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Isobaric mass quartets in $A = 33$ nuclei*

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The $^{36}Ar(^3He,^6He)^{33}Ar$ reaction has been used to measure the mass excess of the ground state and of the first two excited states of ^{33}Ar. The coefficients of the isobaric-mass-multiplet equation are calculated for the three new isobaric spin quartets which are completed by the present results.

[NUCLEAR REACTIONS ^{16}O, $^{36}Ar(^3He,^6He)$, $E = 70$ MeV, measured Q, deduced mass excess of ^{33}Ar.]

I. INTRODUCTION

The nucleus ^{33}Ar is known to be a delayed-proton emitter and its half-life has been measured.[1] However, its mass is not known and is the last remaining measurement of $T_Z = \frac{3}{2}$, $A = 4n+1$ nuclei accessible with the (^3He, ^6He) reaction. This series of nuclei has been used to test the isobaric-mass-multiplet equation (IMME), since in every case they complete $T = \frac{3}{2}$ quartets. In this paper measurements of the mass excess of the ground state and of two excited states of ^{33}Ar are described. The three completed quartets are discussed in terms of the IMME and shell-model calculations of the Coulomb displacement energies.

An accurate mass determination of ^{33}Ar is made difficult by the necessity of using a gas target since such targets are not well suited to small-angle detection in a spectrograph. An additional difficulty in the experiment was the extremely small cross section which necessitated relatively high gas pressures and hence quite large target energy-loss corrections.

II. EXPERIMENTAL METHOD

The experiment was performed using the 70-MeV ^3He beam from the Michigan State University cyclotron. The method for detecting the ^6He particles has been described previously.[2,3] The main difference from the previous measurements was the use of a gas-target system, which is shown schematically in Fig. 1. The gas cell was designed for a fixed angle of 10°. The fixed angle permitted a rigid alignment of the very tight collimation required to create a very short line source at small detection angles. This arrangement prevents misalignments which could allow particles from the entrance and exit windows to enter the spectrograph aperture.

The entrance and exit windows consisted of 1.96-mg/cm^2-thick Havar foils. The gas pressure in the cell ranged between 300 and 460 Torr. The isotopic enrichment of the ^{36}Ar gas was better than 99%. For the calibration reaction $^{16}O(^3He, ^6He)^{13}O$ (see Ref. 4 for the mass of ^{13}O) the same gas cell was used with a pressure of oxygen adjusted to make the energy losses of the ^6He particles in the gas cell the same for both the primary and calibration reactions. As in previous measurements the mass was determined by comparing the magnetic fields required to put the ^6He particles from the primary and calibration reaction at the same position on the focal plane of the spectrograph. In Fig. 2 an example of the spectra obtained is displayed. The over-all energy resolution was about 150 keV. The effect of the target energy loss on the energy resolution was of the same magnitude as the broadening of the image on the focal plane due to the extended line source. Other sources of broadening are negligible compared to these two effects. The determination of the true angle of the emission of the reaction products is important even at forward angles like 10° because of large kinematic differences between the $^{16}O(^3He, ^6He)^{13}O$ and $^{36}Ar(^3He, ^6He)^{33}Ar$ reactions. The angle was measured by filling the gas cell with an oxygen and helium mixture and comparing the energy of the elastically scattered ^3He particles from these nuclei. This established the true angle to be $10.0 \pm 0.1°$.

The main source of the experimental errors was the target energy-loss determination. Since the cross section of the $^{36}Ar(^3He, ^6He)^{33}Ar$(g.s.) was measured to be very small (0.13 ± 0.02 μb/sr at 10°), relatively high gas pressures were used in order to get reasonable counting rates. This resulted in quite large target energy-loss corrections which were calculated using the tables of Williamson, Boujot, and Picard.[5] The calculations were checked by varying the types of the outgoing particles and the gas pressure. The error in the target energy-loss difference between the primary and calibration reactions was estimated to be 20 keV. The error in the Q value of the calibration reaction $^{16}O(^3He, ^6He)^{13}O$ was 15 keV, which was approximately equal to the statistical error in determining the centroids of the peaks. Five separate runs were made on the $^{36}Ar(^3He, ^6He)^{33}Ar$ reaction, and the centroids of the ^6He peaks were found to agree within their statistical errors. The over-all error in the mass determination was 30 keV for the ground state and 40 keV for the excited states. The excitation energies of the states have an error of 20 keV.

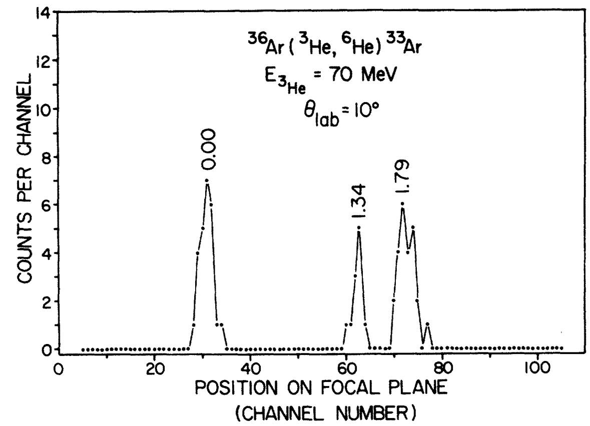

FIG. 2. Spectrum from the $^{36}Ar(^3He, ^6He)^{33}Ar$ reaction at a bombarding energy of 70 MeV and a laboratory angle of 10°. One channel corresponds to 43 keV in excitation.

III. RESULTS AND DISCUSSION

The mass excesses for the three lowest states in ^{33}Ar found in the present experiment are -9384 ± 30, -8040 ± 40, and -7598 ± 40 keV. The mass excess of the ground state can be compared with the prediction of the Garvey-Kelson[6] charge-symmetry relation

$$^{33}Ar = ^{33}P + ^{31}S - ^{31}P + ^{33}Cl - ^{33}S + ^{35}Ar - ^{35}Cl, \quad (1)$$

which yields a value -9348 ± 12 keV if the mass excesses tabulated by Wapstra and Gove[4] are used, and a value -9394 ± 4.8 keV if the corrected mass excess of ^{31}S (see Refs. 7, 8) is applied. The latter value is in excellent agreement with the present results.

In Table I a comparison of the new ^{33}Ar states to their analogs in ^{33}Cl, ^{33}S, and ^{33}P is made. All the data on these nuclei are taken from the compilation of Endt and van der Leun.[9] These values are used in the IMME to predict the mass excesses of the three lowest states of ^{33}Ar. The results (-9372 ± 10, -7980 ± 97, and 07575 ± 37 keV) are in quite good agreement with the measured values. Another way of measuring the deviation of the data from the predictions of the IMME is to cite a d coefficient for a cubic term added to the equation

$$M(T_Z) = a + bT_Z + cT_Z^2 + dT_Z^3 . \quad (2)$$

The three completed mass quartets were used to determine the coefficients of this equation. The results, which are given in Table II, show that the IMME works well in all cases. Also given are the Coulomb displacement energies Δ_d between $T_Z = +\frac{3}{2}$ and $+\frac{1}{2}$ members which are related to the b and c coefficients by the relation

$$\Delta_d = -b - 2c - \Delta_{np}, \quad (3)$$

where Δ_{np} is the neutron-hydrogen mass difference.

The experimentally determined b and c coefficients can be compared (see Table II) with theoretical predictions based on shell-model calculations as done by Auerbach *et al.*[10] and De Meijer *et al.*[11] The experiment observes an independence of these coefficients and of the Coulomb displacement energies on the spin and energy of the states. This may be due to an accidental cancellation of two phenomena which could produce such a dependence. One of these phenomena is the increase of

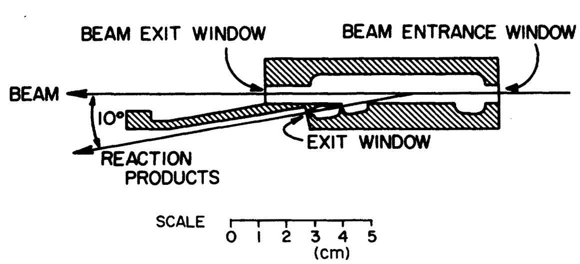

FIG. 1. Schematic view of the gas target.

TABLE I. $T = \frac{3}{2}$ levels in $A = 33$ nuclei. The units are in keV.

J	^{33}P [a]	^{33}S [a]	^{33}Cl [a]	^{33}Ar [b]
$\frac{1}{2}^+$	g.s.	$E_x = 5475$	$E_x = 5546$	g.s.
$\frac{3}{2}^+$	1431	1417	1404	1340 (20)
$\frac{5}{2}^+$	1847	1869	1853	1790 (20)

[a] Taken from Ref. 9.
[b] Present work; the errors are given in parentheses.

TABLE II. Comparison of experimentally determined coefficients of the IMME to various theoretical predictions. All values are in keV with errors in parentheses.

	Experimental				Auerbach *et al.*			DeMeijer *et al.*		
J^π	b	c	d	Δ_d	b	c	Δ_d	b	c	Δ_d
$\frac{1}{2}^+$	−5655 (5)	211 (7)	2.0 (5.5)	6015	−5640	204	6014	−5674	199	6058
$\frac{3}{2}^+$	−5645 (57)	200 (16)	1.0 (26.0)	6027				−5599	200	5981
$\frac{5}{2}^+$	−5640 (16)	189 (13)	3.8 (11.0)	6044				−5611	197	5999

the radius with excitation energy which occurs when a level is close to being unbound. This would decrease the Coulomb energy of the $\frac{3}{2}^+$ and $\frac{5}{2}^+$ states which are bound by about 2.0 and 1.6 MeV, relative to the $\frac{1}{2}^+$ state which is bound by 3.4 MeV. On the other hand, the $\frac{1}{2}^+$ state contains more $2s_{1/2}$ particle strength and therefore would display a reduced Coulomb displacement energy due to the absence of a centrifugal barrier and the presence of one more node in the wave function. The shell-model calculations of De Meijer *et al.*[11] do show a relatively large state dependence which disagrees with the present observations and is difficult to understand. More detailed shell-model calculations treating the protons and neutrons separately would be helpful in understanding the present results.

IV. CONCLUSION

Three levels of ^{33}Ar measured in the present experiment represent three new mass quartets which agree well with the predictions of the isobaric-mass-multiplet equation and the Garvey-Kelson mass relationship. The masses of all of the $A=4n+1$, $T_Z=-\frac{3}{2}$ nuclei which can be reached via the (^{3}He, ^{6}He) reaction are now known. These mass quartets and the shell-model predictions of their Coulomb energies will be summarized in a future paper.[12] Other (^{3}He, ^{6}He) experiments in progress are devoted to improving the accuracy in the masses of the $T_Z=-\frac{3}{2}$ nuclei, to finding new excited states in these nuclei, and to searching for members of $T=2$ quintets.

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