Michigan State University

National Superconducting Cyclotron Laboratory

THE MASS OF ^{11}Li FROM THE ^{14}C(^{11}B,^{11}Li)^{14}O REACTION

B.M. YOUNG, W. BENENSON, M. FAUERBACH, J.H. KELLEY,
R. PFAFF, B.M. SHERRILL, M. STEINER, J.S. WINFIELD,
T. KUBO, M. HELLSTRÖM, N.A. ORR, J. STETSON, J.A. WINGER,
and S.J. YENNELLO

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B. M. Young, W. Benenson, M. Fauerbach, J. H. Kelley, R. Pfaff, B. M. Sherrill,
M. Steiner, and J. S. Winfield
National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy,
Michigan State University, East Lansing, Michigan *48824*

T. Kubot, M. Hellström, N. A. Orr*, J. Stetson, J. A. Winger†, and S. J. Yennello†
National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing,
Michigan 48824

Abstract

The mass of the nucleus ^{11}Li has been determined from a measurement of the Q-value of the reaction ^{14}C(^{11}B,^{11}Li)^{14}O at $E/A \approx 32$ MeV. The results indicate a two-neutron separation energy of $S_{2n}(^{11}\mathrm{Li}) = 295 \pm 35$ keV.

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Since the discovery in 1985 [1] that the interaction radius of the nucleus ^{11}Li is much larger than that of other nuclei in the same mass region, a great deal of work, both theoretical and experimental, has been directed at understanding the structure of this nucleus. Experiments that have been carried out towards this end have included measurements of the Coulomb dissociation cross sections of ^{11}Li [2,3] as well as measurements of ^{9}Li fragments, singly [4,5] and in coincidence with neutrons [6–8], from the breakup of ^{11}Li. The evidence from these experiments indicates that ^{11}Li consists of a ^{9}Li core with a "halo" of two loosely bound neutrons, the matter radius of which extends well beyond the radii of other nuclei with a similar mass. In parallel with these experimental efforts several theoretical models have been developed which treat ^{11}Li as a three–body system comprising a ^{9}Li core and two neutrons [9–15]. It has been shown in two–body models [16,17] that the radius, and even the existence, of a neutron halo is intimately dependent on the binding energy of the halo neutrons. In one of the simplest models, Hansen and Jonson have demonstrated in Ref. [17], by treating ^{11}Li as a quasi–deuteron consisting of a ^{9}Li core coupled to a dineutron ^{2}n, that the wave function of ^{11}Li decays exponentially with a decay length given by $\rho = \hbar/\sqrt{2\mu B}$ where μ and B are the reduced mass and binding energy of the system. Three–body models, such as those described in Refs. [9–15] also predict a sensitive dependence of several ^{11}Li observables on the binding energy of the two halo neutrons. Clearly, it is essential for the understanding of the halo phenomena that the ^{11}Li mass be known as accurately as possible.

There is however, some uncertainty on the value of the mass of ^{11}Li as can be seen in Table I, which lists all of the measurements. In 1975, Thibault *et al.* [18] reported the first measurement of the mass of ^{11}Li. In their measurement, lithium ions were produced by 24 GeV protons incident on iridium foils in a target–ion source. The ions were then accelerated by a DC voltage through a series of slits and magnetic elements into a shielded counter. The ^{11}Li mass was deduced by comparing the voltages necessary to transport ^{9}Li and ^{11}Li through identical trajectories of the optical system. In 1988, Wouters *et al.* [19] measured the mass of ^{11}Li nuclei produced from fragmentation reactions of 800 MeV protons on a thorium target. The mass of the fragments was determined using the TOFI spectrometer at LAMPF.

The substantial disagreement between these measurements as well as the magnitude of their uncertainties limits their usefulness in theoretical calculations. The value frequently used is the more recent, but unpublished, result of Kobayashi *et al.* [20]. They measured the Q-value of the pion double charge–exchange reaction on ^{11}B.

In this paper we present a measurement of the Q–value of the ^{14}C(^{11}B,^{11}Li)^{14}O reaction. The experiment was performed with an $E/A = 32.137 \pm 0.024$ MeV, $^{11}B^{5+}$ beam from the K1200 cyclotron at the National Superconducting Cyclotron Laboratory which was focused onto a self–supporting ^{14}C foil, 0.450 mg/cm^2 thick. The reaction products were analyzed with the A1200 fragment separator set to an achromatic mode [21]. The A1200 focal plane detectors consisted of a position sensitive parallel–plate avalanche counter, a 0.5mm thick Si position–sensitive detector, and a scintillating plastic stopping detector. Redundant and unambiguous particle identification was obtained by combining the energy loss signal from the silicon detector with the total energy signal from the plastic and with the time–of–flight information obtained from the scintillator signal relative to the cyclotron rf. The absence of long-lived reaction products with rigidities similar to that of the ^{11}Li particles made particle identification and the elimination of background quite simple.

The focal plane was calibrated with the reaction ^{14}C(^{11}B,$^{10}Be^{3+}$)^{15}N, where both the ^{15}N ground state and the 5.3 MeV doublet appeared in the focal plane at the same time as the ^{11}Li production reaction (Fig. 1). Uncertainty about the relative strengths with which the states of the unresolved ^{15}N doublet ($E_{ex} = 5.270$ MeV and 5.299 MeV) were populated contributed only a small amount to the total uncertainty of the final measurement. The beam energy, measured from the well–known Q–value of the reaction ^{14}C(^{11}B,^{9}Li)^{16}O, was determined to be $E/A = 32.137 \pm 0.024$ MeV. The uncertainty in the beam energy reflects the uncertainty in the measurement of the known (^{11}B,^{9}Li) Q–value. The contribution of this beam energy uncertainty to the uncertainty of the ^{11}Li mass measurement is given in Table II along with that of other sources of error. The contribution labelled “field integral” refers to the correction for the fact that the bend angle of a charged particle through a dipole magnetic field depends on the path integral through that field, whereas the A1200 field is measured with an NMR probe at a single point in the dipole. The dependence of this path integral on the field as read by the NMR probe has been measured, and the uncertainty given in Table II reflects the uncertainty in that measurement.

The experiment consisted of two runs of approximately 50 hours each, separated by a period during which the beam was refocused onto the target and the spectrometer field setting was changed slightly. The production reaction cross section was determined from the 149 counts obtained in two runs to be 24 nb/sr at 0° in the lab. The data from both runs are shown Figure 1. The momentum spectra collected from the production reaction ^{14}C(^{11}B,^{11}Li)^{14}O are shown in the bottom part of the figure. In addition to the primary peaks, corresponding to the ground states of both ^{11}Li and ^{14}O, another peak, corresponding to unresolved states in ^{14}O near 6.3 MeV excitation energy, is seen in the data from the second run. The momentum spectra from the calibration reaction ^{14}C(^{11}B,^{10}Be^{3+})^{15}N*, collected simultaneous to the production reaction data, are shown in the top portion of the figure. The ground state and 5.3 MeV doublet states of ^{15}N were used as the primary calibration points. Also seen in the calibration spectra are a cluster of ^{15}N and ^{10}Be excited states, corresponding to a total excitation energy between 8.0 and 10.0 MeV, and the 3.37 MeV first excited state of ^{10}Be, which shows marked relativistic broadening of its gamma decay width.

When the statistical uncertainty, which comes from averaging the Q–value measurements from the two runs, is added in quadrature with the estimates of the systematic uncertainties from the other contributions to obtain the final uncertainty, the resulting measured Q–value is -37.120 ± 0.035 MeV. The deduced two–neutron separation energy for ^{11}Li is found to be $S_{2n}(^{11}\mathrm{Li}) = 295 \pm 35$ keV. As can be seen in Table I this result is in good agreement with the previous measurements while substantially lowering the uncertainty. Using the existing four measurements, the weighted best values for the ^{11}Li mass excess and two-neutron separation energy are 40.802 ± 0.026 MeV and 295 ± 26 keV respectively.

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* Present address: LPC–ISMRA, Caen, France.

† Present address: Cyclotron Institute,

‡ On leave from the Institute of Physical and Chemical Research (RIKEN), Hirosawa, Wako, Saitama 351–01, Japan. College Station, Texas.

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FIGURES

FIG. 1. The data from the first and second runs (see text) are shown in the left and right portions of the figure, respectively. The momentum spectra from the reaction $^{14}C(^{11}B,^{10}Be^{3+})^{15}N^{*}$ are shown in the top part of the figure. The ground state and 5.3 MeV doublet states of ^{15}N were used as the primary calibration points. Other features in the calibration spectra are a cluster of ^{15}N and ^{10}Be excited states, and the 3.37 MeV first excited state of ^{10}Be. The momentum spectra collected from the reaction $^{14}C(^{11}B,^{11}Li)^{14}O$ are shown in the bottom part of the figure. It is important to note that both the calibration and ^{11}Li spectra were collected simultaneously.

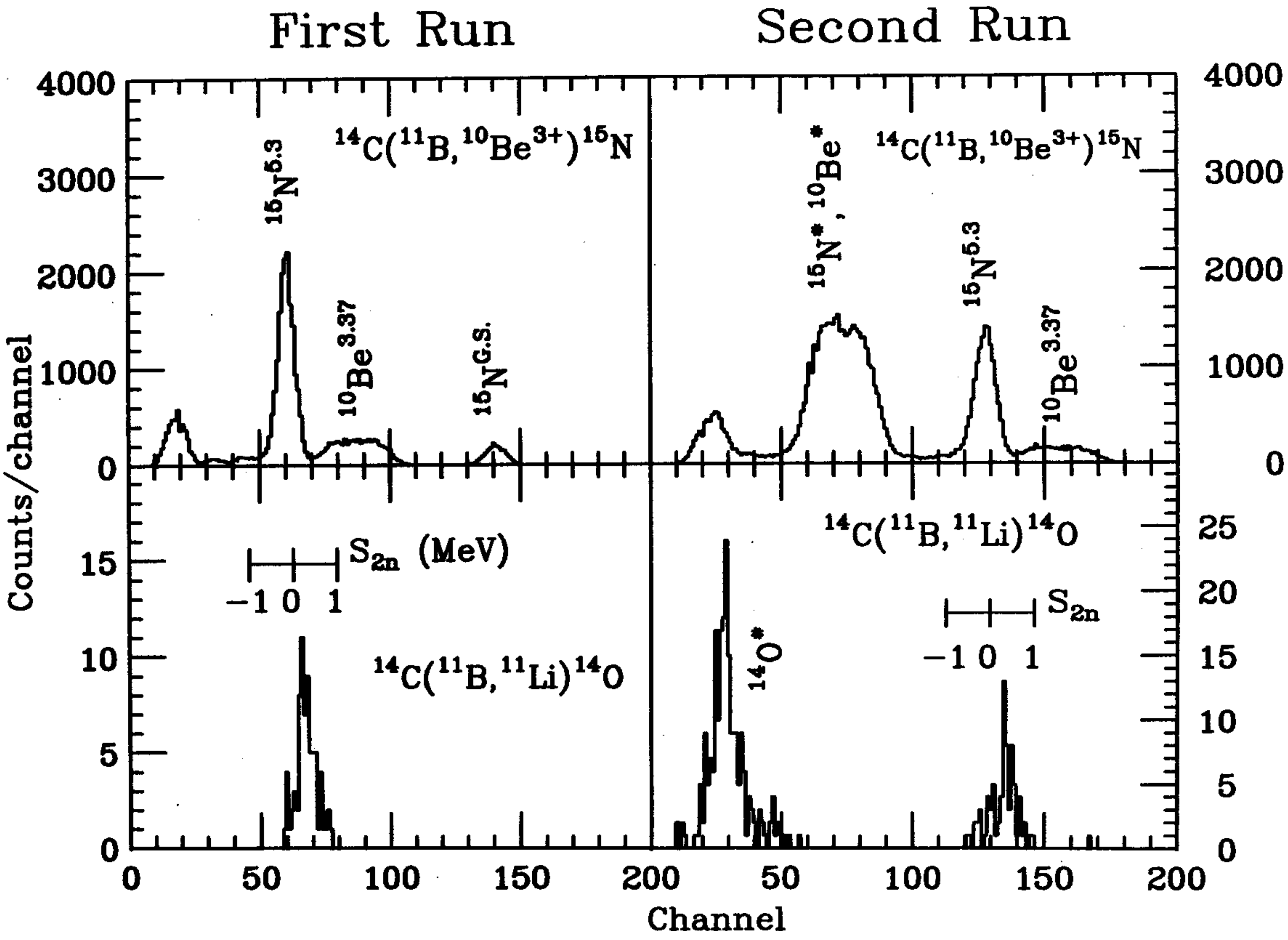
TABLES

TABLE I. Summary of existing measurements of the two–neutron separation energy of ^{11}Li.

Reference	$S_{2n}(^{11}\mathrm{Li})$ (keV)
Thibault *et al.*, 1975 [18]	170 ± 80
Wouters *et al.*, 1988 [19]	320 ± 120
Kobayashi *et al.*, unpubl. [20]	340 ± 50
Present work	295 ± 35

TABLE II. Sources of experimental uncertainty. The four uncertainties listed are added in quadrature to yield the total uncertainty.

Source of uncertainty	σ (keV)
statistics	18
beam energy	23
field integral	11
^{15}N excited state population in calibration	15
total uncertainty	35


First Run
Second Run
Counts/channel
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3000
2000
1000
0
15
10
5
0
25
20
^{14}C(^{11}B,^{10}Be^{3+})^{15}N
^{15}N$^{5.3}$
^{10}Be$^{3.37}$
^{15}N$^{G.S.}$
^{15}N*, ^{10}Be*
S$_{2n}$ (MeV)
S$_{2n}$
−1 0 1
^{14}C(^{11}B,^{11}Li)^{14}O
^{14}O*
0
50
100
150
200
Channel