Proton-Induced Reactions on ^{40}Ar and Analogs of ^{41}Ar Levels*

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(Received 29 March 1968)

Excitation functions have been measured at several angles between 58° and 161° for the ^{40}Ar (p,p) ^{40}Ar, ^{40}Ar (p,p') ^{40}Ar* (first excited level), and ^{40}Ar (p,α) ^{37}Cl reactions. Differential cross sections were measured in 3-keV steps with an energy resolution of 3 keV for incident proton energies from 1.81 to 4.35 MeV. The structures observed in the proton inelastic scattering yields and α-particle yields were not completely resolved. Averaging the cross sections with an interval of ~25 keV revealed a residual resonance structure with widths and spacings between 10 and 40 keV, interpreted as analog resonances. Seventeen resonances are included in an analysis of the averaged cross sections for proton elastic and inelastic scattering. Eight of these correspond to known levels of ^{41}Ar. Reduced proton widths of the eight analogs imply neutron spectroscopic factors for bound levels of ^{41}Ar in agreement with those extracted from an analysis of the ^{40}Ar (d,p) ^{41}Ar reactions.

I. INTRODUCTION

PROTONS incident on a target having isobaric spin T_0 can excite compound nucleus states having isobaric spin $T=T_0\pm\frac{1}{2}$. The identification[1] of resonances in proton elastic and inelastic scattering having $T=T_0+\frac{1}{2}$ provides an effective means of studying the $T_0+\frac{1}{2}$ configurations. Since the ground and low excited levels of the neutron plus target system also have $T=T_z=T_0+\frac{1}{2}$, these special proton resonances are analogs[1] of the low-lying bound states of the neutron plus target system.

In addition to the interest in spectroscopy through analogs, there is special interest in the magnitudes and shapes of the proton scattering anomalies, or analogs, which are evident after energy-averaging over the dense $T=T_0-\frac{1}{2}$ states. The resonances in the energy-averaged cross sections represent the sharing of the analog's single-particle strength by those $T_0-\frac{1}{2}$ states having the same spin and parity as the analog. The measurements and analysis reported here were completed in order to study resonances in ^{41}K which are analogs of bound levels in ^{41}Ar and to explore several questions about resonances in energy-averaged cross sections. The resonances in the ^{40}Ar$+p$ reaction cross sections are then the subjects of this study.

Anomalies in the elastic scattering cross sections at $E_p=1.88$ and 2.45 MeV were studied by Barnard and Kim[2] and assigned as $\frac{3}{2}^-$ and $\frac{1}{2}^+$, respectively. The energy region near 1.88 MeV was also studied for ^{40}Ar$(p,p)^{40}$Ar by Cohen-Ganouna *et al.*[3] In the energy range from 1.63 to 2.60 MeV the ^{40}Ar$(p,p)^{40}$Ar and ^{40}Ar$(p,\alpha)^{37}$Cl reactions were investigated by Keyworth *et al.*[4] with an energy resolution of ~0.2 keV. In that experiment, the widths and spacings of 69 levels were determined and the two analog configurations observed by Barnard and Kim were completely resolved into their $T=T_0-\frac{1}{2}$ "fine-structure" levels.

The data of Young *et al.*[5] on the ^{40}Ar$(p,n)^{40}$K reactions between 2.4- and 5-MeV incident energy suggested that a detailed correspondence could be made between many of the strong (p,n) resonances and bound levels of ^{41}Ar. Finally, a preliminary survey of the resonance structure between 3.5- and 5-MeV incident proton energy was completed by Slivinsky and Winter,[6] who measured excitation functions with an energy resolution of 18 keV. They reported excitation functions for protons from elastic and inelastic scattering and for α particles from the ^{40}Ar$(p,\alpha)^{37}$Cl reaction. Many broad resonances were observed, but their data were not detailed enough[6] to permit analysis.

In the present experiment, differential cross sections for ^{40}Ar$(p,p)^{40}$Ar, ^{40}Ar$(p,p_1)^{40}$Ar*, and ^{40}Ar$(p,\alpha)^{37}$Cl have been measured for incident proton energies from 1.8 to 4.35 MeV with an energy resolution of $\lesssim 3$ keV. Broad resonances are evident in the elastic scattering cross sections and as enhancements of the strength of the inelastic scattering cross sections. They are interpreted as analog resonances. The analog widths are extracted directly from the inelastic scattering cross sections and then the cross sections are averaged and analyzed to obtain other properties of the $T=\frac{5}{2}$ analogs. Seventeen of the resonances observed in the energy-averaged cross sections for proton elastic and inelastic scattering have been analyzed. Most of these correspond to resonances of the ^{40}Ar$(p,n)^{40}$K reactions[5] and eight of them are identified as analogs of known levels of ^{41}Ar. A multiresonance analysis spans most of the energy interval between 3.3- and 4.1-MeV incident proton energy. The averaging interval required to eliminate the $T=\frac{3}{2}$ structure, 25 keV, is comparable to the analog widths.

The analogs at 1.88 and 2.45 MeV, which were resolved into their $T=\frac{3}{2}$ components by Keyworth *et*

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[1] J. D. Fox, C. F. Moore, and D. Robson, Phys. Rev. Letters **12**, 198 (1964).
[2] A. C. L. Barnard and C. C. Kim, Nucl. Phys. **28**, 428 (1961).
[3] J. Cohen-Ganouna, M. Lambert, and J. Schmouker, Nucl. Phys. **40**, 82 (1963).
[4] G. A. Keyworth, G. C. Kyker, Jr., E. G. Bilpuch, and H. W. Newson, Nucl. Phys. **89**, 590 (1966).
[5] T. M. Young, J. D. Brandenberger, and F. Gabbard, following paper, Phys. Rev. **172**, 1148 (1968).
[6] V. W. Slivinsky and R. G. Winter, Nucl. Phys. **A102**, 295 (1967).

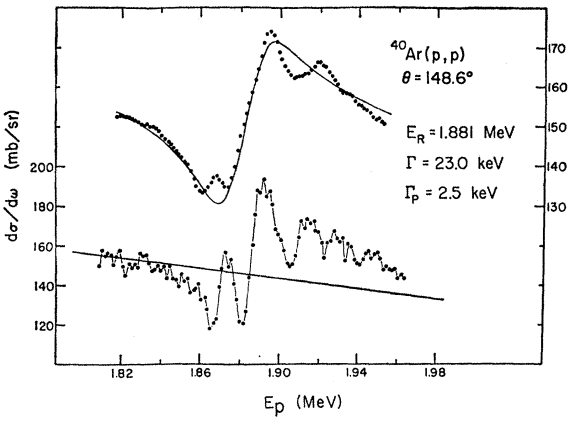

FIG. 1. The 1.88-MeV analog resonance. On this and all subsequent figures the lower set of points are data taken with <3-keV incident energy spread and are referred to the left ordinate. The upper points are the data after averaging over 25 keV, referred to the right ordinate. The smooth curve through the upper data is the resonance fit and the curve through the lower data gives the Coulomb scattering cross sections.

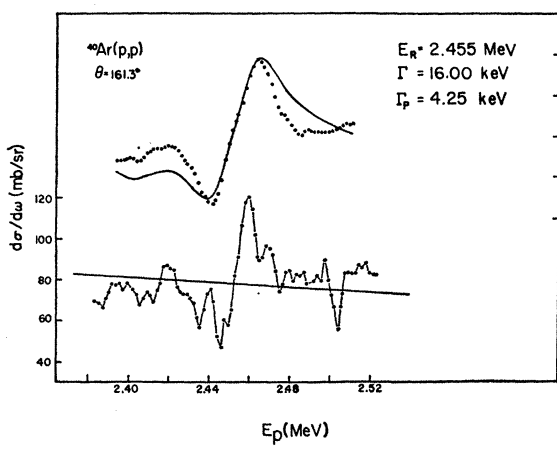

FIG. 2. The 2.46-MeV analog resonance and fit. The caption of Fig. 1 applies to this and all subsequent figures. The abscissa scales are laboratory energies and all indicated angles are laboratory angles.

al.,[4] are separately analyzed to test the method of analysis of energy-averaged cross sections used in this work. The analog widths obtained here are related to the sums of $T=\frac{3}{2}$ widths[4] in a manner described by Robson.[7] Other parameters of the resonances are compared to the expectations of the external mixing model of Robson. The parameters obtained for the two analogs will be shown to be in agreement with results of the high-resolution experiment,[4] consistent with the external mixing hypothesis,[7] and provide single-particle spectroscopic factors for two levels of ^{41}Ar in good agreement with those obtained from analysis of the ^{40}Ar$(d,p)^{41}$Ar reactions.[8,9] The multiresonance analysis of the structure between 3.3 and 4.1 MeV also provides spectroscopic factors in agreement with those inferred[8] from the ^{40}Ar$(d,p)^{41}$Ar reaction cross sections.

II. EXPERIMENTAL PROCEDURE

An argon target of natural isotopic abundance (99.6% ^{40}Ar) was contained in a sealed gas scattering chamber and bombarded with the proton beam from the University of Kentucky 5.5-MeV Van de Graaff accelerator. The scattering chamber was based on the design of Feldl, Meriwether, Choppin, and Fox.[10] The protons passed through incident beam collimating apertures and entered the scattering chamber through a 0.002-mil nickel entrance window. The incident beam collimators have an angular acceptance of 40 min. The chamber was filled to a pressure of 3–4 Torr. With such a thin entrance window, small leaks permitted argon to leak from the chamber, but at a rate <0.03 Torr/h. The protons emerged from the chamber through a 0.05-mil nickel exit foil for collection in an evacuated Faraday cup. The chamber pressure was determined with a differential oil manometer filled with Octoil-S, having a density of 0.9762 ± 0.0014 g/cc. The manometer was read with a carefully leveled Gaertner cathetometer. The argon was purified by flowing it through an activated charcoal trap at dry-ice temperature as it entered the chamber. The number of incident particles per run was determined by integrating the beam with a cycling current integrator of the Lewis and Collinge[11] design, calibrated to $\pm0.5\%$. Scattered protons and α particles from the (p,α) reaction were detected in four silicon surface-barrier detectors which were mounted on a rotating plate inside the scattering chamber. The detector collimators consisted of a vertical rectangular "front" slit and a circular "rear" aperture. With this detection system the published proton-proton scattering cross sections of Knecht, Dahl, and Messelt[12] were reproduced to within 2%.

The particle spectra were sorted and recorded in a Packard 4096-channel pulse-height analyzer. Proton yields were corrected for both dead time in the counting electronics and the leakage of argon from the scattering chamber. The gas-loss correction to the yields was usually less than 4%. The time required to take each data point was approximately 15 min and the total charge per data point collected in the Faraday cup was 1600μC.

Typically the yields for the elastically scattered protons ranged from about 5000 to 70 000 counts, with statistical uncertainties less than $\pm1.5\%$. The yields for the inelastically scattered protons ranged from around 70 to 1000 counts. Usually the statistical un-

[7] D. Robson, Phys. Rev. **137**, B535 (1965).
[8] E. Kashy, A. M. Hoogenboom, and W. W. Buechner, Phys. Rev. **124**, 1917 (1961).
[9] W. R. Coker (private communication); M. Cosack *et al.* (to be published).
[10] E. J. Feldl, J. R. Meriwether, G. R. Choppin, and J. D. Fox, Nucl. Instr. Methods **22**, 333 (1963).
[11] I. A. D. Lewis and B. Collinge, Rev. Sci. Instr. **24**, 1113 (1953).
[12] David J. Knecht, Per F. Dahl, and S. Messelt, Phys. Rev. **148**, 1031 (1966).

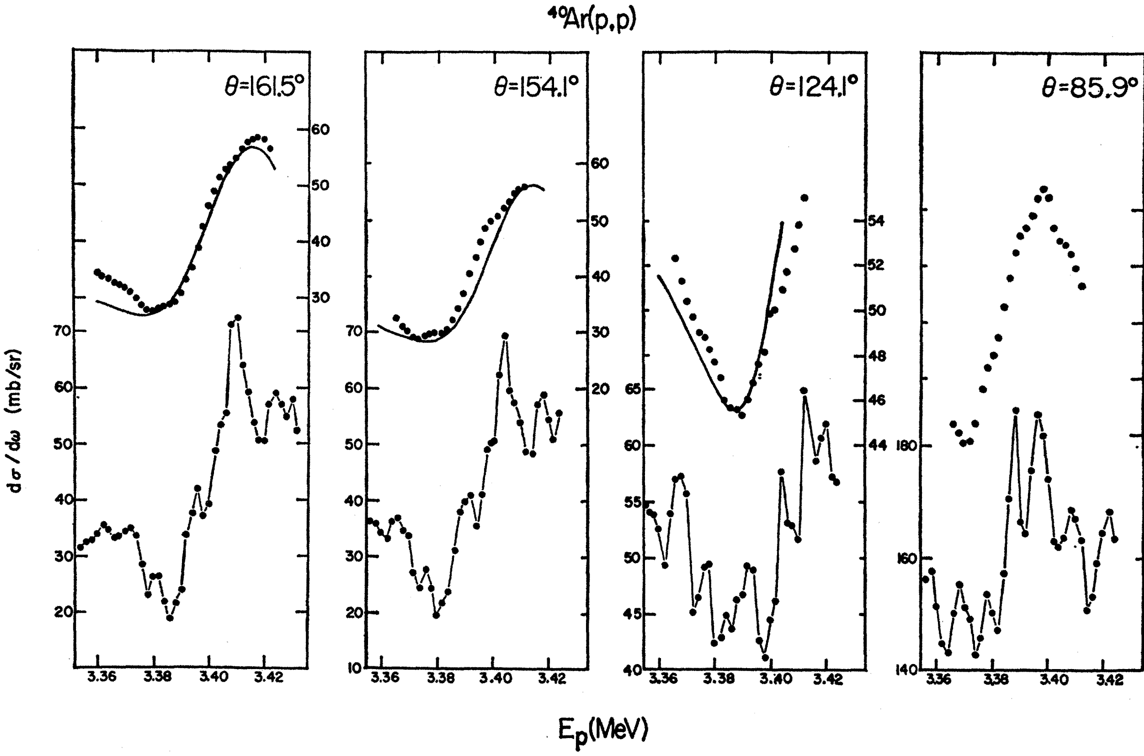

FIG. 3. The 3.39-MeV elastic scattering resonance and calculated fits. The Coulomb cross sections are not shown. Each angle has its own ordinate scale.

certainties for the inelastically scattered protons were about ±5%. The uncertainty in the integration of the beam current was ±0.5%, and the error in the measurements of the argon pressure and the dimensions of the detector collimators was less than 1%. The detector collimator dimensions were used to calculate the gas scattering geometry factors with the formulas of Silverstein.[13] The over-all uncertainties in the inelastic scattering cross sections are essentially the statistical errors in the yields.

At the bombarding proton energy of 2.0 MeV, the average energy loss due to the entrance foil and argon gas was 7.9 keV. The calculation of energy loss in the foil and gas used published tables[14] of the Vavilov distribution. The calculated energy-straggling had a full width at half-maximum (FWHM) of 2.3 keV. For a detection angle of 90°, the detector collimators allowed the counting of particles scattered from 0.885 cm of argon. At 2.0 MeV, the proton energy loss in this target volume was 0.62 keV. Therefore, at 2.0 MeV the total spread in the energy of the protons due to the entrance foil and argon was less than 3.0 keV. The observed energy resolution was consistent with this estimate of energy spread in the incident beam.

[13] E. A. Silverstein, Nucl. Instr. Methods 4, 53 (1959).

[14] S. M. Seltzer and M. J. Berger, in *Studies in Penetration of Charged Particles in Matter* (U. S. Government Printing Office, National Academy of Sciences—National Research Council, Washington, D.C.), p. 187.

III. RESULTS

Differential cross sections for protons leaving ^{40}Ar in the ground and first excited state as well as α particles from the (p,α) reaction to the ground state of ^{37}Cl were measured at various laboratory angles ranging from 58.5° to 161.5° in the bombarding proton energy region from 1.81 to 4.35 MeV. In the elastic scattering excitation functions 27 prominent resonances were observed. These resonances are correlated quite strongly with the structure observed in the (p,n) reaction.[5] Of the observed resonances in the energy-averaged cross sections, 17 were analyzed and resonance parameters for each were extracted. Above 3.3 MeV the analog resonances were readily identified in the inelastic scattering cross sections, both averaged and unaveraged. The resonances treated in the analysis occur at incident proton energies of 1.88, 2.46, 3.39, 3.45, 3.49, 3.54, 3.58, 3.60, 3.65, 3.71, 3.74, 3.88. 3.90, 3.93, 3.96, 4.03, and 4.07 MeV. Differential cross sections are presented in Figs. 1–19. The elastic scattering yield at $\Theta_L = 58.5°$ in Fig. 8 is shown in arbitrary units. The problem of separating contaminant groups at small angles prevented accurate cross-section measurements at 58.5°.

A 20–26-keV energy average of the cross sections is shown in the upper portion of the figures. The unweighted average of 13 adjacent data points was plotted at the energy corresponding to the middle of the inter-

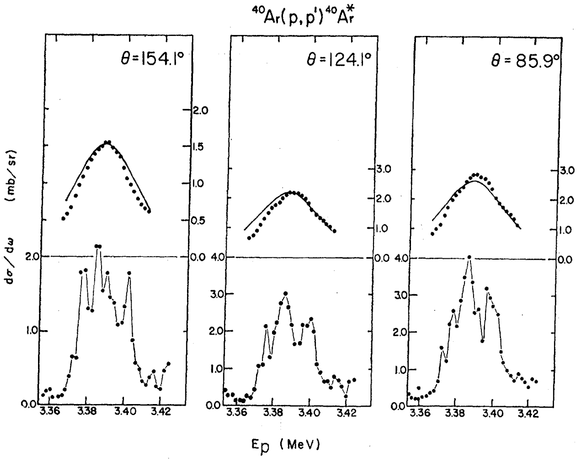

FIG. 4. Cross sections to the first excited level of ^{40}Ar near the 3.39-MeV resonance. Note the similarity of the fine structure at the three angles and the small cross sections off resonance in the unaveraged data.

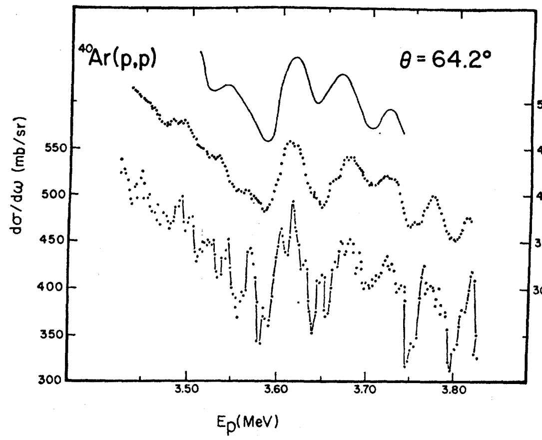

FIG. 6. Cross sections and fit including the resonances listed for Fig. 5. The fit has been displaced above its calculated position to facilitate comparison. If not displaced, it would run 5% above the averaged data. The Coulomb scattering cross sections are not shown.

val. The averaging interval was large enough to remove most of the "fine-structure" fluctuations, but small enough to reveal a residual resonance structure corresponding to states with widths between 9 and 35 keV. The widths of the assigned analogs were estimated from the structure observed in the unaveraged inelastic scattering cross sections, since the averaging interval was comparable to the widths of the analog states.

The analogs are not evident in the competing (p,α_0) channel. The (p,α_0) cross sections, in fact, show perhaps more fluctuations than do the inelastic scattering cross sections in the same energy region. This structure, however, appears not to be correlated with the structure in any other channel; i.e., cross correlations calculated between the (p,α_0), (p,p'), and (p,p) channels showed no correlation between the (p,α_0) and other channels. The same conclusion has been reached in Ref. 6.

Part of the interest in the ^{40}Ar$(p,\alpha)^{37}$Cl reactions stemmed from an early report[15] of an excited state in ^{37}Cl near an excitation energy of 0.84 MeV. For proton bombarding energies near 5 MeV, α groups were observed to the ground and 1.726-MeV levels of ^{37}Cl but no groups were observed to possible lower excited states, although the sensitivity of this test would have permitted observation of any group whose cross section was 0.1% or more of the ground-state cross section. The absence of an α group to the proposed 0.84-MeV state was noted in Ref. 6.

IV. ANALYSIS

The resonance analysis was based on a sum of single-level amplitudes of the Breit-Wigner form, except that

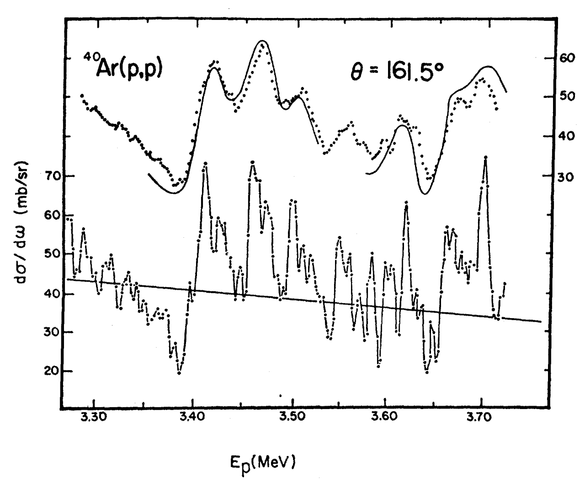

FIG. 5. Cross sections and multiresonance fit. Resonances are included at 3.39, 3.45, 3.49, 3.54, 3.58, 3.60, 3.65, 3.17, and 3.74 MeV. The fit is not good between 3.52 and 3.58 MeV and is not shown there.

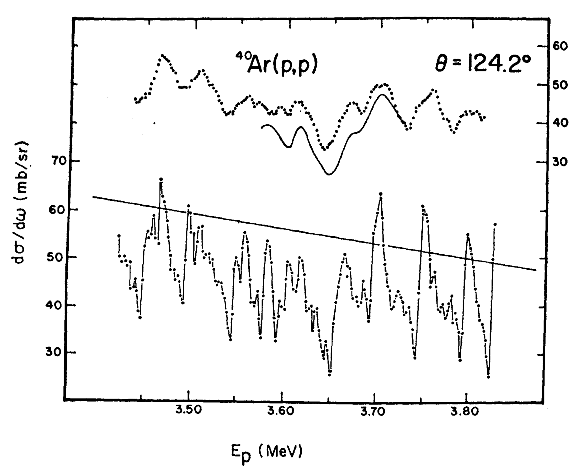

FIG. 7. Cross sections and fit including the resonances listed for Fig. 5. The fit has been displaced below its calculated position. If not displaced it would run 10–15% above the averaged data.

[15] P. M. Endt, C. H. Paris, A. Sperduto, and W. W. Buechner, Phys. Rev. **103**, 961 (1966).

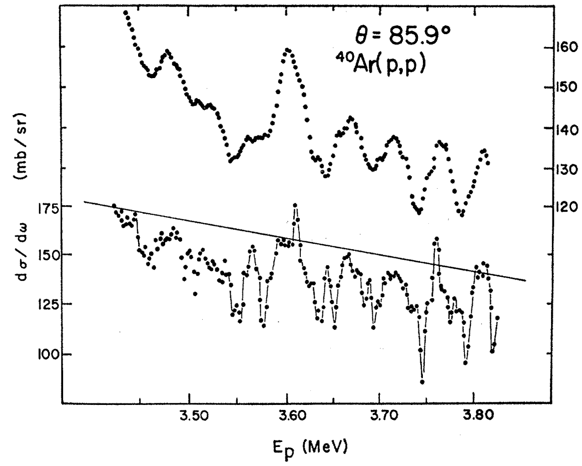

FIG. 8. Elastic scattering cross sections.

each amplitude was modified by the introduction of the resonance mixing phase of Robson.[7]

$$U_c = e^{2i\xi_l}\left[1+\sum_{\lambda}\frac{i\Gamma_{p,\lambda}e^{2i\phi_{c,\lambda}}}{E_\lambda - E - \frac{1}{2}i\Gamma_0}\right], \quad (1)$$

where ξ_l is the potential phase shift for the elastic scattering for the lth partial wave and $\phi_{c,\lambda}$ is Robson's resonance mixing phase. The quantities E_λ, Γ_0, $\Gamma_{p,\lambda}$ are, respectively, the energy, the total width, and elastic proton partial width of the resonance λ.

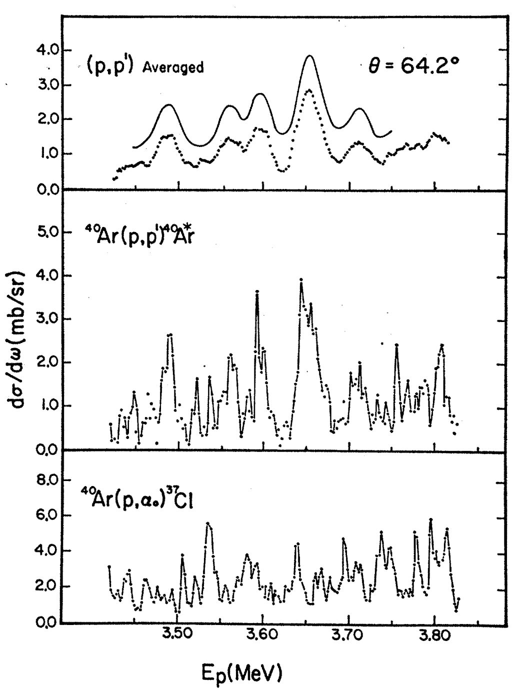

FIG. 9. Differential cross sections for inelastic scattering to the first excited level and for the (p,α) reaction to the ground level of ^{37}Cl. The multiresonance fit to the averaged (p,p') data includes the resonances listed for Fig. 5. $\theta = 64.2°$.

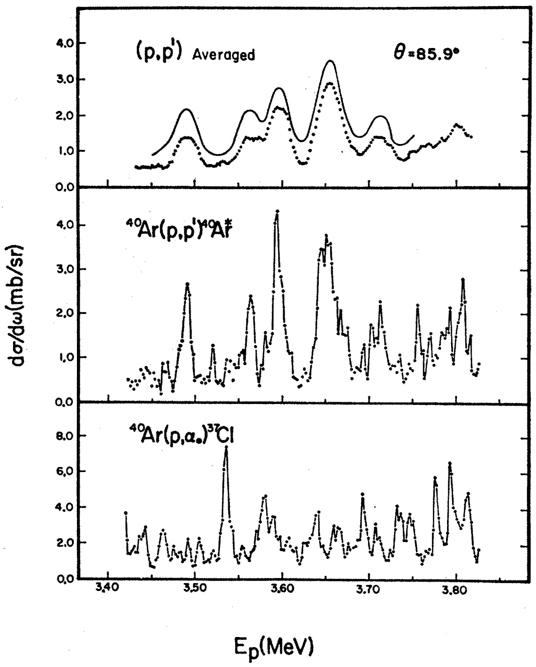

FIG. 10. Same as Fig. 9, except that $\theta = 85.9°$.

Cross sections were calculated using codes written for IBM-7040 and -360/50 computers at the University of Kentucky Computing Center. The variable parameters for each resonance were Γ_0, $\Gamma_{p,\lambda}$, E_λ, the spin and parity (J^π) of the compound state, and the orbital angular momentum of the incoming proton. The potential phase shifts and the resonance mixing phases were also adjusted. Fits to the measured cross sections were

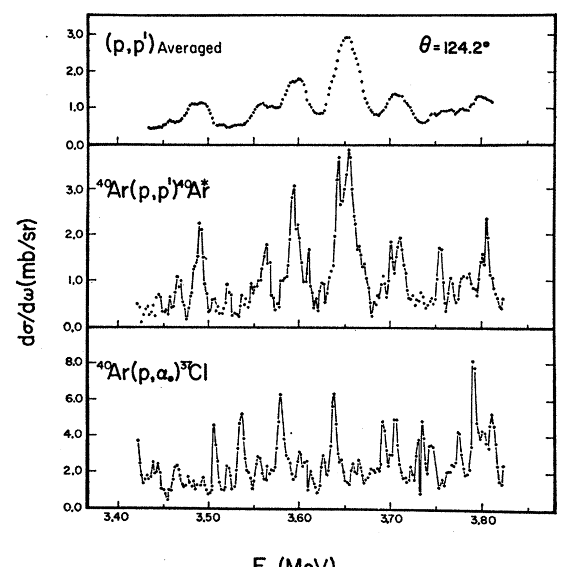

FIG. 11. Differential cross sections for inelastic scattering to the first excited levels of ^{40}Ar and for the (p,α) reaction to the ground level of ^{37}Cl. $\theta = 124.2°$.

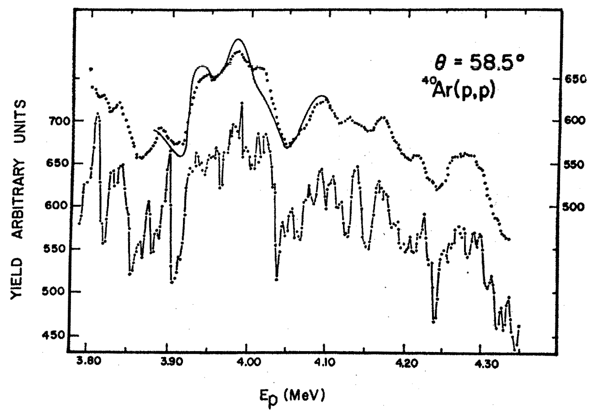

FIG. 12. Elastic scattering yields and multiresonance fit. At this angle and energy region, only the averaged yields have been normalized to the fit. Resonances are included at 3.88, 3.90, 3.93, 3.96, 4.03, and 4.07 MeV.

made by manually adjusting the parameters to give the best fit and also by using a search code written by Allison,[16] which varied the parameters simultaneously to obtain minimum deviation of the calculated from the measured cross sections.

Nonzero values for the resonance mixing phases were necessary for fits to most of the resonances of this work. The appearance of the phase $\phi_{c,\lambda}$ is a direct consequence of working with cross sections which are the result of an average over fine-structure states.[7,17] In several experiments, values of ϕ_c in the range $0\leq|\phi_c|\leq 30°$ have been observed. The analog of the first excited state of ^{49}Ca was observed[18] in proton scattering from ^{48}Ca and analyzed here to yield $E_\lambda=3.937$ MeV and $\phi_{c,\lambda}=+23°$. A fit could not be obtained with a small value for $\phi_{c,\lambda}$. The need for nonzero $\phi_{c,\lambda}$ has also been shown to be important for polarization measurements near isobaric analog states in heavy nuclei.[19]

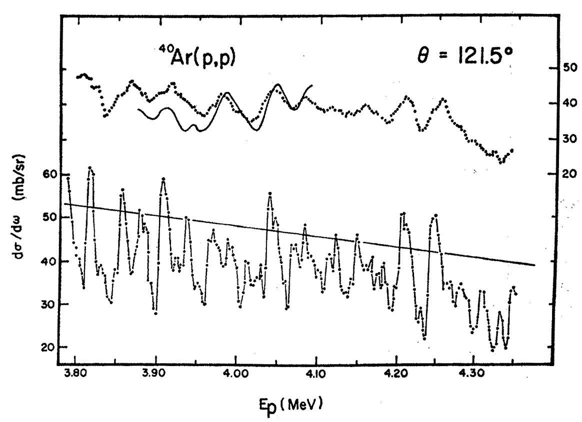

FIG. 13. Elastic scattering cross sections and fit including the resonances listed for Fig. 12. $\theta=121.5°$.

[16] J. L. Allison, Ph.D. thesis, University of Kentucky, 1966 (unpublished).

[17] D. Robson, in *Recent Progress in Nuclear Physics with Tandems* (Max-Plank Institut für Kernphysik, Heidelberg, Germany, 1966).

[18] K. W. Jones, J. P. Schiffer, L. L. Lee, Jr., A. Marinov, and J. L. Lerner, Phys. Rev. **145**, 894 (1966).

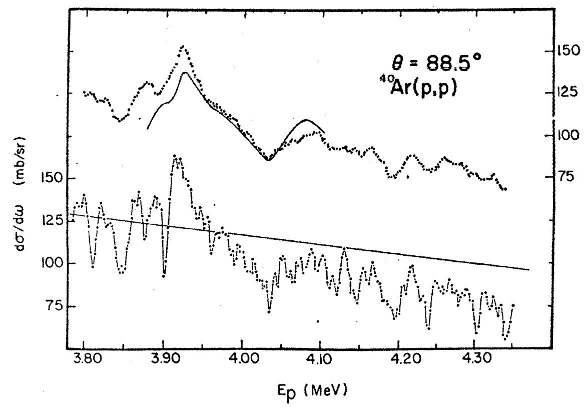

FIG. 14. Same as Fig. 13, except that $\theta=88.5°$.

The first step in the analysis of the ^{40}Ar$+p$ elastic scattering excitation functions was to calculate cross sections for proton bombarding energies in energy intervals approximately equal to the energy intervals in which the data were taken. The theoretical cross sections were then averaged with the same unweighted energy average as were the experimental data. The averaged calculated curves were compared to the energy-averaged data and the parameters were varied until a reasonable fit was obtained. The parameters of all resonances analyzed are listed in Table I. Difficulties were encountered with the analysis near a few of the resonances, and their parameters are less certain. They are shown in parentheses in Table I.

The fit to present measurements of the 1.88-MeV resonance is shown in Fig. 1, with $J^\pi=\frac{3}{2}^-$, $\Gamma_0=23$ keV, $\Gamma_p=2.5$ keV, and $\phi_c=+22.5°$. The Γ_p of 2.5 keV implies[7] an analog width Γ_λ of 2.9 keV [see Appendix, Eq. (A1), for the relationship between Γ_p and Γ_λ]. The value $\Gamma_\lambda=2.9$ keV is consistent with a reported[4] sum of 3.2 keV for the widths of $\frac{3}{2}^-$ fine-structure states.

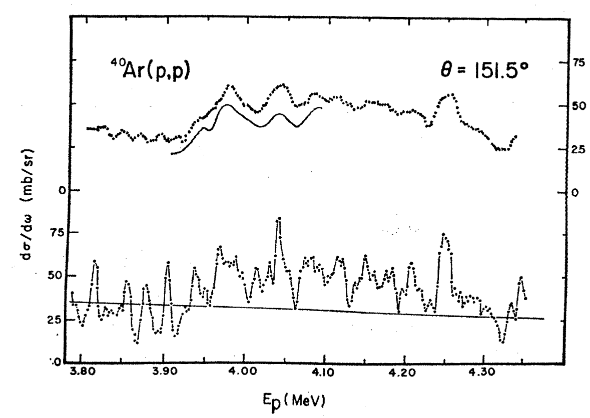

FIG. 15. Same as Fig. 13, except that $\theta=151.5°$.

[19] L. Veeser, J. Ellis, and W. Haeberli, Phys. Rev. Letters **18**, 1063 (1967).

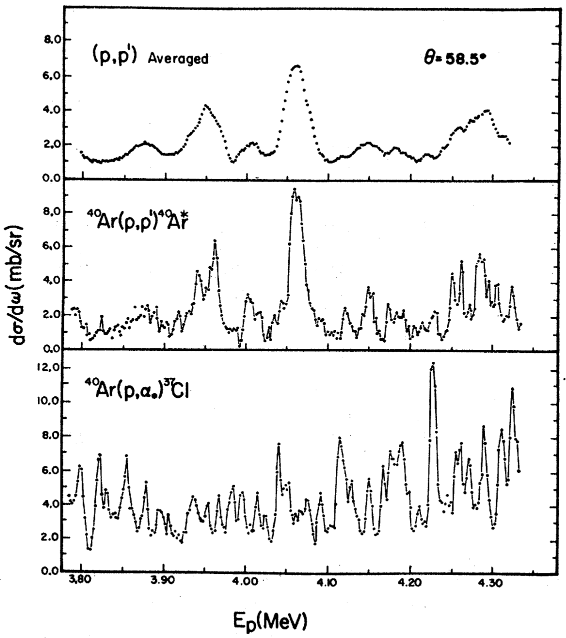

FIG. 16. Same as Fig. 11, except that $\theta=58.5°$.

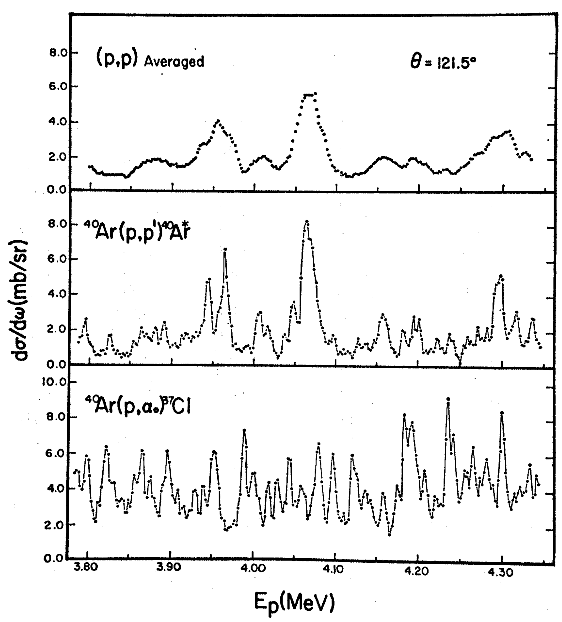

FIG. 18. Same as Fig. 11, except that $\theta=121.5°$.

When the fine-structure data of Ref. 4 were energy-averaged and analyzed,[4] a $\Gamma_p=1.3$ keV was obtained, which was not consistent with the sum 3.2 keV quoted above. The success of the present analysis is attributed to the introduction of ϕ_c into the analysis of the energy-averaged data. The fit to the $\frac{1}{2}^+$ resonance at 2.46 MeV, corresponding to the analog of the sixth excited level of ^{41}Ar, is shown in Fig. 2. The best fit was found for $\Gamma_0=16.0$ keV, $\Gamma_\lambda=4.25$ keV, and ϕ_c nearly equal to zero. The sum of the widths of the fine-structure states reported by the group at Duke is 3.2 keV. The fit shown in Fig. 2 also includes a separate $\frac{1}{2}^+$ resonance at $E_p=2.445$ MeV with $\Gamma_0=9.0$ keV and $\Gamma_p=0.5$ keV.

The spreading widths $W_\lambda^e=\Gamma_0-\Gamma_\lambda$ and mixing phases $\phi_{c,\lambda}$ of the 1.88- and 2.46-MeV analogs may be compared to expectations of the external mixing model.[7]

From these single-channel resonances we have determined values of W_λ^e and $\phi_{c,\lambda}$. They can be related to

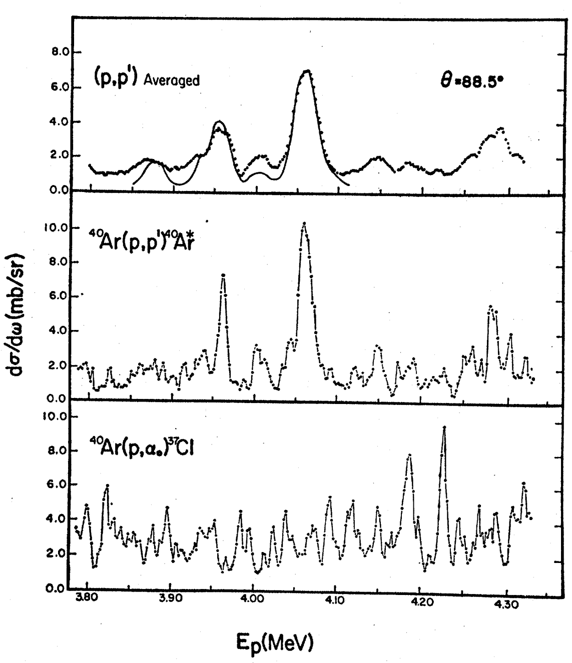

FIG. 17. Differential cross sections and multiresonance fit including resonances listed for Fig. 12. $\theta=88.5°$.

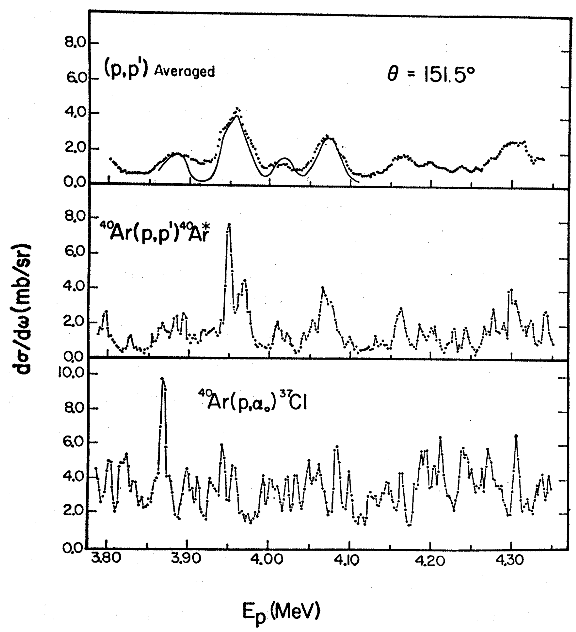

FIG. 19. Same as Fig. 17, except that $\theta=151.5°$.

TABLE I. Parameters for states ^{41}K and comparison to ^{41}Ar levels. Energies are in MeV; widths are in keV.

E_R	$E_p^{\text{c.m.}}-0.52$	Γ	Γ_p	$\Gamma_{p'}$	Γ_n[a]	l_p	J^π	S_{pp}	E_x ^{41}Ar	l_n[b]	S_{dp}[b]
1.88	1.31	23.0	2.50			1	$\frac{3}{2}^-$	0.33	1.35	1	{0.36[c] / 0.48}
2.46	1.88	16.0	4.25		<0.3	0	$\frac{1}{2}^+$	0.05	1.87	0	0.05
3.39	2.79	34.5	7.50	3.10	12	1	$\frac{3}{2}^-$	0.06	2.74	1	0.08
3.49	2.89	18.0	7.00	4.17	<2	1	$\frac{1}{2}^-$	0.05			
(3.54)	(2.93)	(20.0)	(6.0)			2					
(3.58)	(2.97)	(14.0)	(3.50)	1.80		0	$\frac{1}{2}^+$	(0.02)	2.90	0	0.01
3.60	2.99	12.0	3.60	0.85	3	1	$\frac{3}{2}^-$	0.03	2.96	1	0.05
3.65	3.04	18.0	7.70	2.80	8	1	$\frac{1}{2}^-$	0.06	3.02	1	0.06
3.71	3.10	20.0	4.50	2.80		0	$\frac{1}{2}^+$	0.02	3.12		
3.74	3.13	9.0	3.00	1.10	3	0	$\frac{1}{2}^+$	0.02	3.12		
(3.88)	(3.27)	(13.0)	(3.00)	(1.50)	6	2	$(\frac{3}{2}^+)$	(0.05)			
(3.90)	(3.29)	(13.0)	(3.50)			(0)	$(\frac{1}{2}^+)$	(0.02)			
3.93	3.32	13.5	5.50	0.90	7	1	$\frac{3}{2}^-$				
3.96	3.35	15.5	5.50	2.00		1	$\frac{3}{2}^-$	0.05	3.34	1	0.13
4.03	3.41	17.0	4.50	2.10	8	0	$\frac{1}{2}^+$	0.01			
4.07	3.45	21.0	3.50	8.70	8	1	$\frac{3}{2}^-$	0.01	3.44	1	0.01

[a] The neutron partial widths are from the ^{40}Ar$(p,n)^{40}$K experiment of Ref. 5.
[b] The ^{41}Ar level parameters are from the ^{40}Ar$(d,p)^{41}$Ar measurements of Ref. 8.
[c] Reference 9.

the level-shift–to–width ratio $\Delta_\lambda/\Gamma_\lambda$ and the strength function of the $T_0-\frac{1}{2}$ levels, S_c. The parameter $S_c \equiv \langle\Gamma_<\rangle/D$, where $\langle\Gamma_<\rangle$ denotes the average of the fine-structure widths and D their average spacing. The relationships defining the needed parameters of the external mixing model $\Delta_\lambda/\Gamma_\lambda$, S_c and g_c^2, are given in the Appendix. The parameter g_c^2 relates $\Gamma_{p,\lambda}$ to Γ_λ.

For the 1.88-MeV resonance, $\phi_c=+22.5°$ and $W_\lambda^e=20$ keV. These imply $\Delta_\lambda/\Gamma_\lambda=-10$, $S_c=0.008$, and $g_c^2=1.15$. For the 2.46-MeV analog $\phi_c\lesssim 5°$, and $W_\lambda^e=12$ keV. These imply $\Delta_\lambda/\Gamma_\lambda\lesssim-12$, $S_c\lesssim 2\times10^{-3}$, and $g_c^2\simeq 1$. These may also be determined from the resolved fine-structure resonances of the Duke experiment.[4] After making the corrections determined[4] for missed levels, we find $S_c\sim 0.006$ for the 1.88-MeV analog and $S_c\sim 1.5\times10^{-3}$ for the 2.45-MeV analog. The good agreement already noted between the Γ_λ of the present data and the sum of widths of the fine-structure resonances[4] and also between the values S_c as obtained from the two experiments supports not only the method of analysis employed for these energy-averaged data but also the external mixing model.[7]

The fits to the proton elastic scattering excitation functions at $\Theta_L=124.10°$, 154.10°, and 161.5° for the analog of the 2.74-MeV excited level in ^{41}Ar are shown in Fig. 3. These fits give for this resonance $J^\pi=\frac{3}{2}^-$, $\Gamma=34.5$ keV, and $\Gamma_p=7.5$ keV. Except for the two analogs discussed above, this resonance is the most nearly isolated resonance which was observed. These fits were calculated with the inclusion of only one additional resonance, a weak $\frac{3}{2}^-$ level at $E_p=3.45$ MeV which is not listed in Table I. Using the above parameters, fits were made to the inelastic scattering cross sections and are shown in Fig. 4. These fits gave a value of 3.1 keV to the inelastic proton partial width. Note the small values of the inelastic scattering cross sections away from the analog in the unaveraged data.

The structure observed in the energy region from 3.45 to 3.75 MeV is quite complex and the resonances appear to overlap even in the energy-averaged cross sections. Calculations were made for the elastic scattering excitation functions in this energy region which included contributions from nine resonances. These fits are shown in Figs. 5, 6, and 7. The incident energy region from 3.50 to 3.60 MeV is not well reproduced by the calculations at back angles. Examination of the ^{40}Ar$(p,n)^{40}$K excitation functions[5] suggested the existence of an $l=2$ resonance near 3.54 MeV which is included in this analysis, but its properties are not readily discerned in any of the proton scattering data. For this reason the 3.54- and 3.58-MeV resonance properties are listed as tentative in Table I. Figure 9 shows the fit over the whole energy interval. The large peak near 3.60 MeV is the result of interference between the $\frac{1}{2}^+$ resonance at 3.58 and the $\frac{3}{2}^-$ resonance at 3.60 MeV. The curves on Figs. 6 and 7 have been displaced from their calculated positions and from the data to facilitate comparison of the energy dependence of the calculated and measured cross sections. The calculations are typically 5% high at 64.2° and 10–15% high at 124.2°. Fits to the inelastic scattering cross sections over the incident energy interval from 3.45 to 3.75 MeV are shown in Figs. 9 and 10. These fits are also displaced from the measurements. If they were not displaced, they would lie on top of the data points.

In the energy region from 3.88 to 4.1 MeV, six resonances were included in the analysis. A d-wave resonance observed[5] in the ^{40}Ar$(p,n)^{40}$K reactions was included in the analysis at 3.88 MeV although its properties were not very apparent in the proton scattering data. The parameters of the 3.88- and 3.90-MeV resonances in Table I are listed as probable assignments. Since the Wigner limit for $l=3$ resonances is only a few keV, they were not expected to be observed and none were identified.

The magnitude of the channel-spin mixing ratio for the two inelastic proton channels can be determined at two resonances. The ratio is determined as $|\delta_s|=[A^2(s'=\frac{5}{2})/A^2(s'=\frac{3}{2})]^{\frac{1}{2}}$, where $A(s')$ is the reaction amplitude for the channel spin s'. The extraction can be based on the anisotropy of the inelastic scattering angular distributions near the $\frac{3}{2}^-$ resonance at 3.39-MeV incident energy because it is close to being an isolated resonance and at the $\frac{3}{2}^-$ resonance at 4.07 MeV because its inelastic proton width, 8.7 keV, is the largest partial width observed. At the 3.39-MeV resonance we find $|\delta_s|=1.5\pm0.2$ and at the 4.07-MeV resonance $|\delta_s|\leq0.3$. The 4.07-MeV resonance has subsequently been used[20] for an ^{40}Ar$(p,p',\gamma)^{40}$Ar angular correlation experiment and analyzed there to confirm the $\frac{3}{2}^-$ assignment and determine $\delta_s=-0.22\pm0.02$.

According to Moore *et al.*,[21] if isobaric spin is a good quantum number, the spectroscopic factors of the analog states are related by

$$(2T_0+1)\gamma_p^2/\gamma_{sp}^2\equiv S_{pp}=S_{dp}, \quad (2)$$

where T_0 is the isobaric spin of the target, γ_p^2 is the proton reduced width of the "proton analog," and γ_{sp}^2 is the proton single-particle reduced width. The factor S_{pp} obtained from the proton scattering data should be equal to S_{dp} from the analysis of the (d,p) stripping reaction to the analogous levels in ^{41}Ar. Penetrabilities needed to extract reduced widths from measured proton widths were obtained by correcting values from tables[22] and graphs[23] with correction factors derived from calculated widths[18] of single-particle levels in a Woods-Saxon potential well. Proton spectroscopic factors S_{pp} were calculated using Eq. (2) and are compared in Table I to neutron spectroscopic factors S_{dp} which were extracted from the (d,p) data of Kashy *et al.*[8] using the systematics of MacFarlane and French.[24] A second value appears for the analog of the 1.88-MeV resonance which comes from a DWBA analysis[9] of recent data for the ^{40}Ar$(d,p)^{41}$Ar reaction.

The good agreement between the S_{dp} and S_{pp} values shows that level properties can be obtained from analog resonance analysis even when the analogs are not isolated. The spin and parity assignments of Table I are all from this analysis and are consistent with the orbital angular-momentum transfer assignments of Ref. 8.

V. CONCLUSIONS

The analysis of isobaric analog resonances has demonstrated the usefulness of this spectroscopic method even when the resonances are close to one another. Energy-averaging over the dense and narrow $T=\frac{3}{2}$ levels has revealed a $T=\frac{5}{2}$ structure of many broad resonances having substantial proton amplitudes. Resonant energies, total and partial widths, spectroscopic factors, and spins and parities of 17 resonances of ^{41}K have been determined. Eight of these are analogs of known levels of ^{41}Ar.

The ^{40}Ar$(p,\alpha)^{37}$Cl reaction does not show the analog resonances. The high degree of correlation between the scattering excitation functions of this experiment and the (p,n) excitation functions of Ref. 5 and the complete lack of correlation with the α-particle channel are striking results. The (p,α) cross sections and the non-analog part of the (p,n) cross sections together comprise about 20% of the total compound nucleus decay probability near an incident proton energy of 4 MeV. That is, 80% of the single-proton strength of the compound nuclear levels comes from the analogs. No amplitude corresponding to direct excitation of the energy-averaged $T=\frac{3}{2}$ levels has been included in the analysis reported here. The potential scattering phases used were real.

This analysis absolutely requires the use of a resonance mixing phase both for isolated, single-channel analogs and for overlapping, multichannel analogs. The analog widths determined from these energy-averaged cross sections are consistent with the widths determined in an experiment which resolved the fine structure, and the spreading widths imply $T=\frac{3}{2}$ strength functions S_c which are consistent with those obtained from averaging over the resolved resonances.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the assistance of A. Obst and M. K. Leung in the data-taking and data-reduction phases of the experiment, and the generous assistance of the University of Kentucky Computing Center in the completion and use of analysis programs.

APPENDIX

The relationships of the external mixing model used in the analysis of isolated, single-channel analogs are given here. They are written in terms of the strength function for $T_<$ states[7] defined as $S_c\equiv\langle\Gamma_<\rangle/D$. In Ref. 7 the strength function is defined in terms of the reduced widths γ^2. The present definition is used here because

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the Γ's are directly available in an experiment. Other than the change in the definition of S_c, the notation is that of Ref. 7. The analog width Γ_λ is related to the proton partial width:

$$\Gamma_\lambda=\Gamma_{p,\lambda}g_c^2, \quad \text{with } g_c^2=(1+\tfrac{1}{2}\pi S_c)^2+(\pi S_c\Delta_\lambda/\Gamma_\lambda)^2 \quad \text{(A1)}$$

and Δ_λ is the level shift or analog-energy shift caused by the mixing with the $T_<$ states. The mixing phase ϕ_c is given:

$$\tan\phi_c=-\pi(\Delta_\lambda/\Gamma_\lambda)S_c/(1+\tfrac{1}{2}\pi S_c)\approx-\pi(\Delta_\lambda/\Gamma_\lambda)S_c, \quad \text{(A2)}$$

if $S_c\ll 1$. The spreading width $W_\lambda{}^e$ is given:

$$W_\lambda{}^e=\tfrac{1}{2}\pi[(2\Delta_\lambda/\Gamma_\lambda)^2+1]\Gamma_\lambda S_c. \quad \text{(A3)}$$

PHYSICAL REVIEW VOLUME 172, NUMBER 4 20 AUGUST 1968

^{40}Ar$(p,n)^{40}$K Reaction from Threshold to 5.0 MeV*

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(Received 29 March 1968)

Excitation functions have been obtained for the reaction ^{40}Ar$(p,n)^{40}$K from threshold to 5 MeV. For bombarding energies between threshold and 3.7 MeV, a long counter was used to measure the total cross sections and the differential cross sections at 0° and 90°. Between proton bombarding energies of 3.3 and 5.0 MeV, time-of-flight techniques were used to measure the excitation functions at 0° for two neutron groups. Pronounced resonant structure was observed throughout the proton energy range. The results are compared with expected energies for isobaric analogs of states in ^{41}Ar. Neutron partial widths are given for selected resonances.

I. INTRODUCTION

The purpose of the present study was to obtain excitation functions for the reaction ^{40}Ar$(p,n)^{40}$K for proton bombarding energies between threshold at 2.34 and 5 MeV. This work was undertaken with the expectation, based in part on results reported by Barnard and Kim,[1] that isobaric analog states[2,3] would be observed in this region of excitation in ^{41}K.[4] Isobaric analog resonances in ^{40}Ar$+p$ have been studied at Duke University for proton bombarding energies near 1.88 and 2.45 MeV with a proton energy resolution of about 200 eV.[5] Proton elastic scattering measurements on ^{40}Ar have also been made at the University of Kentucky for proton bombarding energies up to 4.35 MeV with a proton energy resolution of about 2 keV.[6] Analysis of resonances as isobaric analogs in ^{41}K of states in ^{41}Ar has been made in both of these studies.

Other previous work on the ^{40}Ar$(p,n)^{40}$K reaction includes an accurate measurement of the ground-state threshold with an uncertainty of 1 keV by Parks *et al.*[7] Other measurements of the threshold were made by Holland and Lynch,[8] using time-of-flight techniques, and by Richards and Smith.[9]

In the work reported here, excitation functions for the (p,n) reactions have been measured with two detection techniques. A long counter was used to obtain cross sections for the sum of all neutron groups for bombarding energies between the ground-state threshold and 3.7 MeV. Time-of-flight techniques were used to detect separately two neutron groups in the incident energy interval from 3.35 to 5.0 MeV. One group included neutrons exciting the ground and first excited levels in ^{40}K and the other group included neutrons exciting the second and third excited levels in ^{40}K.

II. EXPERIMENTAL PROCEDURE

Protons for the ^{40}Ar$(p,n)^{40}$K reaction were accelerated by the University of Kentucky Van de Graaff accelerator. A 90° analyzing magnet, whose field was measured by a proton magnetic-resonance flux meter, was used to define the incident proton energy.

The gas target assembly was modeled after a design of Johnson and Banta.[10] The beam, which was collimated to $\frac{1}{5}$ in. diam by a tantalum aperture, entered

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