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Mass of ^{39}Sc via the ^{40}Ca(^{7}Li, ^{8}He) reaction

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The Q value of the ^{40}Ca(^{7}Li, ^{8}He) ^{39}Sc reaction has been measured, and a value of $-37.40(4)$ MeV was obtained. The corresponding mass excess of ^{39}Sc is $-14.14(4)$ MeV, which makes ^{39}Sc proton unbound by 630(40) keV. Under the assumption of a quadratic form, the b and c coefficients of the isobaric multiplet mass equation for 39 ($T=\frac{3}{2}$) were obtained. They agree well with systematics and the predictions of the isospin-nonconserving Hamiltonian model of Ormand and Brown.

INTRODUCTION

One of the goals of the study of very neutron-rich or proton-rich nuclei is the determination of the limits of particle stability. Recently, these limits have been observed in very neutron-rich nuclei with $A<40$ (Refs. 1 and 2) by the absence of certain nuclei in the spectra of fragmentation reactions. Using similar techniques the stability of proton-rich isotopes has recently been studied via projectile fragmentation and proton spallation, and the proton drip line has been studied up to $Z=20$ (Ref. 3) and in the region $20<Z<28$.[4] From these works the $Z<21$ proton drip line is thought to be well established, and in the $20<Z<28$ region the proton drip line is at least partially determined. However, to conclude that an isotope is unbound based on evidence of this type can be misleading since the production of a given isotope may be reaction dependent. An example is the nucleus ^{14}Be, which was for many years believed to be unstable because it was not seen in deep-inelastic-scattering reactions.[5] Additionally, unstable nuclei can have states with definite spin and parity; these states can neither be observed nor their widths measured in experiments of this type. A more direct method is to observe the ground-state proton decay directly as has been done in heavier nuclei.[6] Another technique is to measure the Q value of a two-body final-state reaction, which leads to the unknown nucleus. In the present project the proton unbound nucleus ^{39}Sc was observed for the first time, and its ground-state mass was determined via the Q-value measurement of the ^{40}Ca(^{7}Li,^{8}He)^{39}Sc reaction. From its mass, we deduce that ^{39}Sc is 633(42) keV proton unbound, and therefore, it is just over the proton drip line. This result is important for determining whether or not ^{39}Sc is a candidate for measurable ground-state proton radioactivity. The usefulness of the (^{7}Li,^{8}He) reaction has been discussed by Stiliaris *et al.*,[7] and the reaction has been used to measure the mass of ^{57}Cu (Ref. 8) and the first excited state of ^{23}Al.[9]

The ground state of ^{39}Sc is the third known member of the $A=39$ isobaric quartet, and hence its mass can be used to determine the b and c coefficients in the isobaric multiplet mass equation[10] (IMME) if the assumption of a quadratic form for this equation is made. The $A=39$ coefficients are compared to systematics and the predictions of the isospin-nonconserving Hamiltonian formulation of Ormand and Brown.[11] In general, the ^{39}Sc results provide a comparison for nuclear structure calculations which involve both the *sd* and *f* shells and are a good test for the extrapolation of various mass formulas beyond the proton drip line.

EXPERIMENT

The (^{7}Li,^{8}He) reaction was measured using an $E/A=27.24(5)$ Mev ^{7}Li^{2+} beam from the K500 cyclotron at the National Superconducting Cyclotron Laboratory. The target was ^{40}Ca (99.97% enriched) made from the reduction of ^{40}CaCO$_3$ with Zr powder and the subsequent evaporation onto a glass slide. The calcium layer was then peeled off and mounted as a self-supporting layer 5.4(1) mg/cm^2 thick. Target uniformity measurements using an ^{241}Am source showed that the energy loss in the target remained constant to within 1% over the area of the ^{7}Li beam spot. The reaction products were detected in the S320 spectrometer.[8] This spectrometer has a quadrupole-quadrupole–dipole-multipole configuration, with an energy acceptance of 20% and a solid angle of 0.5 msr. The horizontal position and angle at the focal plane is measured by charge division in two single-wire proportional counters. Energy loss (ΔE) information is given by two ion chambers, and a signal roughly proportional to the total energy is obtained from the light output of the plastic scintillator at the end of the detector. The scintillator signal is also used for time of flight (TOF) relative to the cyclotron rf.

The ^{8}He ions were identified by a combination of TOF in the spectrograph, ΔE in the ion chambers, and light output from the plastic scintillator. Although the ^{8}He^{2+} and ^{4}He^{1+} ions overlap in the ΔE-TOF spectrum, they are clearly resolved with the light output signal from the stopping plastic scintillator since ^{4}He^{1+} has only half the energy of the ^{8}He^{2+} ions of the same rigidity. A potential problem with this reaction is the very high rate of tritons from ^{7}Li$\rightarrow t+\alpha$ breakup. However, a hardware TOF gate allowed the rejection of tritons.

The ^{40}Ca(^{7}Li,^{8}He) ^{39}Sc reaction was measured at an angle of 4.80(6) degrees, and a nominal dipole field of 14.8770 kG. The dipole field remained constant during each run but varied by as much as 1 G over the period of the experiment. Therefore, the ^{8}He position peaks from each run were corrected to a field of 14.8770 kG before they were summed. The focal plane was calibrated by measuring the ground state and first excited state of the reaction ^{9}Be(^{7}Li,^{8}He)^{8}B at the same field setting, as well as the ground-state peak of the reaction ^{24}Mg(^{7}Li,^{8}He)^{23}Al, since the mass excesses of all the products are well known. For this same reason, the (^{7}Li,^{6}He) reaction on ^{58}Ni, ^{40}Ca, ^{24}Mg, and ^{9}Be targets was used to calibrate the laboratory angle of the spectrometer. By measuring the difference between the focal plane positions of the ^{58}Ni(^{7}Li,^{7}Li^{2+}) elastic-scattering peak and the ^{9}Be(^{7}Li,^{8}He)^{8}B ground-state peak at 4.80(6) degrees, we determined that the beam energy was 27.24(5) MeV per nucleon. The energy losses in each target (and hence, the target thicknesses) were found by comparing the various elastic-scattering peak positions with that of a ^{58}Ni target of well-known thickness. These energy losses were incorporated into the focal plane calibration of the (^{7}Li,^{6}He) reactions. The calibration was determined by iterating the spectrometer angle and target energy losses between the (^{7}Li,^{6}He) and elastic-scattering calibrations. From this process, we obtain the best values of the spectrometer angle and the target thicknesses used in the (^{7}Li,^{8}He) calibration. The calibration error is determined by finding the change in the fit to the (^{7}Li,^{6}He) peaks when data from any one target are left out of the calibration and subsequently predicted by the fit.

RESULTS

The position spectra for the ^{9}Be(^{7}Li,^{8}He) and ^{24}Mg(^{7}Li,^{8}He) calibration reactions are shown in Figs. 1 and 2, and the spectrum for the ^{40}Ca(^{7}Li,^{8}He)^{39}Sc reaction is shown in Fig. 3. The overall resolution was 240-keV full width at half maximum (FWHM). Using mass excesses from Wapstra and Audi,[12] we calculate the Q value of the ^{40}Ca(^{7}Li,^{8}He)^{39}Sc reaction to be $-37.40(4)$ MeV. The corresponding ^{39}Sc mass excess is $-14.14(4)$ MeV. The error is found by directly adding the average systematic error from the calibration (15 keV) to the statistical error in the ground-state ^{39}Sc position peak (26 keV). The measured ^{40}Ca(^{7}Li,^{8}He)^{39}Sc cross section at 191 MeV and 4.8° is 70(30) nb/sr. The uncertainty in the cross section came approximately equally from the statistics in the peak, the target thickness uncertainty, and uncertainties in the charge collection calibration of the Faraday cup.

DISCUSSION

The ^{39}Sc mass excess determined in this experiment is compared to various models in Table I. In general, the agreement is similar to that expected from the overall accuracy of the predictions.[13] It is interesting that Moller and Nix predict that ^{39}Sc should be proton unbound by only 40 keV. If this had been true, then ^{39}Sc would be a candidate for long-lived proton decay, or perhaps for decay by branching to both protons and β^+ emission. However, given that the present experiment finds the proton unbound by 633(42) keV, one can estimate that the lifetime is on the order of 4×10^{-13} sec. This estimation was carried out by calculating the barrier penetration for an $l=3$ proton through a barrier with $R=1.2A^{1/3}$ fm. The calculated spectroscopic factor in the $0d_{3/2}$-$0f_{7/2}$ model space[14] is 0.90. Therefore, ^{39}Sc does not seem to be a candidate for proton decay with a lifetime comparable to that of β decay.

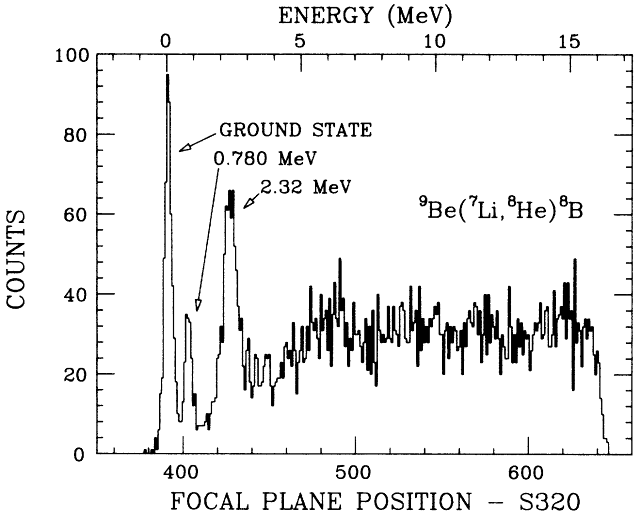

FIG. 1. ^{8}He position spectrum at the focal plane of the S320 spectrometer for the ^{9}Be(^{7}Li,^{8}He)^{8}B reaction.

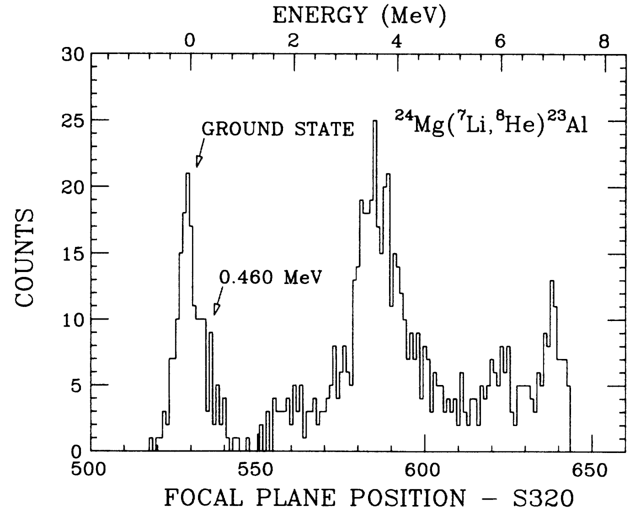

FIG. 2. ^{8}He position spectrum at the focal plane of the S320 spectrometer for the ^{24}Mg(^{7}Li,^{8}He)^{23}Al reaction.

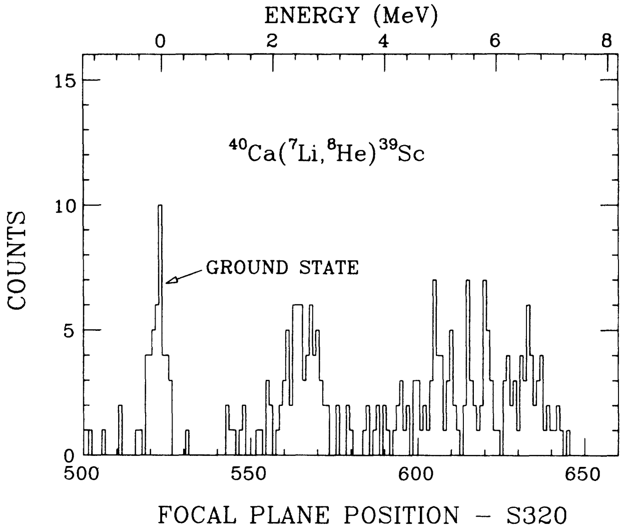

FIG. 3. ^{8}He position spectrum at the focal plane of the S320 spectrometer for the ^{40}Ca(^{7}Li,^{8}He)^{39}Sc reaction.

The measured mass of ^{39}Sc also allows the *b* and *c* coefficients of the IMME to be extended to the $A=39$, $T=\frac{3}{2}$ isobaric quartet ($BE=a+bT_Z+cT_Z^2+dT_Z^3+\cdots$), under the very-well-established assumption that the *d* coefficient of the IMME can be set to zero.[10] From the two other known members of the quartet, ^{39}Ar [g.s., $ME=-33.242(5)$ MeV][12] and the $T=\frac{3}{2}$, $J^{\pi}=\frac{7}{2}^-$ state in ^{39}K [$ME=-27.261(2)$ MeV],[12,15] we obtain the results given in Table II. These are compared in Fig. 4 to systematic trends in *b* and *c* coefficients from Refs. 10 and 16. Also included in Table II are the corresponding *b* and *c* coefficients predicted by the recent empirical isospin-nonconserving (INC) Hamiltonian developed for the $0d_{3/2}$-$0f_{7/2}$ shell-model space by Ormand and Brown. In that work, Hamiltonians were developed for the purpose of calculating INC processes and were determined empirically under the requirement that the parameters of a Coulomb plus phenomenological isovector and isotensor potential reproduce experimental *b* and *c* coefficients. For the $0d_{3/2}$-$0f_{7/2}$ space,[14] 22 *b* coefficients, including 3 from $T=1$ doublets in the $A=39$ system, and 14 *c* coefficients were fit. An rms deviation of approximately 21 keV was obtained for both. The resulting Hamiltonian contained a small charge-asymmetric interaction in which the neutron-neutron two-body interaction was approximately 1.8% more attractive than the proton-proton interaction, and a short-range charge-dependent interaction in which the proton-neutron interaction was 2.4% more attractive than the average of the proton-proton and neutron-neutron interactions. Aside from being able to calculate the extent to which isospin conservation is violated, the empirical Hamiltonian can also be used to predict other isobaric mass shifts as shown by the good agreement between the experimental and predicted values. The excellent agreement of the INC calculations with the results from our experiment indicate the good predictive power of the INC formulation.

TABLE I. Predictions of the mass excess of ^{39}Sc, and the result from this work.

Model[a]	Value (MeV)
Myers	−15.85
Groote Hilf Takahashi	−15.73
Liran Zeldes	−13.98
Beiner Lombard Mas	−13.6
Janecke Garvey Kelson	−14.07
Wapstra	−14.18
Moller[b] Nix	−14.72
Experiment	−14.14(4)

[a] S. Maripuu, At. Nucl. Data Tables **17**, 411 (1976).

[b] P. Moller and J. R. Nix, At. Data Nucl. Data Tables **26**, 165 (1981).

TABLE II. *b* and *c* coefficients for the $A=39$ quartet using the experimental mass of ^{39}Sc and using the INC formalism of Ormand and Brown.

	b (MeV)	*c* (keV)
Experimental	7.150(14)	194(7)
INC Calculation	7.154(21)	207(21)

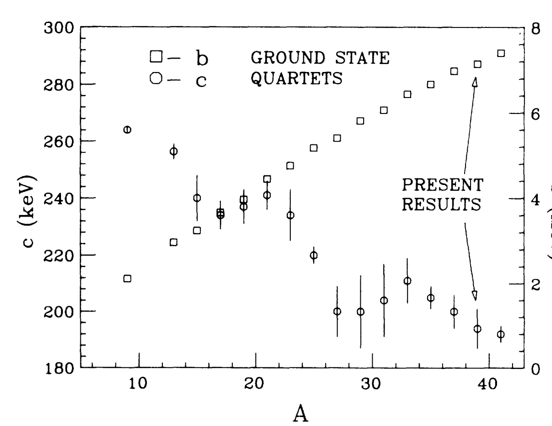

FIG. 4. Comparison of the $T=\frac{3}{2}$ *b* and *c* coefficients from the isobaric multiplet mass equation for the ground-state quartets.

CONCLUSIONS

The $^{40}Ca(^{7}Li,^{8}He)$ reaction has been used to measure the mass excess of ^{39}Sc as $-14.14(4)$ MeV. This value agrees within the uncertainties of the various mass models. From the mass excess, we have estimated that the ground-state proton decay of ^{39}Sc has a lifetime of 4×10^{-13} sec. The ground-state mass measurement also allows the b and c coefficient systematics for isobaric quartets to be extended to $A=39$, and the results are in very good agreement with the Ormand-Brown INC shell-model predictions.

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