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MASSES FOR ^{43}Ar AND THE NEW ISOTOPES ^{45}Ar AND ^{46}Ar

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MASSES FOR ^{43}Ar AND THE NEW ISOTOPES ^{45}Ar AND ^{46}Ar*

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Abstract:

The reactions (α, ^{9}Be), (α, ^{7}Be), and (^{6}Li, ^{8}B) on ^{48}Ca, at $E(\alpha)$ = 78 MeV and $E(^{6}Li)$ = 80 MeV, were used to determine the mass excesses of ^{43}Ar (−31.98 ± 0.07 MeV), ^{45}Ar (−29.727 ± 0.06 MeV), and ^{46}Ar (−29.732 ± 0.07 MeV) by counter telescope techniques. Excited states in ^{43}Ar at 1.74 ± 0.05, 2.55 ± 0.05, 3.56 ± 0.07, and 4.74 ± 0.10 MeV and in ^{45}Ar at 1.66 ± 0.05, 2.42 ± 0.05, and 3.25 ± 0.07 MeV were also observed. Comparisons are made with mass predictions calculated from simple mass relations based on the shell model and with those obtained from the Garvey and Kelson approach.

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In the region of light nuclei (A < 50), masses of highly neutron-rich nuclides have been predicted by Garvey et al.[1] by extrapolating away from the valley of stability on the basis of an independent particle model description of nuclear ground states. A simple alternative approach[2] based on an extension of a j-j coupling shell model description[3] for the ground states of even-even and even-odd nuclei, though not as general as that of Garvey et al.,[1] has recently[2,4] been applied to describe successfully the masses of the known T_z = 5/2 nuclei in the s-d shell. Experiments that help determine the validity of the assumptions of either model are of importance in assessing the reliability of predictions of the particle stability of nuclei, and also in determining the significance of, for instance, the explicit neglect in both models of the effects of deformation.

Recent measurements[5] of the masses of high-T_z sodium isotopes (^{27}Na to ^{30}Na) showed that there was considerable disagreement (> 1.4 MeV) between the revised predictions[6] of Garvey _et al._[1] and experiment for ^{29}Na and ^{30}Na. The very neutron-rich argon isotopes ^{43}Ar, ^{45}Ar, and ^{46}Ar also extend far from stability (T_z = 7/2 to 5), and their masses are of considerable interest not only as a means of investigating the effect of increasing neutron-excess on nuclear binding energies, but also because in this region the predictions of Garvey _et al._[1] and those of the shell model differ significantly.

With a ^{48}Ca target we have successfully observed the (α,^{9}Be) reaction (Q = $\sim$ -21 MeV), determining the previously unknown mass of ^{43}Ar[7] and the excitation energies of several of its levels. By also detecting ^{7}Be nuclei from the ^{48}Ca(α,^{7}Be)^{45}Ar reaction (Q = $\sim$ -28 MeV), excited states in ^{45}Ar and the mass of this new isotope were determined. Similarly, since the feasibility of employing the (^{6}Li,^{8}B) two-proton transfer reaction as a means of studying neutron-rich nuclei has been demonstrated,[8] the ^{48}Ca(^{6}Li,^{8}B)^{46}Ar reaction (Q = $\sim$ -23 MeV) was used to establish the mass of ^{46}Ar.

Beams of 77.7 MeV α-particles ($\sim$ 1 μA) and 80.1 MeV $^{6}Li^{2+}$ ($\sim$ 100 nA) from the Lawrence Berkeley Laboratory 88-inch cyclotron were used to bombard a 96.25% isotopically enriched self-supporting ^{48}Ca target (410 μg/cm^2). In both experiments outgoing particles were detected by two counter telescopes located on opposite sides of the beam. For the detection of ^{7}Be and ^{9}Be nuclei the counter telescopes, each subtending a solid angle of 0.43 msr, consisted of two transmission (ΔE) detectors 59 and 35 μm thick, a 260 μm E detector, and a 500 μm reject detector; for the (^{6}Li, ^{8}B) experiment the two ΔE detectors were 15 and 11 μm thick and the solid angle subtended was 0.64 msr. The method of data handling has been described previously[4] and involves in part a comparison of two particle identification signals to reduce background; this comparison eliminated ∿ 35% of the α and ∿ 45% of the ^{6}Li induced events. During both experiments electronic and beam energy stability were monitored, and the beam energy was determined using a high-precision analyzing magnet.

Figure 1a shows a ^{7}Be energy spectrum from ^{48}Ca obtained at $\theta_{lab} = 32°$. Transitions arising from ^{12}C and ^{16}O contaminants in the target can be seen, as well as peaks (FWHM ∿ 250 keV) corresponding to the ground state of ^{45}Ar and to a level at 3.25 MeV excitation. An energy calibration was obtained for the ^{7}Be spectra by recording the $^{28}Si(\alpha, {}^{7}Be)^{25}Mg$ and $^{40}Ca(\alpha, {}^{7}Be)^{37}Ar$ reactions at intervals throughout the experiment. Adequate separation between the ^{7}Be(g.s.) and $^{7}Be^{*}$(0.429 MeV) transitions was obtained for $(\alpha, {}^{7}Be)$ on ^{28}Si, ^{40}Ca and ^{48}Ca, though not on ^{12}C and ^{16}O. Spectra at several angles between $\theta_{lab} = 28°$ and 45° (see Fig. 1b) were collected, kinematically confirming observation of the reaction $^{48}Ca(\alpha, {}^{7}Be)^{45}Ar$, as well as enabling the region up to 5 MeV excitation to be seen. Over this angular range the cross-section to the ground state of ^{45}Ar varied between 1.4 and 0.5 μb/sr, and transitions to levels at 1.66 ± 0.05, 2.42 ± 0.05, and 3.25 ± 0.07 MeV excitation were identified. All states were seen at more than one angle.

For the ^{9}Be spectra the ^{7}Be energy calibration was used as a primary reference since it was well determined in the region of interest. Analysis of ^{9}Be energy spectra from ^{12}C and SiO_2 targets showed that the ground state of the residual nucleus was always populated. A ^{9}Be energy spectrum from ^{48}Ca

at θ_{lab} = 28° is shown in Fig. 1c. Peaks are indicated corresponding to the ground state ($d\sigma/d\Omega \sim 100$ nb/sr) and excited states at 1.74 ± 0.05, 2.55 ± 0.05, and 3.56 ± 0.07 MeV excitation in ^{43}Ar. These and a state at 4.74 ± 0.10 MeV were all seen at more than one angle.

Large basis shell model calculations[9,10] for ^{43}Ar and ^{45}Ar indicate an approximate similarity between the low-lying level spectra of ^{39}Ar and ^{45}Ar, and between ^{41}Ar and ^{43}Ar, as would be expected on the basis of simple particle-hole theorems. For ^{45}Ar the large level spacing we observe between the ground state and the lowest excited state is in qualitative agreement with the prediction that the excited states of ^{45}Ar begin above ∿1 MeV. The predicted level density in ^{43}Ar compared with our observations implies that the ^{48}Ca(α,^{9}Be)^{43}Ar reaction is quite selective. A state at ∿ 0.2 MeV excitation is predicted, with the next state at ∿ 1 MeV; however, we have assumed on the basis of reaction systematics that the highest energy peak corresponds predominantly to population of the ground state of ^{43}Ar. (The below comparison of the ^{43}Ar ground state mass with either of the predicted values reinforces this assumption.)

For the ^{48}Ca(^{6}Li,^{8}B)^{46}Ar data, an energy calibration was obtained by periodically collecting spectra from a carbon target, and from the position of the ^{16}O(^{6}Li,^{8}B)^{14}C ground state peak arising from slight oxidation of the ^{48}Ca target. A ^{8}B energy spectrum from ^{48}Ca at θ_{lab} = 15° is shown in Fig. 2a. Identification of the peaks followed from comparison with spectra taken at θ_{lab} = 15° on ^{40}Ca, ^{12}C and SiO_2 (as an oxygen target). Spectra from ^{12}C and SiO_2 are shown in Figs. 2b and 2c, respectively. (As was the case for the lighter targets, the level most strongly populated in the ^{40}Ca(^{6}Li,^{8}B)^{38}Ar reaction was the ground state.) Observed kinematic shifts between θ_{lab} = 10° and 17° provided additional confirmation of peak assignments. The cross-section to the ground state of ^{46}Ar was found to be $\sim$ 1 μb/sr at forward angles. No transitions to excited states of ^{46}Ar were observed; shell model calculations[10] predict the first excited state to be at $\sim$ 2 MeV excitation.

Analysis of the data gave the mass excesses of the argon isotopes as $^{43}Ar = -31.98 \pm 0.07$ MeV, $^{45}Ar = -29.727 \pm 0.06$ MeV, and $^{46}Ar = -29.732 \pm 0.07$ MeV, which are compared in Fig. 3 to the predictions of Garvey et al.[1] and to those based on a shell model description of nuclear ground states. A preliminary value[11] (-32.27 ± 0.04 MeV) for the mass excess of ^{44}Ar via the $^{48}Ca(^{3}He,^{7}Be)^{44}Ar$ reaction is also compared. In this shell model description, which is an extension of the approach given in the original work,[3] the mass excess of a nucleus with m j-protons beyond a closed shell and n j'-neutrons filling a different shell, $M(\pi j^{m} \nu j'^{n})$, is related simply to that of the nucleus with no j'-neutrons, $M(\pi j^{m})$, by the equation:

$$M(\pi j^{m} \nu j'^{n}) = M(\pi j^{m}) + n\alpha_{j'} + V(j'^{n}) + V(j^{m}, j'^{n}) \quad ,$$

where $\alpha_{j'}$ denotes the sum of the kinetic energy and the interaction with the closed shells of each j'-neutron, $V(j'^{n})$ their mutual interaction energy, and $V(j^{m}, j'^{n})$ their interaction with the m j-protons. The value of $V(j^{m}, j'^{n})$ simplifies considerably if no odd-odd nuclei are considered, depending then only on a single average interaction potential, $V(jj')$, through the relation $V(j^{m}, j'^{n}) = nm\, V(jj')$.[1,12] With this restriction we have determined the 14 parameters $M(\pi j^{m})$, $\alpha_{j'}$, $V(j'^{n})$ and $V(jj')$ for the 37 nuclei with $\pi d_{3/2}\ \nu f_{7/2}$ configurations by a least squares fit to the 24 known masses.[13] The root mean square deviation between the fitted and experimental values is 85 keV. The predicted values for the mass excesses of the high-T_z argon isotopes are $^{43}Ar = -31.78$, $^{44}Ar = -32.35$, $^{45}Ar = -29.69$, and $^{46}Ar = -29.72$ MeV.

As can be seen in Fig. 3, these predicted values agree well with the observed mass excesses of the argon isotopes. However, significant discrepancies between experiment and the predictions of Garvey _et al._[1] are observed for ^{44}Ar (490 keV) and ^{46}Ar (750 keV). It will be particularly interesting to compare these measurements, both of masses and of excitation energies, with the results of large basis shell model calculations.[10] It would appear, though, that the above shell model approach[2] to masses may be useful as an alternate predictive scheme for experimentalists studying highly neutron-rich light nuclei.

We would like to thank Dr. Creve Maples very much for writing the multiparameter analysis program, and Drs. R. D. Lawson and S. Maripuu for communicating results from their calculations on $^{43-46}Ar$.

FOOTNOTES AND REFERENCES

*Work performed under the auspices of the U. S. Atomic Energy Commission.

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FIGURE CAPTIONS

Fig. 1. (a) An energy spectrum from the reaction $^{48}Ca(\alpha,{}^{7}Be)^{45}Ar$ at θ_{lab} = 32° (7250 μcoul). The double arrows represent ^{7}Be(g.s.) and $^{7}Be^{*}$(0.429 MeV) transitions.

(b) As (a) but taken at θ_{lab} = 45° (30,000 μcoul).

(c) A composite spectrum of data taken with one counter telescope at θ_{lab} = ±28° from the reaction $^{48}Ca(\alpha,{}^{9}Be)^{43}Ar$ (17,000 μcoul). Contributions to this spectrum from the $(\alpha,{}^{9}Be)$ reaction on ^{12}C and ^{16}O fall below ∿ 46 MeV.

Fig. 2. Energy spectra from the $({}^{6}Li,{}^{8}B)$ reaction taken at θ_{lab} = 15° on (a) ^{48}Ca (6300 μcoul), (b) ^{12}C, and (c) ^{16}O; all are displayed with the same ^{8}B energy scale.

Fig. 3. Comparison of the difference between the measured mass excesses and predictions for the argon isotopes, $^{43-46}Ar$.

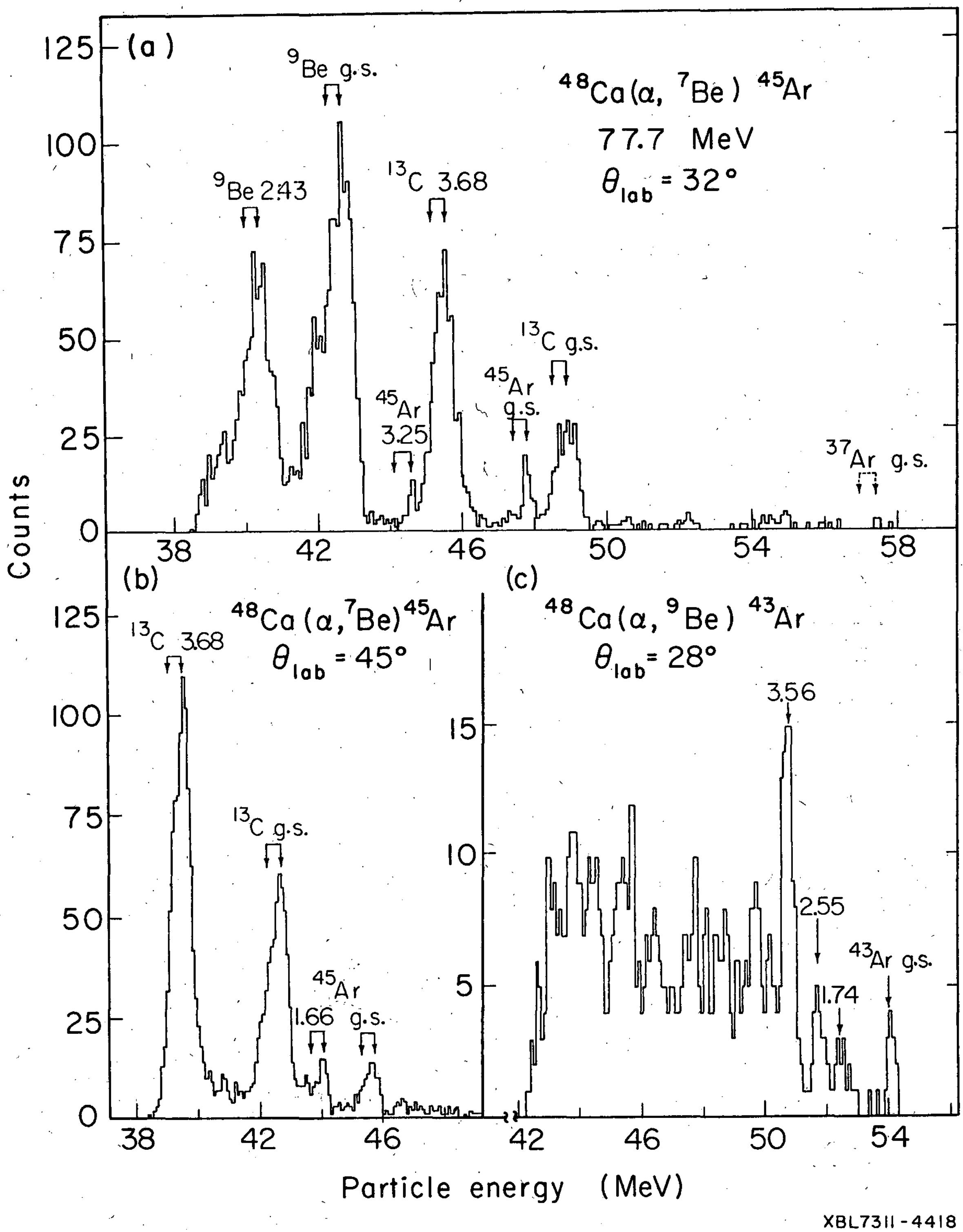

(a)
^{9}Be g.s.
^{48}Ca(α, ^{7}Be) ^{45}Ar
77.7 MeV
θ_{lab} = 32°
^{9}Be 2.43
^{13}C 3.68
^{13}C g.s.
^{45}Ar 3.25
^{45}Ar g.s.
^{37}Ar g.s.
Counts
(b)
^{48}Ca(α, ^{7}Be)^{45}Ar
θ_{lab} = 45°
^{13}C 3.68
^{13}C g.s.
^{45}Ar
1.66
g.s.
(c)
^{48}Ca(α, ^{9}Be) ^{43}Ar
θ_{lab} = 28°
3.56
2.55
1.74
^{43}Ar g.s.
Particle energy (MeV)
XBL7311-4418

Fig. 1

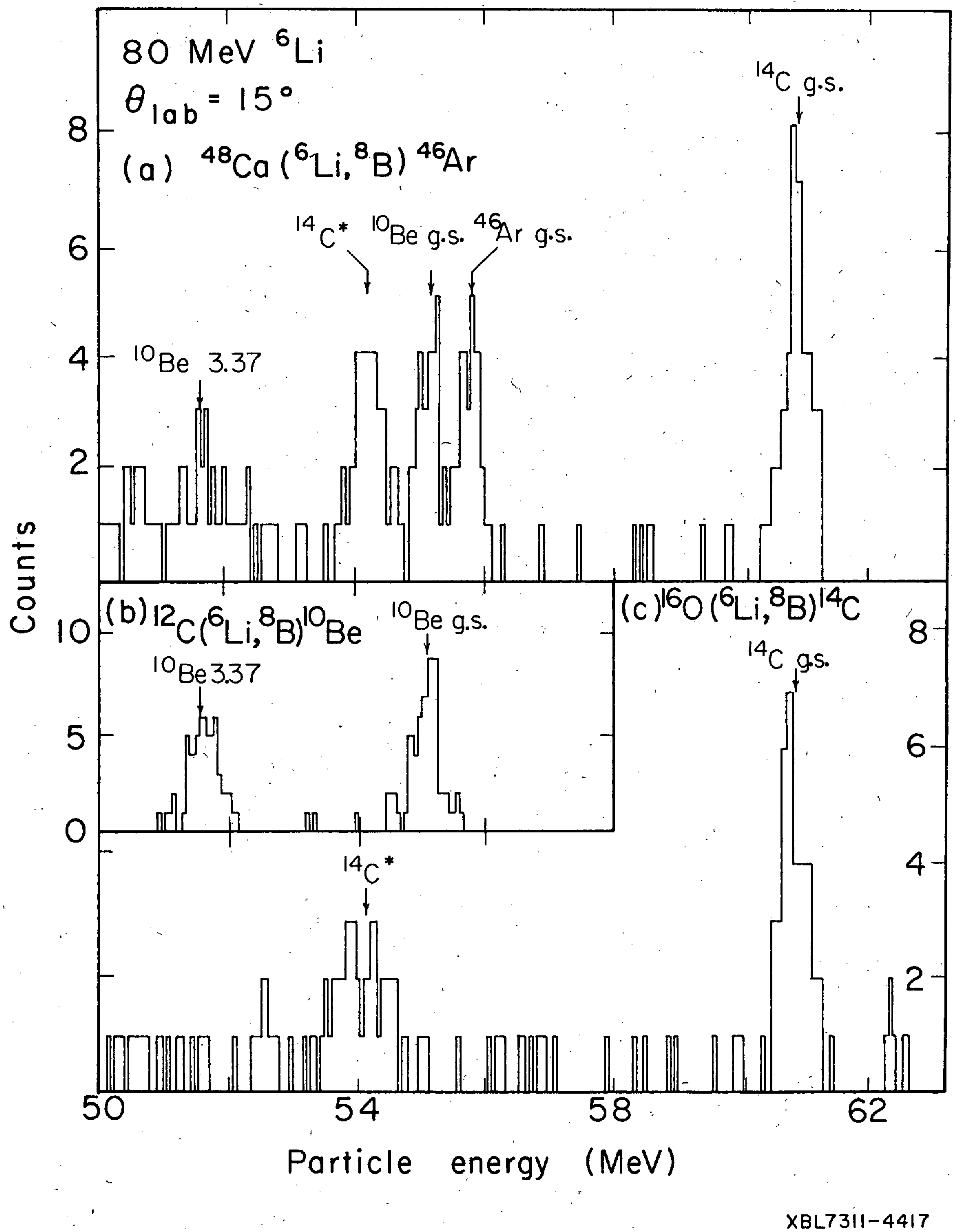
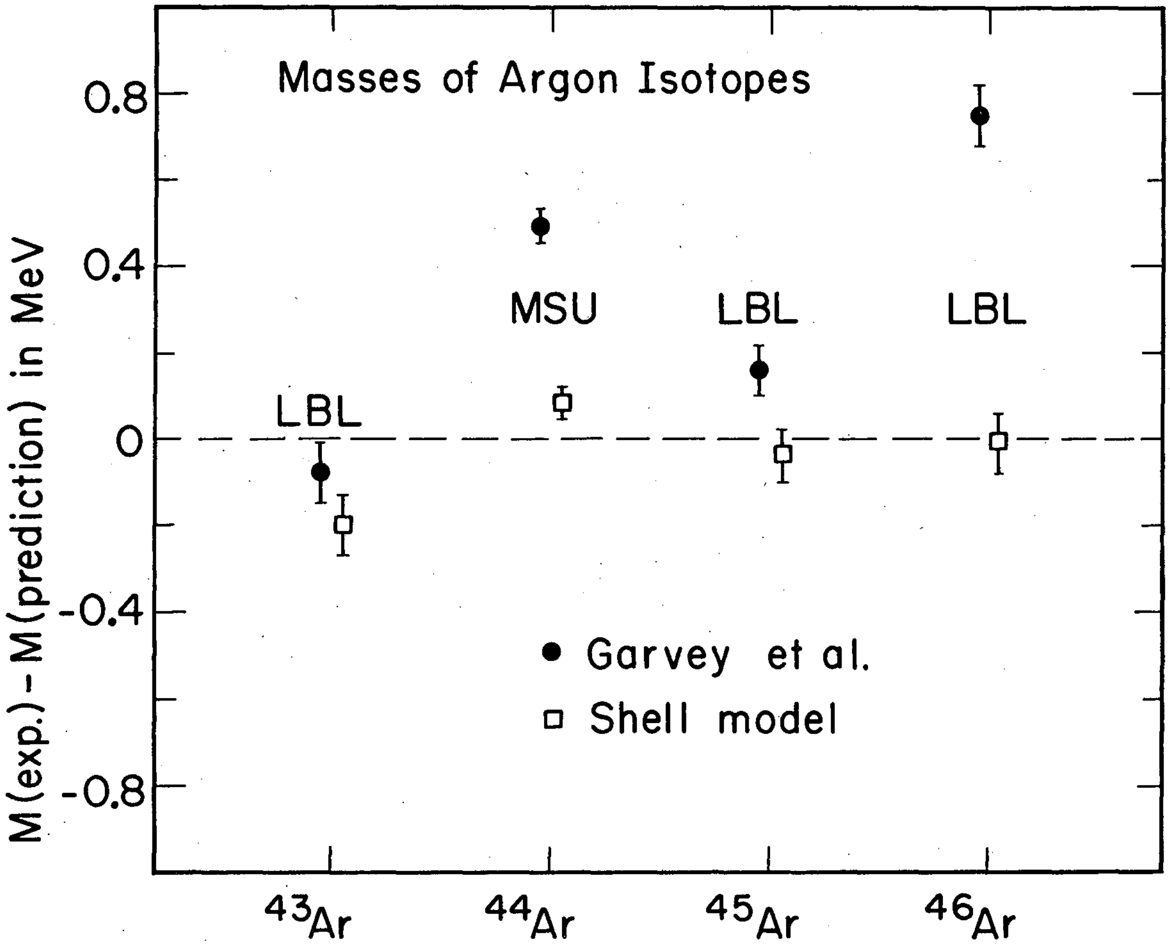

80 MeV 6Li
θlab = 15°
(a) 48Ca (6Li, 8B) 46Ar
14C g.s.
14C*
10Be g.s.
46Ar g.s.
10Be 3.37
(b) 12C(6Li, 8B)10Be
10Be g.s.
10Be 3.37
(c) 16O (6Li, 8B)14C
14C g.s.
14C*
Counts
Particle energy (MeV)
50
54
58
62
XBL7311-4417

Fig. 2



XBL7311-4564

Fig. 3

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