2.217 MeV state in ^{37}Ar

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Cross section and vector analyzing power data for the 2.217 MeV state in ^{37}Ar have been measured via the (d,p) reaction at an incident deuteron energy of 11 MeV. Distorted wave Born approximation analysis of the data establishes the spin parity of this relatively weak state as $7/2^+$. The data are fairly well reproduced by the calculations indicating that the one-step process plays a dominant role in populating the state in the (d,p) reaction. The spectroscopic factor for the state is found to be 0.04 ± 0.01. Model calculations indicate that two-step and compound nuclear processes have negligible effects on the conclusions.

[NUCLEAR REACTIONS ^{36}Ar$(\vec{d},p)$, $E=11.0$ MeV; measured $\sigma(\theta)$, $iT_{11}(\theta)$. Deduced J, π, S. DWBA analysis.]

The energy levels of ^{37}Ar have been investigated extensively via various reactions.[1] Of particular interest is the low-lying state at 2.217 MeV which is observed to be relatively weakly excited in the (d,p) reaction.[2-4] The most recent compilation[1] lists its J^{π} value as $\frac{7}{2}^+$ and one does not expect that such a state in an s-d shell nucleus will be populated by a single-step process in the (d,p) reaction.

Ericson fluctuation analysis of the excitation functions in the reaction ^{39}K$(d,\alpha)^{37}$Ar by Naude *et al.*[5] indicate a $\frac{5}{2}$ spin value for the 2.217 MeV state. Champlin *et al.*[6] concluded from lifetime and angular correlation measurements in the $(d,p\gamma)$ reaction that the spin of the state is either $\frac{5}{2}$ or $\frac{7}{2}$. γ-ray angular distribution and lifetime measurements in the reaction ^{34}S$(\alpha,n)^{37}$Ar by Ragan *et al.*[7] yield a most probable assignment of $\frac{7}{2}^+$ for this state. One of the arguments used in Ref. 7 is that the 2.217 MeV state is not observed in the (d,p) reaction, which is not valid. Taras *et al.*[8] make a $\frac{7}{2}^+$ assignment from the angular distribution and linear polarization of the decay γ rays via ^{37}Cl$(p,n)^{37}$Ar and ^{34}S$(\alpha,n)^{37}$Ar reactions. Later on, Alenius *et al.*[9] and Gadeken *et al.*,[10] studying the ^{34}S$(\alpha,n)^{37}$Ar reaction, constructed a decay scheme for the levels of ^{37}Ar. A decay scheme was also constructed on the basis of the results of a heavy-ion fusion-evaporation reaction (^{12}C + ^{25}Mg) by Warburton *et al.*[11] Although no direct attempt was made to determine the J^{π} of the 2.217 MeV level, the authors of Refs. 9–11 found that a $\frac{7}{2}^+$ assumption was consistent with their respective observations.

The positive parity states of ^{37}Ar have been examined in several shell-model calculations.[12-15] These calculations do predict a $\frac{7}{2}^+$ level in the neighborhood of 2.0 MeV, which has been associated with the observed 2.217 MeV state.

In the (d,p) reaction studies of Refs. 2 and 3, the angular-distribution data for the 2.217 MeV state could not be extracted. An attempt to extract and analyze the (d,p) data for this state was made in Ref. 4, where the reaction was initiated by a vector-polarized deuteron beam. Because of low beam intensity ($\simeq 2\ nA$), the data for this state were statistically insufficient and no definitive information could be derived. (The error bars shown in the data of Ref. 4 were actually underestimated because of an error in the calculations.) The availability of a high-intensity polarized beam[16] permits one to make accurate measurements even for weak states, and this has prompted us to investigate the 2.217 MeV state in ^{37}Ar via the $(\vec{d},p)$ reaction.

Data were acquired using a vector-polarized deuteron beam obtained from the University of Wisconsin colliding beam ion-source[16] and accelerated to 11 MeV. The target consisted of ^{36}Ar gas isotopically enriched to 99.9% enclosed in a 1.9-cm-diam gas cell with 6μm thick Havar foil walls. A gas pressure of approximately 1 atm was used. The outgoing particles were detected by a pair of 3 mm thick Si(Li) detectors. Data were collected at 23 laboratory angles between 16° and 145°. The sign of the beam polarization was reversed every 0.25 sec by switching radio frequency (rf) transitions at the source, and the corresponding spectra were routed into separate 512 channel blocks of the computer memory. The beam polarizations were measured and were monitored continuously using a precision polarimeter[17] located downstream of the scattering chamber. The magnitude of the beam polarization it_{11} was typically 0.51 ($p_y = 0.59$). A small tensor polarization ($|p_{zz}| \leq 0.02$) was present in the vector polarized beam. The intensity of the beam at the target for angles $\geq 45°$ varied between 100 and 125 nA. Typical run times per angle per polarization mode were approximately 5 h. For further forward angles, much lower beam currents were used and pile-up rejection modules were utilized. Two detectors kept at fixed angles (one to the right and the other to the left of the beam direction) served as monitors.

The weakly excited state at 2.217 MeV is flanked by the states at 1.611 and 2.490 MeV which are strongly excited and have peak cross sections approximately two orders of magnitude higher. Because of limited proton resolution in the present experiment [typically 100 keV full width at half maximum (FWHM)], the peak sums for the 2.217 MeV state along with those of 1.410, 1.611, 2.490, and 2.796 MeV states were obtained using a peak-fitting program.[18] The peak shape consisted of a dominant Gaussian term, a low-energy tail, a skew term with a low-energy tail, and a background term which was assumed to be flat over the region. Starting values of the fitting parameters were determined by fitting the isolated ground state peak. For each detection angle, the data corresponding to two opposite directions of the beam polarization were analyzed using the same fitting parameters. The errors in the peak sum were taken to be the fit errors weighted by chi-square. The vector analyzing powers (VAP) were calculated using standard expressions. Errors in VAP include the peak-sum errors and the errors in beam polarization values.

The cross-section data were obtained from the spin-up and spin-down yields using standard relations [Eqs. (2) and (3) of Ref. 4]. The relative normalizations were obtained from the monitor detector spectra. A Faraday cup with an electron suppressor was inserted and data were taken at a few selected angles using unpolarized deuteron beams at 10 and 11 MeV. The 10 MeV cross-section data of Ref. 4 were then used to obtain the absolute normalization factor. For some angles, cross-section data could not be obtained because of particular detector setup arrangements or due to inconsistent normalization factors. Errors in the cross-section data include the peak-sum errors, beam polarization errors, and the errors in relative and absolute normalization factors. To this should be added an overall uncertainty of $\pm 15\%$ as reported in Ref. 4. The small tensor polarization present in the vector polarized beam was considered to have a negligible effect compared to the other uncertainties.

The data extraction and other procedures were checked by comparing the derived data for deuteron elastic scattering and for the relatively strong ground state, 1.410, 1.611, 2.490, and 2.796 MeV states of ^{37}Ar with those of Ref. 4. A change of the incident deuteron energy from 10 to 11 MeV is not expected to produce much difference in the data and very good consistency was indeed obtained.

The data for the 2.217 MeV state are shown in Fig. 1. (The overall uncertainty of $\pm 15\%$ in the cross-section data has not been included.) The cross-section and VAP data have been analyzed using the zero-range distorted wave Born approximation (DWBA) code DWUCK[19] including corrections for nonlocality of the optical potentials.[20] Bound-state neutron wave functions were calculated using a Woods-Saxon well of standard geometry with $r_0 = 1.25$ fm and $a_0 = 0.65$ fm. The spin orbit depth was chosen as 6.25 MeV. The real central well depth was varied to reproduce the experimental separation energy.

The optical model potential parameters were taken from Ref. 4. The deuteron potential set was found to reproduce the present elastic data at 11 MeV. In Ref. 4, the proton potentials are basically those of Becchetti and Greenlees[21] changed slightly to improve the fit to the stripping data. In the present work, calculations were also performed using unmodified Becchetti-Greenlees parameters. The DWBA predictions for $J^\pi = \frac{7}{2}^+$, $\frac{9}{2}^+$ are shown in Fig. 1. All calculations were performed without radial cutoff and using the normalization constant $D_0^2 = 1.53 \times 10^4$ MeV^2 fm^3. The magnitude of the spectroscopic factor was obtained by normalizing the calculated cross sections at forward angles to the experimental data.

The data are reasonably well reproduced by DWBA calculations assuming $J^\pi = \frac{7}{2}^+$. That the back-angle data are not so well reproduced is not surprising since other reaction mechanisms certainly contribute in populating this weak state. In fact, the reproducibility of the VAP data compares

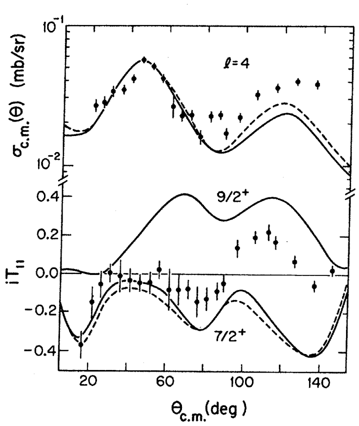

FIG. 1. Cross-section and vector analyzing power data for the 2.217 MeV state in ^{37}Ar along with DWBA predictions. The solid curves correspond to optical model potentials of Ref. 4 and the dotted ones were obtained using proton potentials from Ref. 21.

in quality with those of some of the stronger, lower angular momentum states in s-d and f-p shell nuclei. The fits lead to an unambiguous J^π value of $\frac{7}{2}^+$ for the 2.217 MeV state.

Since the deuteron optical potential set reproduces the elastic scattering data, the sensitivity of the calculations to small variations in proton potential parameters alone (as mentioned earlier) are shown in Fig. 1. One expects this sensitivity since the angular momentum mismatch is large.

The present analysis yields the spectroscopic factor for the state as

$$0.04 \pm 0.01 .$$

We write the wave function $|\chi\rangle$ for the state as

$$|\chi\rangle = \sum_{Ij} b_{Ij} |[|\phi_I\rangle \times |\phi_j\rangle]\rangle_{7/2} , \qquad (1)$$

where $|\phi_I\rangle$ represents target states with angular momentum I ($I=0$ for ground state), $|\phi_j\rangle$ represents the odd particle state of spin j, and b_{Ij} represents the expansion coefficients. Since both the cross-section and VAP data are well reproduced by DWBA calculations, it would seem reasonable to assume that most of the contribution to the stripping peak arises from the one-step process. In that case

$$b_{0,7/2} = (0.04)^{1/2} = \pm 0.2 ,$$

i.e., the $g_{7/2}$ single particle component of the wave function is quite large. This result is somewhat surprising since the $g_{7/2}$ single particle orbit lies beyond the $N=50$ magic number and one does not expect to observe any fraction of its strength in the low-lying states of an s-d shell nucleus. The present result cannot be compared with existing shell-model calculations,[12-15] since they do not allow explicit occupation of f-p or higher shell orbits. For positive parity states the other terms in the expansion [Eq. (1)] will involve 2p-5h and higher configurations with respect to the ^{40}Ca core. An exact determination of the contributions to the wave function from such configurations is a difficult task. However, since the measured cross sections are of relatively small magnitudes, the contributions arising from these terms (multistep processes) as well as those from compound nuclear (CN) processes need to be estimated.

A coupled channel calculation (CC) was performed using the code CHUCK2 (Ref. 22) considering vibrational excitation of the first 2^+ state of the target nucleus ^{36}Ar, followed by a $d_{3/2}$ single particle transfer to the residual nuclear state. Direct single particle transfer to the $\frac{3}{2}^+$ ground state of ^{37}Ar followed by inelastic proton scattering on the residual nucleus was also included. The deformation parameter β_2 and the ^{37}Ar ground state spectroscopic factor were taken from the literature.[23,4] The predicted cross section at the stripping peak is a factor of 7 lower than the observed value and the angular distribution is essentially flat.

Since the excitation energy of the compound nucleus is high ($\simeq 22$ MeV) and the target is fairly thick, the observed cross sections could be considered as energy averaged. The energy-averaged CN cross sections were obtained from Hauser-Feshbach calculations.[24] The predicted angular distribution is nearly flat with a small dip at 90° c.m. (The ratio of the maximum predicted cross section to that at 90° is 1.5.) The calculated cross sections are dominated by low partial waves.

Since the predicted angular distributions from CC and CN calculations are essentially flat, the corresponding processes have little effect at the stripping peak and, in particular, the resultant change in the magnitude of the spectroscopic factor lies within the quoted error limits. The inclusion of these processes do not improve the reproduction of the cross-section data. The two processes also tend to cancel each other's contribution to the VAP and consequently do not improve the reproduction of the data, and are, therefore, not included in Fig. 1.

In summary, the results obtained from the present investigation are as follows: (i) the spin-parity of the 2.217 MeV state of ^{37}Ar is established as $\frac{7}{2}^+$, which is consistent with the conclusions from decay measurements; (ii) the spectroscopic factor of the state is determined, and (iii) the data are reasonably well reproduced by DWBA calculations. The inclusion of two-step and compound nuclear processes does not improve the overall reproduction of the data and the magnitude of the spectroscopic factor is essentially unaffected, indicating thereby that the state is primarily populated by a one-step process.

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