Level Structure of Ar^{37} from the $Ar^{36}(d,p)Ar^{37}$ Reaction*

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The level structure of Ar^{37} has been investigated by bombarding Ar^{36} gas enriched >99% with 15-MeV deuterons. Nineteen energy levels up to an excitation energy of 6.5 MeV were found. For eight of the levels angular distributions up to 145° were taken and l_n value and spectroscopic factors were determined. The 1.60-MeV level was found to be populated via $l_n=3$ transition and the 2.50-, 3.55-, 4.49-, and 5.18-MeV levels via $l_n=1$. From the j dependence of the $l_n=1$ distributions, the spin values of these states were determined. The mean energies of the shell-model configurations were $1f_{7/2}$, 1.60 MeV; $2p_{3/2}$, 2.95 MeV; and $2p_{1/2}$, 5.04 MeV. The rate of change of the binding energy and the symmetry energy is discussed by comparing these results to the Ar^{41} energy spectrum.

INTRODUCTION

In this study, the stripping reaction $Ar^{36}(d,p)Ar^{37}$ with 15-MeV deuterons was performed on the Ar^{36} gas target. The level structure of Ar^{37} has already been studied by various reactions such as $S^{34}(\alpha,n)$,[1] $Cl^{37}(p,n)$,[2] $K^{39}(d,\alpha)$ and $Cl^{35}(He^3,p)$,[3] $K^{37}(\beta^+)$,[4] and $Ar^{36}(d,p)$ with low-energy deuterons.[5] This study, however, provides additional information about the energy and spin of the levels of Ar^{37}, as well as the transition intensities leading to them. This additional information is very important for the study of the nuclear structure of this nucleus which has a single neutron hole in the otherwise closed d-s shell, and is also needed in the calculation of the results obtained in the solar neutrino experiments.[6]

With the aid of distorted-wave Born approximation (DWBA)[7] calculations, definite predictions were made about the value of the angular-momentum transfer of the captured neutron for the strongly excited levels, and several assignments thus obtained in this study differ from previously assigned values.[5]

Recently it has been reported that for deuteron energies from 8 to 12 MeV the angular distributions of the protons in stripping reactions show j-dependent effects,[8] especially for $l_n=1$. In Ar^{37}, if sufficient bombarding energy is available, the $p_{3/2}$ and $p_{1/2}$ levels of the (28–50) neutron shell should be observed. Angular distributions were taken up to 145° and spin assignments for four excited states obtained via $l_n=1$ angular-momentum transfer are proposed.

EXPERIMENTAL PROCEDURE

Samples of Ar^{36} isotopically enriched to >99% were used in the present experiment. The gas cell, mounted at the center of the scattering chamber, consists of a brass cylinder with a thin (0.15 mil) Havar[9] window which allows the incident beam to pass through the cell and the reaction products to exit at any lab angle from 0° to 180°. The window is secured and sealed to the cell by a clamp and O-ring arrangement. Up to $\frac{1}{2}$ atm pressure of target gas may be used without rupturing the window. (In this experiment, the pressure of the target gas was only about 120 mm Hg to secure good resolution and accurate energy calibration.)

A magnetically-analyzed and well-collimated incident beam of ~15-MeV deuterons was obtained from the University of Pittsburgh's cyclotron. The scattering chamber could be remotely controlled to pivot about a point in the beam path so that the zero angle could be adjusted. Auxiliary detectors placed on the periphery of the chamber at +15° and −15° assist in determining the zero angle. These detectors monitor the elastically scattered deuterons from the target; and when the zero angle is correct, they have equal counting rates.

The scattering chamber has a motorized turntable which can be rotated remotely to any lab angle. The solid-state detectors used in this study were mounted to the turntable so that angular distributions could be very conveniently obtained. Collimating slits were placed between the target cell and the solid-state detectors, and were also rotated with the solid-state detectors.

Angular distributions were obtained on two separate occasions. The detector used in the first run was a 3-mm Li-drifted silicon detector. This detector had a deep enough depletion layer to detect the ground state protons for Ar^{37} having a Q value of 6.55 MeV. Proton groups up to an excitation energy of 6.5 MeV were observed. The resolution obtained was approximately

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[1] J. W. Nelson, E. B. Carter, G. E. Mitchell, and R. H. Davis, Phys. Rev. **129**, 1723 (1963).

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[3] J. M. McNally, Bull. Am. Phys. Soc. **9**, 553 (1964).

[4] R. W. Kavanagh and D. R. Gooseman, Phys. Letters **12**, 226 (1964).

[5] S. S. Yamamoto and F. E. Steigert, Phys. Rev. **121**, 600 (1961).

[6] John N. Bahcall, Phys. Rev. **135**, B137 (1964); R. Davis, Jr., Phys. Rev. Letters **12**, 303 (1964).

[7] DWBA parameters used in this work are: deuterons: $V=112.8$ MeV, $r_0=1.021$ F, $a=0.864$ F, $W=79.2$ MeV, $r_0'=0.147$ F, $a'=0.444$ F; protons: $V=45.6$ MeV, $r_0=1.250$ F, $a=0.65$ F, $W=48.0$ MeV, $r_0'=1.25$ F, $a'=0.47$ F. The optical potentials are of Saxon form with surface derivative absorption.

[8] L. L. Lee, Jr. and J. P. Schiffer, Phys. Rev. Letters **12**, 108 (1964).

[9] Obtained from Hamilton Watch Company, Lancaster, Pennsylvania.

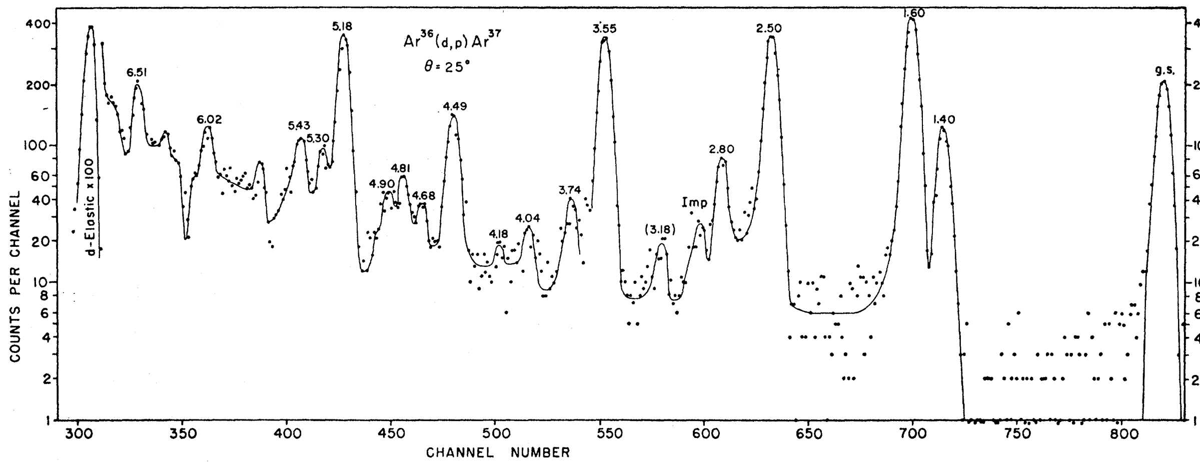

FIG. 1. Energy spectrum of protons from $Ar^{36}(d,p)Ar^{37}$ reaction. The excitation energies of the final nucleus are given in MeV units.

60 keV. An angular distribution was taken at angles up to 60°. At a later time when the angular distributions for the strong peaks were measured up to 150°, the Li-drifted silicon detector was not available to us. For this run we used a 1- and a 2-mm silicon surface-barrier detectors mounted in a telescope arrangement and added the pulses from each to obtain the energy spectrum. The energy resolution in this case was approximately 80 keV. The pulses were amplified by means of Ortec linear amplifiers and energy-analyzed by a Nuclear Data model 160M multichannel analyzer.

RESULTS AND DISCUSSION

The results of the stripping reaction on Ar^{36} are listed in Table I. This table lists the excitation energies, the values of assigned l_n, the values of assigned spins, the absolute cross-sections and the spectroscopic factors. The latter are determined by the relation

$$d\sigma/d\Omega = [(2j+1)/(2I+1)]\sigma(l_n,\theta,Q)S, \qquad (1)$$

in which $d\sigma/d\Omega$ is the experimental absolute cross section at the first maximum of the angular distribution beyond 10°, j is the spin of the final state observed in the stripping process, I is the spin of the target nucleus, $\sigma(l_n,\theta,Q)$ is the single-particle cross section calculated by DWBA, and S is the spectroscopic factor.

A typical spectrum of the protons from $Ar^{36}(d,p)Ar^{37}$ is shown in Fig. 1. The angular distributions for 8 of these levels are given in Fig. 2. To the right of these distributions are the energy and assigned value of l_n for these levels. Angular distributions for the remaining 11 peaks were not obtained as the transitions are relatively weak, and therefore no assignment could be made for them.

TABLE I. Summary of results for energy level scheme of Ar^{37}.

	E (MeV)	l_n	J^π	$d\sigma/d\Omega$ max (mb/sr)	S
0	g.s.	2	$\frac{3}{2}^+$	2.10	0.43
1	1.40	0	$\frac{1}{2}^+$	0.82	0.14
2	1.60	3	$\frac{7}{2}^-$	6.75	0.82
3	2.50	1	$\frac{3}{2}^-$	14.3[a]	0.45
4	2.80	1 2			
5	(2.18)				
6	3.55	1	$\frac{3}{2}^-$	12.3[a]	0.36
7	3.74				
8	4.04				
9	4.18				
10	4.49	1	$\frac{1}{2}^-$	2.74[a]	0.16
11	4.68				
12	4.81				
13	4.90				
14	5.18	1	$\frac{1}{2}^-$	1.07[a]	0.59
15	5.30				
16	5.43				
17	6.02				
18	6.51				

[a] Taken at 20°.

The Ground-State Transition, $l_n = 2$

This transition is undoubtedly an $l_n = 2$ as can be seen in Fig. 3 from the comparison of the experimental angular distribution to the angular distribution predicted by the DWBA calculation. The $\frac{3}{2}^+$ assignment rather than a $\frac{5}{2}^+$ assignment for this level is based on the following arguments:

(1) According to the shell model, Ar^{36} has 2 neutron holes in the $d_{3/2}$ subshell; whereas the $d_{5/2}$ subshell which lies lower in the shell is already full in this region and the addition of a neutron into it is very improbable.

(2) The ${}_{20}Ca_{19}{}^{39}(\beta^+){}_{19}K_{20}{}^{39}$, ${}_{18}Ar_{17}{}^{35}(\beta^+){}_{17}Cl_{18}{}^{35}$ and ${}_{17}Cl_{16}{}^{33}(\beta^+){}_{16}S_{17}{}^{33}$ represent beta decays between mirror nuclei all having the $\frac{3}{2}^+$ assignments for their ground states and have log ft values of 3.5, 3.8, and 3.7, respectively, for their super-allowed ground-state transi-

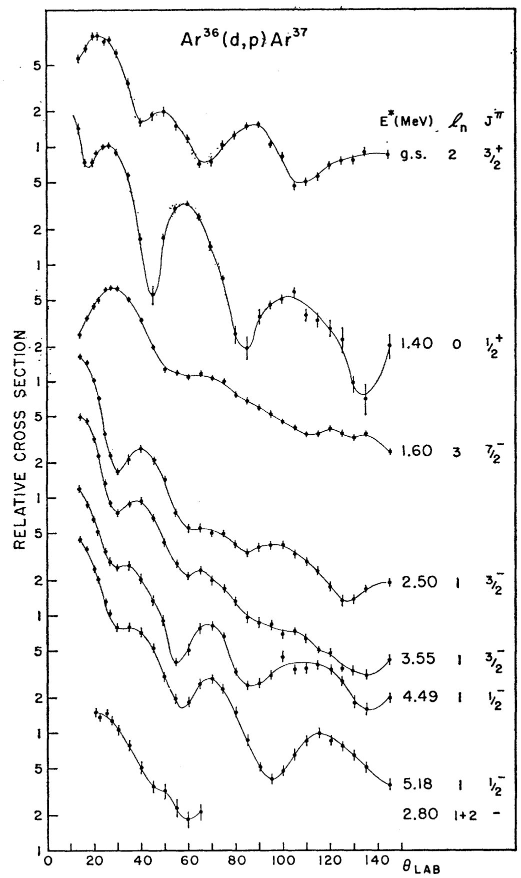

FIG. 2. Angular distribution of protons from $Ar^{36}(d,p)Ar^{37}$ reaction for eight proton groups are shown. To the right of these distributions the excitation energies, angular momentum transfer, and the spin of the final nucleus are indicated.

tions.[10] The K^{37} nucleus also has the $\frac{3}{2}^+$ spin assignment for its ground state and the log ft value for the ${}_{19}K_{18}{}^{37}(\beta^+){}_{18}Ar_{19}{}^{37}$ ground-state decay is found to be 3.66.[4] This indicates that the decay is of the same nature as the above decays, and therefore must lead to the $\frac{3}{2}^+$ state of Ar^{37}.

(3) From the study by Robertson *et al.*[11] on the hyperfine structure in the arc spectrum of Ar^{37}, the nuclear spin was determined to be $J=\frac{3}{2}$.

(4) A spectroscopic factor of $S=0.43$ is obtained for the ground state transition under the assumption that this level has a $J=\frac{3}{2}$ spin assignment. This value is in accord with the 2-neutron-hole configuration of Ar^{36}.

The 1.40-MeV State $l_n=0$

This state is populated via a $l_n=0$ transition and therefore is certainly a $s_{1/2}$ state. The transition intensity is rather small, $S=0.13$, but indicates that the $s_{1/2}$ subshell is not full in this nucleus. This is not surprising, since even beyond the closed-shell configuration of Ca^{40}, the stripping reaction still populates this state.[12]

The 1.60-MeV State $l_n=3$

Our assignment of $l_n=3$ to the 1.60-MeV level is based on the following arguments:

(1) In Fig. 4, the comparison between the experimental angular distribution and the predicted DWBA angular distribution for $l_n=2$ and $l_n=3$ transitions is given. The angular distribution for $l_n=3$ transition has a remarkable fit whereas the angular distribution for $l_n=2$ does not agree with the experiment even for the small angles.

(2) Further evidence for a $l_n=3$ assignment is the fact that the angular distribution is almost identical to the angular distribution from the stripping reaction on Ar^{40} leading to the ground state of Ar^{41}, which is known to be an $f_{7/2}$ state and therefore must proceed via $l_n=3$ transition. This comparison is likewise shown in Fig. 4.

(3) An argument against a $l_n=2$ assignment and for a $l_n=3$ assignment comes from the beta decay of Kr^{37} which was recently re-examined by Kavanagh and Gooseman.[4] This β^+-decay populates only the $d_{3/2}$ ground state (g.s.) and a $d_{5/2}$ state at the excitation energy of 2.80 MeV. If the 1.60-MeV state were also

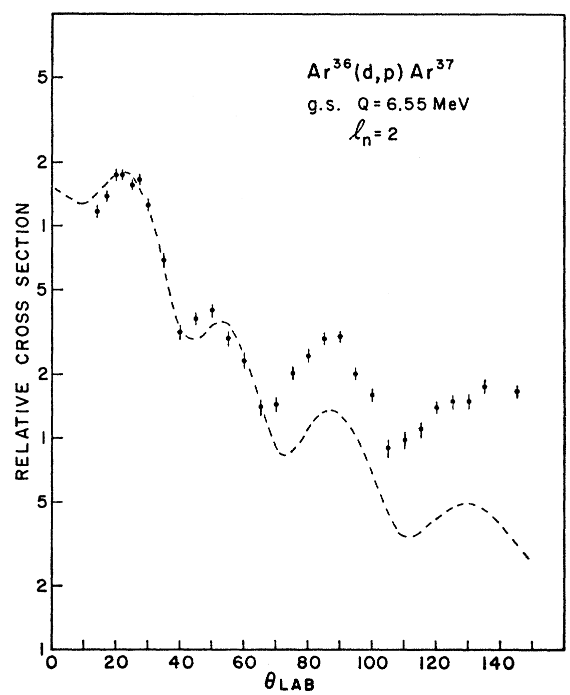

FIG. 3. Angular distribution of protons for the ground-state transition is compared with the DWBA prediction for $l_n=2$.

[10] Nuclear Data Sheets, compiled by K. Way *et al.* (National Academy of Sciences—National Research Council, Washington, D. C.).

[11] Merton M. Robertson and J. E. Mack, Bull. Am. Phys. Soc. **5**, 411 (1960).

[12] E. Kashy, T. W. Condon, and B. F. Bayman, Bull. Am. Phys. Soc. **10**, 70 (1965).

a d state of the $(d_{3/2})^3$ configuration of Ar^{37}, there is no simple reason why the β^+-decay would not populate it.

(4) The last argument is based on the transition intensity leading to this level. The assignment of $f_{7/2}$ to this level yields a spectroscopic factor of 0.82 which is quite reasonable. If we consider a $d_{5/2}$ assignment[6] to this level, the spectroscopic factor is 0.69 which is rather unreasonable since the $d_{5/2}$ subshell should be full or nearly full in Ar^{36}.

The assigned $l_n=2$ for this transition obtained by Yamamuto and Steigert[5] could be in error as their bombardment energy was rather low ($E_d=4$ MeV). They could not resolve very well the 1.60- and 1.40-MeV states, and they used plane-wave Born approximation to fit their data.

Our $J=\frac{7}{2}$ spin assignment to the 1.60-MeV state is based on the fact that the energy difference between the $f_{7/2}$ and $f_{5/2}$ states, due to the spin-orbit interaction, is about 6.5 MeV[13] and it is rather unlikely that the $f_{5/2}$ level is populated by stripping reaction in Ar^{37} at this low excitation energy. Further evidence for the $J=\frac{7}{2}$ assignment for the 1.60-MeV state comes from the remarkable similarity between the angular distribution of the protons to this state and to the well-known $J=\frac{7}{2}$ ground state of Ar^{41} by the $Ar^{40}(d,p)Ar^{41}$ reaction (Fig. 4). It was already pointed out[14] that $l_n=3$ transitions leading to $f_{7/2}$ and $f_{5/2}$ states have rather different angular distribution even at small angles.

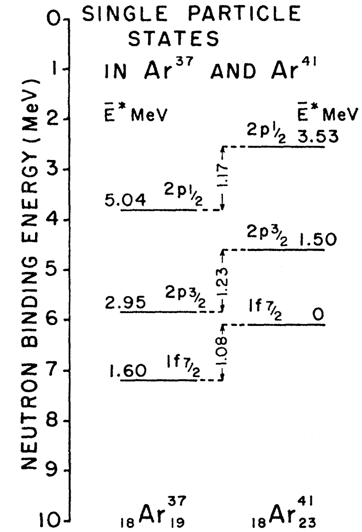

FIG. 5. The location of the single-particle states in Ar^{37} and Ar^{41}. The mean energies for Ar^{41} were taken from Ref. 16.

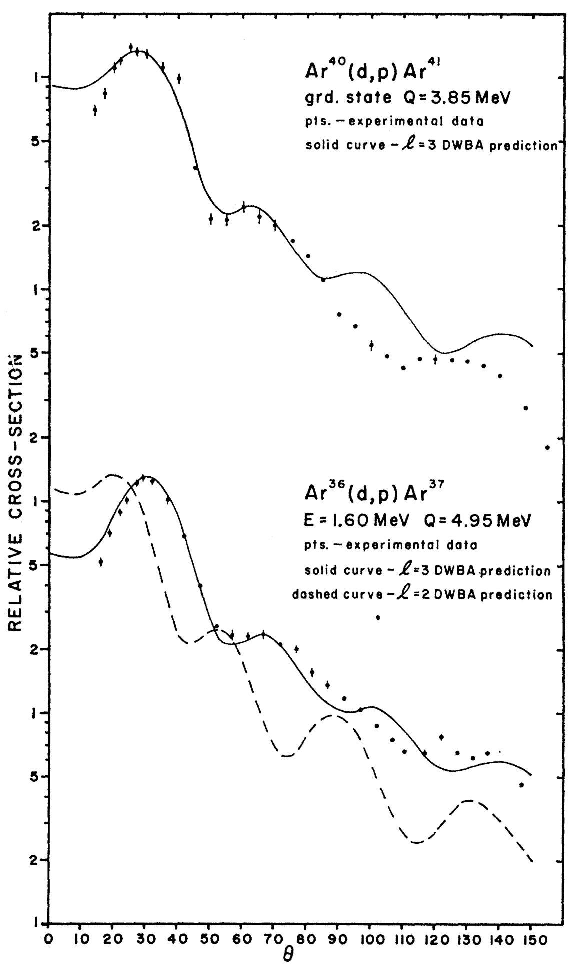

FIG. 4. Angular distribution of protons to the ground state of Ar^{41} known to go via $l_n=3$ transition and to the 1.60-MeV state in Ar^{37} are given. These distributions are compared with the DWBA predictions for $l_n=3$ transitions (solid curve) and for $l_n=2$ transition (dashed curve).

J Dependence of the Angular Distribution for the 2.50-, 3.55-, 4.49-, and 5.18-MeV $l_n=1$ States

In stripping reactions with 12-MeV deuterons the angular distribution of the protons for $l_n=1$ transitions have a very strong j dependence.[8] This effect appears especially for backward angles. This work performed with 15-MeV deuterons likewise shows a j-dependence effect for $l_n=1$ transitions; however, it does not appear as strong as it did at 12 MeV. The angular distributions for the $l_n=1$ levels in Ar^{37} can be seen in Fig. 2. The cross sections for the (d,p) reactions leading to levels which were given the assignment $J=\frac{3}{2}$ are very slowly varying at backward angles as compared to those which were assigned $J=\frac{1}{2}$. Using this criterion the levels at the excitation energies of 2.50 MeV and 3.55 MeV are $p_{3/2}$ states and the levels at the excitation energies of 4.49 and 5.18 MeV are $p_{1/2}$ states. These assignments are in agreement with the shell model which predicts that the $p_{3/2}$ state should lie lower in energy than the $p_{1/2}$ state. A rather complete theoretical calculation for the location of the different $l_n=1$ states in Ar^{41} was

[13] B. L. Cohen, P. Mukherjee, R. H. Fulmer, and A. L. McCarthy, Phys. Rev. 127, 1678 (1962).

[14] J. P. Schiffer (private communication).

performed by Shadmi and Talmi,[15] and the same structure in the energy spectrum was found.

One more angular distribution up to 65° for the 2.80-MeV level was attempted. Only if we assume that this level is an unresolved doublet can the experimental angular distribution be fitted to the DWBA prediction. A good fit can be obtained by adding $l_n=1$ and $l_n=2$ angular distributions with equal intensities. For the rest of the levels reported in this work, no angular distributions could be constructed, as they are weakly excited.

Location of the Single-Particle State in Ar^{37}

The mean energy of the single-particle (s.p.) states in Ar^{37}, which has a closed shell minus one neutron, can be determined by the following procedure. If one is able to detect all levels with a given spin value, e.g., obtaining the theoretical spectroscopic factor for the transition, then the location of the single-particle level can be obtained from the following equation:

$$\bar{E}=\sum E_j S_j / \sum S_j . \quad (2)$$

The only $f_{7/2}$ state that has been found and which has all the expected transition intensity is the 1.60 MeV state, therefore $\bar{E}(f_{7/2})=1.60$ MeV. The same procedure yields $\bar{E}(f_{7/2})=1.60$ MeV. Two levels were assigned as $p_{3/2}$ levels and the sum of their spectroscopic factors is 0.81. Although there may be more $p_{3/2}$ levels, they will be only weakly populated. If we take into the calculation only the two strong transitions leading to the 2.50- and 3.55-MeV levels, the mean energy will be $\bar{E}(p_{3/2})=2.95$ MeV. Similar consideration leads to $\bar{E}(p_{1/2})=5.04$ MeV.

A comparison between these mean energies and the mean energies for similar levels in Ar^{41} which were obtained by Kashy[16] is given in Fig. 5. The $2p_{3/2}$–$2p_{1/2}$ energy interval is almost the same in the two nuclei, and very close to the value of 2.04 MeV obtained[17] in Ca^{40}. The $1f_{7/2}$–$2p_{3/2}$ energy interval is slightly larger in Ar^{41} compared to Ar^{37}. This is expected as the $f_{7/2}$ subshell is already filling in Ar^{41} and therefore it is pushed downward. The large energy difference between the location of the s.p. states in Ar^{37} compared to Ar^{41} is a result of two factors[18]: the rate of change of binding energy with the mass number which can be written as

$$dE/dA=-k/A\,, \quad k=13 \text{ MeV}, \quad (3)$$

which tends to lower the s.p. states in Ar^{41} by 1.3 MeV; and the symmetry energy effect which can be written as

$$dE=b(N-Z)/A \text{ MeV}, \quad b=27 \text{ MeV}, \quad (4)$$

which tends to raise the energy of these states of Ar^{41} compared to those of Ar^{37} by 2.7 MeV with a net effect of a 1.4-MeV rise in energy.

The experimental results obtained are +1.23 MeV for the $2p_{3/2}$ states and 1.17 MeV for the $2p_{1/2}$ states. A better agreement with theoretical predictions can be obtained by using a lower value for b as was already discussed by Cohen,[18] or by using the higher values for k obtained by theoretical calculation using Saxon potentials.[19]

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[16] E. Kashy, A. M. Hoogenboom, and W. W. Buechner, Phys. Rev. **124**, 1917 (1961).

[17] T. A. Belote, E. Kashy, A. Sperduto, H. A. Enge, and W. W. Buechner, Argonne National Laboratory Report No. ANL-6848, 1964 (unpublished), p. 172.

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