theory to reproduce the three-body effect and to understand the neutron-neutron interaction. The two-neutron separation energy, derived from the mass, is a critical input parameter to modern three-body models, and gives a better idea of the weight of the s and p-wave ground-state configuration of the two valence neutrons. It also constrains calculations based on the resonance energy of the unbound ^{10}Li.

The MISTRAL experiment (Mass measurements at ISOLDE/CERN with a Transmission RAdiofrequency spectrometer on Line), determines the mass of short-lived nuclides by measuring their cyclotron frequency in a homogeneous magnetic field [3]. The ISOLDE beam is injected directely in the spectrometer alternately with an offline stable boron reference beam used to measure the magnetic field from its cyclotron frequency. With a resolving power up to 10^5, we can reach a relative mass uncertainty of a few 10^{-7} for a production rate of 1000 ions/s. The accessible half-life is only limited by the time-of-flight of the ions through the beamline. The rapidity of this on-line method allows us to measure nuclides with *ms* half-lives. ^{11}Li was provided by a tantalum thin-foil target and surface ionized [4] while the Laser Ion Source of the ISOLDE facility was used for Be beams.

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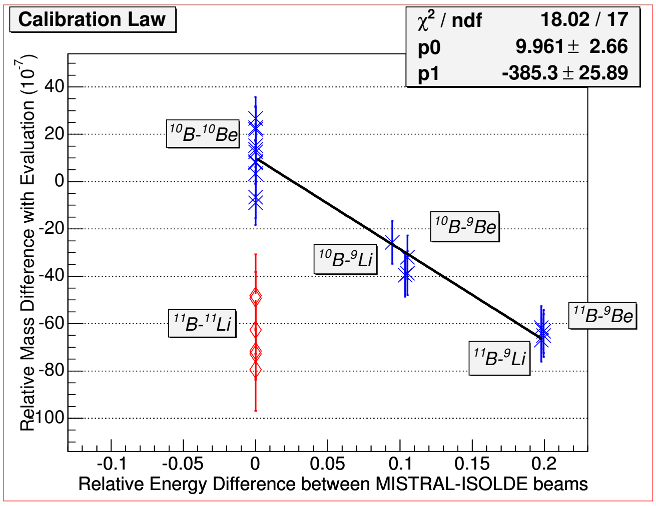

Fig. 1. Calibration law for the ^{11}Li run. The spectrometer was calibrated with 3 nuclei provided by ISOLDE target (^{9,10}Be and ^{9}Li), in comparison with ^{10,11}B from the MISTRAL reference source. We used five combinations of these nuclides to determine the calibration law. Moreover, ^{11}Li measurements were added to show the difference.

In order to transmit the ISOLDE beam and the reference beam with the same magnetic field, the energy of the reference ions is adjusted in proportion. A deviation of the measurement with the mass from the AME ($\frac{m_{\rm MISTRAL} - m_{\rm AME}}{m_{\rm AME}}$), proportional to the relative difference of the beam energies ($\frac{E_{\rm ISOLDE} - E_{\rm Ref}}{E}$) required a calibration law to correct the ^{11}Li measurement (see fig. 1) [5].

Table 1. Summary of the different measurements of the ^{11}Li mass.

Reference	Method	S_{2n} (keV)
Thibault *et al.* [6]	Mass Spec.	170 ± 80
Wouters *et al.* [7]	TOF	320 ± 120
Kobayashi *et al.* [8]	$^{11}B(\pi^-,\pi^+)^{11}Li$	340 ± 50
Young *et al.* [9]	$^{14}C(^{11}B,^{11}Li)^{14}O$	295 ± 35
MISTRAL03	Mass Spec.	376 ± 5

Table 2. Summary of the different measurements of the ^{11}Be mass.

Reference	Method	Mass excess (keV)
Pullen *et al.* [10]	$^{9}Be(t,p)^{11}Be$	20175 ± 15
Gooseman *et al.* [11]	$^{10}Be(d,p)^{11}Be$	20174 ± 7
MISTRAL03	Mass Spec.	20171 ± 4

Table 3. Different calculations of the neutron-neutron rms radii for ^{11}Li [12,13], with respectively $S_{2n} = 0.29$ MeV and $S_{2n} = 0.37$ MeV, as a function of the ^{10}Li virtual state energy. To compare the experimental value [14].

(^{11}Li) S_{2n} (MeV)	(^{10}Li) S_n (keV)	$\sqrt{\langle r^2_{nn}\rangle}$ (fm)	$\sqrt{\langle r^2_{nn}\rangle_{\rm exp}}$ (fm)
0.29	0	9.7	6.6 ± 1.5
	−50	8.5	
0.37	0	8.6	6.6 ± 1.5
	−50	7.7	

With the seven corrected measurements of ^{11}Li, we have a preliminary measured value in comparison with the mass of AME95, $m_{\rm MISTRAL} - m_{\rm AME95} = -75 \pm 5$ keV.

The new measurement of ^{11}Li is seven times more precise than the value of Young *et al.* [9], having the dominant weight in the 1995 mass evaluation. Moreover, we find the mass more bound by 75 keV compared to this value, with the $^{14}C(^{11}B,^{11}Li)^{14}O$ reaction (table 1). Though small, this represents a sizable shift in the two-neutron separation of more than 20%. To make us sure of the value found, the mass of the ^{11}Be has been measured and be found nearly equal with the past one. Its precision has been improved by a factor near of two: $m_{\rm MISTRAL} - m_{\rm AME95} = -4 \pm 4$ keV (table 2).

Yamashita *et al.* [12] have developed a zero-range interaction model in which the two-neutron separation energy is an input parameter to calculate the neutron-neutron distance in core-n-n halo nuclei as a function of the resonant energy of the core-n unbound nuclei. This model reproduced well the experimental value of ^{6}He and ^{14}Be but not the one of ^{11}Li with the previous S_{2n}. Calculations have been done with the new preliminary value [13] and the results are reported in table 3. The results are now in better agreement with the experimental value of Marqués *et al.* [14], and also for the 50 keV ^{10}Li resonant energy measured by Thoennessen *et al.* [15].

Recent results using nuclear field theory that include core polarization give ground state binding energies for ^{11}Be and ^{12}Be within a few percent [16]. For ^{11}Li, their result ($S_{2n} = 360$ keV [17]) was higher than that given by other models. As it turns out, their calculation is in excellent agreement with our higher S_{2n}.

The MISTRAL measurement program on short-lived halo nuclides will be continued at ISOLDE for the cases of ^{12,14}Be and ^{19}C. An upgrade to the spectrometer is in program to improve the sensitivity in order to match the extremely low production rates of these exotic nuclides [18].

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