A DETERMINATION OF THE MASS AND SOME ENERGY LEVELS OF THE NUCLIDE ^{44}Ar☆

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The mass and some energy levels of the nuclide ^{44}Ar have been determined from the ^{48}Ca(^{3}He, ^{7}Be)^{44}Ar reaction. A comparison with theoretical values of the mass is made.

The lifetime of the nucleus ^{44}Ar has been reported [1, 2] but until now its mass and energy levels were unknown. This letter reports a measurement of the mass of ^{44}Ar and the excitation energies of several of its excited states as determined from the ^{48}Ca(^{3}He, ^{7}Be)^{44}Ar reaction at 70 MeV ^{3}He bombarding energy.

The ^{3}He beam was produced by the Michigan State University isochronous cyclotron. The reaction products were analyzed by an Enge split-pole magnetic spectograph [3]. Detection of ions in the focal plane of the spectrometer was accomplished by a system composed of a plastic scintillator photomultiplier unit behind a 25 cm single wire charge division gas proportional counter [4]. The counter measures both position along the focal plane and differential energy loss of an ion, while the scintillator is used to measure time-of-flight of ions through the spectrograph.

As the Q-values for many (^{3}He, ^{7}Be) reactions are nearly equal [5], contaminants in the target often produce peaks which interfere with those of primary interest. Contamination by carbon and oxygen is particularly severe because they are commonly present on calcium targets and the (^{3}He, ^{7}Be) reaction on these nuclides has a relatively large cross section [6]. Consequently, an effort was made to minimize the amount of carbon and oxygen to come into contact with the ^{48}Ca target. Targets were prepared by evaporating a layer, approximately 200 μg/cm^2 thick, of 97.16% isotopically enriched ^{48}Ca onto both gold and silver foils of between 100 and 200 μg/cm^2. The metal evaporated after reduction of calcium carbonate mixed with molybdenum powder in a molybdenum tube. The silver backing foils gave a smoother target presumably because the coefficient of expansion of silver is closer to that of calcium than is the expansion coefficient of gold. The targets were prepared, stored and transferred to the target chamber under vacuum. Nevertheless, as can be seen from fig. 1, peaks arising from carbon and oxygen are still larger than the peaks corresponding to levels in ^{44}Ar.

To help minimize the effect of the oxygen impurities in the ^{44}Ar ground-state region, 1.5 mm diameter pins were placed at the positions where ^{7}Be ions from the oxygen contaminant in the target would focus. This reduced the size of the peaks due to the 4.4 MeV state of ^{12}C arising from the oxygen impurity by about a factor of ten. This technique is described in detail elsewhere [7]. In addition to contaminants, the ^{7}Be spectra are complicated by those outgoing ^{7}Be ions which are in the 0.43 MeV particle stable first excited state. Thus each level in the residual nucleus produces two peaks in the ^{7}Be spectrum which are separated by about 0.4 MeV, the exact amount depending on the kinematical parameters. The experimental resolution (FWHM), due primarily to target thickness, of the spectrum measured at 7° laboratory angle (fig. 1) is about 66 keV, which allows discernment of these peak pairs, including those of impurities.

Ten independent spectra were measured at angles ranging from 5° to 15°. Small angles were chosen because the cross sections are larger at forward angles and to maximize the separation of the peaks corresponding to ^{44}Ar from the contaminant peaks. Even

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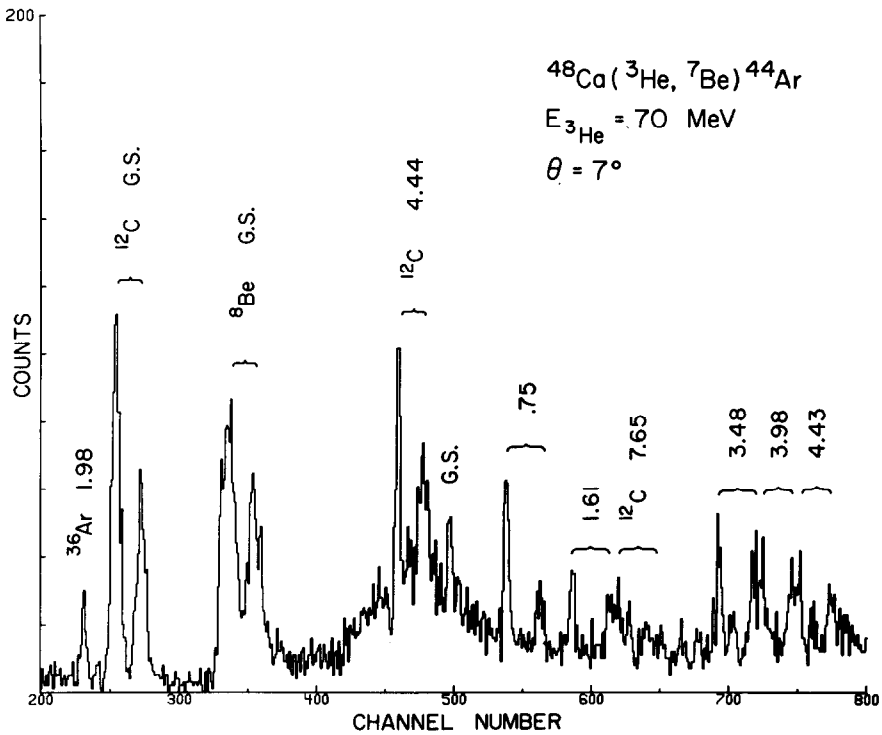

Fig. 1. The spectrum displayed is for the $^{48}Ca(^{3}He, ^{7}Be)^{44}Ar$ reaction at 70 MeV at 7°. Brackets are used to indicate the pair of peaks corresponding to the two states of ^{7}Be for each level in the final nucleus.

at 5°, the peaks corresponding to the lowest observed level of ^{44}Ar are very close to the peaks representing the 4.44 MeV level in ^{12}C but care was taken that the pins did not interfere with the peak identified as the ground state of ^{44}Ar. The pair of peaks corresponding to the 4.44 MeV state of ^{12}C together with the background produced by the broad 2.9 MeV level of ^{8}Be, could obscure peaks from potential lower levels of ^{44}Ar.

In order to check this possibility, a spectrum was taken at 15°, where any lower-energy peaks due to ^{44}Ar would be placed between the peaks due to the ^{8}Be ground state and the 4.44 MeV state of ^{12}C. No such peaks were observed.

A further check on the possibility that the peak identified as the ground state of ^{44}Ar is really that from the 0.43 MeV first excited state of ^{7}Be, is provided by the width of the peak. The peak observed has a width of only 54 keV, which is consistent with this peak corresponding to the ground state of ^{7}Be but is too narrow to correspond to the first excited state. Peaks corresponding to the first excited state of ^{7}Be, which decays by γ-emission in flight, are therefore broadened by about 76 keV due to the recoil effect. The average width of ^{44}Ar peaks in fig. 1 corresponding to the 0.43 MeV state of ^{7}Be is 110 keV which is consistent with folding the 66 keV ground-state width with the recoil contribution.

Finally both the kinematic shift with angle and previous measurement of the spectrum from a natural calcium target [6] and from the plain silver and gold backings ensured that the states observed were from the $^{48}Ca(^{3}He, ^{7}Be)^{44}Ar$ reaction.

The coefficients for a quadratic relationship between radius of curvature and channel number are determined by least-squares fitting, using the ^{36}Ar 1.98 MeV peak and various ^{12}C peaks for calibration. The calibration points came from the 7° spectrum shown in fig. 1, a spectrum using a WO_3 target with everything else unchanged and a spectrum using the WO_3 target with a slightly shifted spectrograph magnetic field. These last two spectra provide calibration

Table 1
^{44}Ar mass excess (in MeV)

Experimental value	Theoretical predictions					
	Garvey-Kelson [9]	Janecke [10]	Comay-Kelson [10]	Jelley et al. [12]	Gloeckner et al. [13]	
					Set A	Set B
−32.27 ± 0.02	−32.76	−32.41	−32.75	−32.25	−32.21	−32.17
Difference experimental − theoretical value	0.49	0.14	− 0.02	0.08	− 0.06	− 0.10

points in the region of the ^{44}Ar peaks from the ^{12}C 4.44, 7.65 and 9.64 MeV peaks. The position of the ^{36}Ar 1.98 MeV peak relative to the ^{12}C peaks verifies the assumption that ^{48}Ca and ^{16}O are in the same target layer. The r.m.s. deviation of the 15 calibration points is 15 keV which is larger than the uncertainty in centroid determination. The cause of this deviation is assumed to be nonuniformity of the proportional counter's anode wire. Uncertainties in the measured energies are estimated from the 15 keV r.m.s. deviation.

Table 1 presents the experimental value of the mass excess of ^{44}Ar together with a number of theoretical predictions. The Garvey-Kelson prediction [9], which is based on an extrapolation from known ground state masses assuming an independent particle model, disagrees with the experimental value by 490 keV. This is more than twice the average deviation of the Garvey-Kelson mass prediction. The calculation by Jänecke [10], shown in table 1, is basically a Garvey-Kelson model calculation but uses more recent mass values [11]. This value is much closer to the measured value, differing only by 140 keV. The Comay-Kelson calculation uses a statistical technique to extrapolate from known masses and is very close to the measured mass. However, they quote an uncertainty of 640 keV on their calculated value.

An alternative approach using a j-j coupled shell model description for the ground states of even-even and even-odd nuclei is also quite successful and the prediction by Jelley et al. [12] differs by only 80 keV from the measured value which compares favorably with the r.m.s. deviation of 85 keV for this model.

Detailed shell model calculations which include particles in the $d_{3/2}$, $f_{7/2}$, and $p_{3/2}$ shells by Gloeckner et al. [13] also give mass values quite close to but less bound than the experimental mass excess.

The energy levels observed in ^{44}Ar are shown in table 2 together with the shell model calculations of Gloeckner et al. [13]. In general the agreement for the first few levels is very good. Of particular interest is the prediction that the first excited state of ^{44}Ar is a 0^+ state, consisting of two proton and two neutron holes in the $d_{3/2}$ shell. Such a state would readily be formed by the ^{48}Ca(^{3}He, ^{7}Be) reaction by simply picking up four particles from the $d_{3/2}$ shell. The state observed at 750 keV excitation is the strongest state in the spectrum.

By using the peaks from the ^{40}Ca impurity in the target, a comparison of the cross sections for the ^{40}Ca(^{3}He, ^{7}Be)^{36}Ar and ^{48}Ca(^{3}He, ^{7}Be)^{44}Ar reactions is possible. The cross sections for the (^{3}He, ^{7}Be) reaction on ^{48}Ca are substantially smaller than for the

Table 2
Energy levels of ^{44}Ar

Experiment (MeV)	$\frac{d\sigma}{dr}$ 7° (μb/sr)	Shell model [13]	
		E_x (MeV)	Predicted J^π
0	1.0	0	0^+
0.75 ± 0.03	2.0	0.83	0^+
1.61 ± 0.03	1.0	1.25	2^+
3.48 ± 0.03	1.3		
3.98 ± 0.05	0.7		
4.43 ± 0.04	0.8		

same reaction on ^{40}Ca. This result agrees with the previously published results on a number of isotope chains [6]. The ratio of the ground-state cross sections is 8:1 and for the 2^+ states (assuming the state in ^{44}Ar at 1.61 MeV is the 2^+ state predicted by the shell model) the ratio is about 24:1.

These ratios agree qualitatively with a simple shell model prediction. If one uses the shell model wavefunctions of Maripuu and Evwaraye [14] for the $J^\pi = 0^+$ ground states of ^{36}Ar, ^{40}Ca, ^{44}Ar and ^{48}Ca and assumes the (^{3}He, ^{7}Be) reaction to proceed via α-particle pick-up [6, 15], one obtains a ratio of 15:1 for the squared ratio of wave-function overlaps between the partitions $^{40}\text{Ca} \rightarrow {}^{36}\text{Ar} + \alpha$ and $^{48}\text{Ca} \rightarrow {}^{44}\text{Ar} + \alpha$. For a more sophisticated calculation one must take into account the transformation coefficients describing the internal motion of the particles in the α-cluster as well as four-particle transfer fractional parentage coefficients. Such a calculation, however, would not at present be justified because of the uncertainties in the reaction mechanism.

To summarize, the mass excess of ^{44}Ar has been measured to be -32.27 ± 0.02 MeV and the differential cross section ratio of the ^{40}Ca (^{3}He, ^{7}Be)^{36}Ar(g.s.) reaction to the ^{48}Ca(^{3}He, ^{7}Be)^{44}Ar(g.s.) reaction agrees qualitatively with a shell model prediction.

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