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:

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

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:

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

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

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

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

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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

[1] A. C. L. Barnard and C. C. Kim, Nucl. Phys. **28**, 428 (1961).
[2] J. D. Fox, C. F. Moore, and D. Robson, Phys. Rev. Letters **12**, 198 (1964).
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[4] F. Gabbard, J. D. Brandenberger, L. W. Cochran, and T. Young, Bull. Am. Phys. Soc. **9**, 649 (1964).
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[8] R. E. Holland and F. J. Lynch, Phys. Rev. **113**, 903 (1959).
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[10] C. H. Johnson and H.E. Banta, Rev. Sci. Instr. **27**, 132 (1956).

the gas through a nickel foil 0.008 mils thick. The target assembly was electrically insulated from the beam tube and served as a Faraday cup for collection of beam current. The integrated charge served to measure the incident proton flux. Natural argon, 99.99% pure, was used as the target material. The target thickness was calculated from the measured pressure, volume, and temperature of the gas in the cell. This thickness was adjusted between 1 and 7 keV for the various measurements.

The target and detectors were mounted over a scattering pit 20 ft square by 8 ft deep. Detectors were mounted on a rotatable carriage allowing neutron yield measurements in the horizontal plane at angles from 0° to 146° relative to the direction of the incident beam.

The absolute determination of the efficiency of the long counter[11] was made by counting neutrons from a standard Pu-Be source and neutrons from the ^{7}Li(p,n)^{7}Be reaction using a LiF target whose thickness was determined by weighing. The two efficiency measurements agreed to within 5%. The energy dependence of the long-counter efficiency was obtained from the data of Allen and Ferguson.[12]

Excitation functions at 0° and 90° were measured with the front face of the long counter at 50 cm from the target. The total cross-section and threshold measurements were made with the argon target inserted about 3 in. into one of the holes in the long-counter face. With the neutron source in this position, the long counter detects neutrons from all directions with respect to the incident beam and hence measures the total cross section in relative units. The relative efficiency of the long counter as a function of neutron energy in this configuration was assumed to be the same as given by Allen and Ferguson.[12] For neutron energies above 100 keV, this assumption is estimated to be accurate to about ±5%. These data were normalized to the 0° excitation function at the 3.38-MeV resonance where

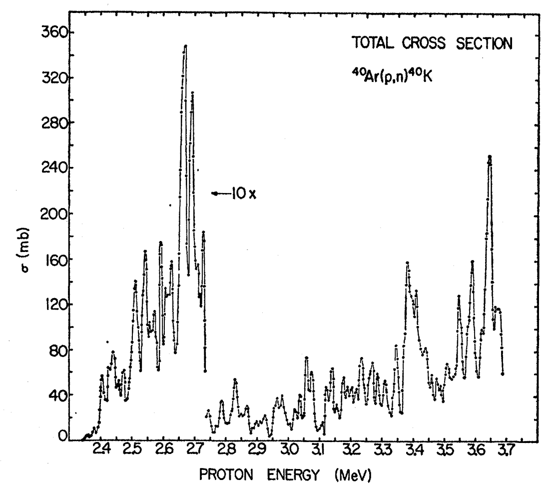

FIG. 2. Total cross section for ^{40}Ar(p,n)^{40}K measured with a long counter.

the angular distribution of neutrons was nearly isotropic.

Data were taken from 3.3 to 5.0 MeV with a neutron time-of-flight system. For time-of-flight operation, the Van de Graaff accelerator was terminal pulsed at a repetition rate of 5 Mc and a pulse width of 5–7 nsec. The detector for this system was a 2×2-in. liquid organic scintillator (NE 213) mounted on an RCA 6810 photomultiplier tube. This detector employed pulse-shape discrimination in order to reject pulses produced by γ rays. The relative efficiency for the time-of-flight detector was measured by using neutrons from the ^{7}Li(p,n) and $T(p,n)$ reactions with a bias level of 750 keV for the detection of neutrons. The absolute efficiency was determined to about 10% by using a lithium-fluoride target evaporated on a 10-mil tantalum disk. The target thickness was determined by weighing.

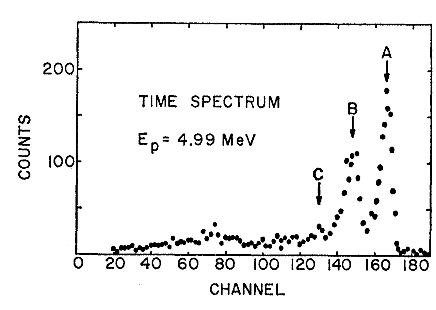

FIG. 1. Typical time-of-flight spectrum: (A) neutrons exciting ground and first excited states, (B) neutrons exciting second and third excited states, (C) neutrons exciting the fourth excited state of ^{40}K.

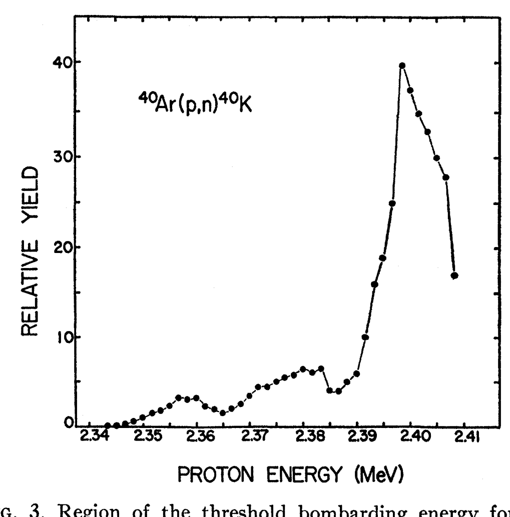

FIG. 3. Region of the threshold bombarding energy for the ^{40}Ar(p,n)^{40}K reaction. The measured ground-state threshold is 2.345±0.005 MeV.

[11] W. D. Allen, in *Fast Neutron Physics*, edited by J. B. Marion and J. L. Fowler (Interscience Publishers, Inc., New York, 1960), Part I, p. 361.

[12] W. D. Allen and A. Ferguson, Proc. Phys. Soc. (London) **70**A, 639 (1957).

A typical time spectrum taken with the argon target is shown in Fig. 1 for a bombarding energy of 4.99 MeV. Peak A represents neutrons to the ground and first excited states of ^{40}K, peak B to the second and third excited states, and peak C to the fourth excited state. The neutron yields extracted from the spectra were used to calculate the cross sections. The background was estimated by averaging the number of counts in channels away from the neutron peaks.

III. RESULTS

The total ^{40}Ar$(p,n)^{40}$K cross section from threshold to 3.7 MeV is shown in Fig. 2. These data were taken with energy resolution of 7 keV in steps of 5 keV or less. The neighborhood of the ^{40}Ar(p,n) threshold is shown in Fig. 3. The measured threshold is 2.345±0.005 MeV giving a Q value of -2.288 ± 0.005 MeV as compared to $Q=-2.2865\pm0.001$ MeV recently measured by Parks *et al.*[7] The rapid increase in yield due to the structure near 2.4 MeV can be easily mistaken for a (p,n) threshold. The present measurement of the threshold gives an expected first excited state threshold of 2.374 MeV. This latter threshold is not evident in Fig. 3.

Excitation functions taken at 0° and 90° with the long counter are shown in Fig. 4. The energy resolution is about 5 keV at 3.5 MeV, Note the detailed correspondence of resonance structure observed at the two angles of Fig. 4. The highest resolution data of this experiment indicate that many resonances are still unresolved. Recent work by Keyworth *et al.*[5] at Duke University shows that the total widths are smaller than 200 eV for many of the resonances near 2.5 MeV. Figure 5 shows data in the neighborhood of the 3.4-MeV structure with an energy resolution of about 3 keV. This resolution is still insufficient to resolve the resonant structures, which further illustrates the complexity of the excitation functions.

Time-of-flight data were taken with an energy resolution of about 5 keV for bombarding energies between 3.3 and 5.0 MeV in steps of 4 keV or less. The 0° excitation functions for neutrons exciting the ground and first excited states and neutrons exciting the second and third excited states of ^{40}K are shown in Fig. 6. Time resolution was insufficient to resolve neutrons exciting the ground and first excited states or neutrons exciting the second and third excited states. Prominent resonant structure is evident in the excitation functions. Structure near 3.38 and 3.65 MeV was also observed in the long-counter data (Figs. 2 and 4). Comparison of Fig. 4 with Fig. 6 shows that most of the neutron yield below 3.7 MeV leads to the ground and first excited states of ^{40}K.

The sources of experimental error considered in the determination of the standard error in the cross-section measurements were as follows: (1) monitoring of incident proton charge, (2) target thickness, (3) detector efficiency, (4) counting statistics, and (5) scattered

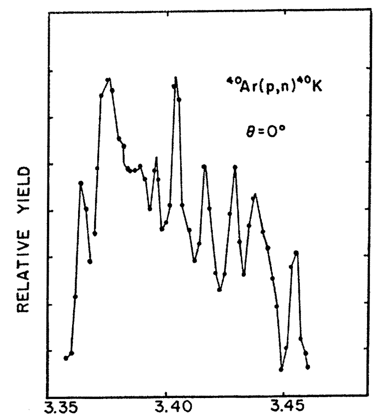

FIG. 5. Region of the 3.38-MeV resonant structure with a proton energy resolution of ~3 keV. Widths of individual energy levels is less than this proton energy resolution. Data were taken with a long counter.

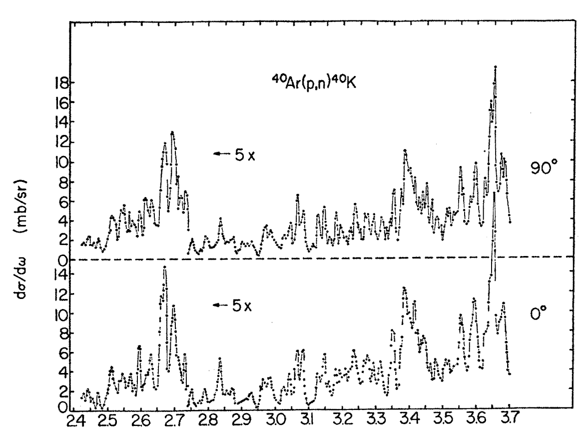

FIG. 4. Excitation functions at laboratory angles of 0° and 90° for ^{40}Ar$(p,n)^{40}$K measured with long counter.

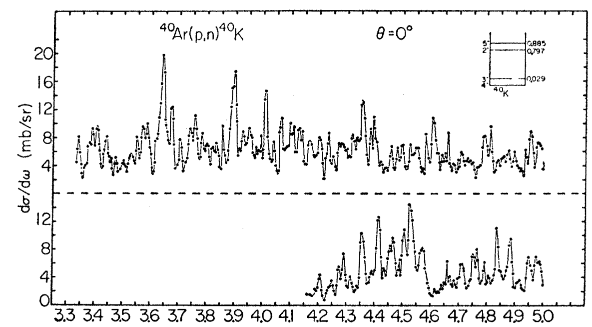

FIG. 6. Time-of-flight data for two neutron groups. Upper graph shows the excitation function for exciting the ground and first excited states in ^{40}K and the lower graph shows the same for the second and third excited states. Individual groups are not resolved (see inset level diagram for ^{40}K). Data were taken at a laboratory angle of 0°.

neutrons. Of these sources of error, the largest contributors were beam monitoring and detector-efficiency uncertainties estimated at ± 7 and $\pm 10\%$, respectively. The long-counter measurement of the total cross section has an additional uncertainty due to the assumption regarding the energy dependence of the counting efficiency referred to above. Our estimate of the standard error in the absolute cross sections of Figs. 3 and 4 are ± 15 and $\pm 13\%$, respectively. The time-of-flight data presented in Fig. 6 have an estimated standard error of $\pm 15\%$.

IV. DISCUSSION

Table I lists selected resonances observed in the ^{40}Ar$(p,n)^{40}$K reaction. Much of the structure observed appears near the expected positions of isobaric analogs of states in ^{41}Ar, observed in ^{40}Ar$(d,p)^{41}$Ar measurements.[13] The second column gives the expected excitation energy in ^{41}Ar of the analog states in ^{41}K. The energy given corresponds to a Coulomb energy difference of 6.60 ± 0.04 MeV for analog states in ^{41}Ar and ^{41}K. This value is in agreement with the value given by Keyworth[5] and with the empirical results of Long *et al.*[14] The formula of Bethe and Bacher,[14] with Long's best-fit parameters, gives a value of 6.584 ± 0.056 MeV. The masses used in the energy-difference calculations were taken from the mass tables of Mattauch *et al.*[15] The agreement in the values of the Coulomb energy difference derived from direct comparison of the masses of the final states which are analogs and by comparison using the ^{41}Ar-^{41}K ground-state mass difference verifies the consistency of the ^{41}K ground-state mass.[15] The third column in Table I gives the excitation energy in ^{41}Ar, where states were observed in the (d,p) data of Kashy *et al.*[13] Parentheses indicate uncertainty about identification of the two states as isobaric analogs.

In the proton energy range between threshold at 2.345 and 5.0 MeV, 130 "resonances" are observed in the data shown in Figs. 2 and 6. In this energy interval Kashy *et al.*[13] report 24 levels in ^{41}Ar. Much of the structure seen in Figs. 2 and 6 very probably represents fine structure[16] associated with isobaric analog states which are excited. This hypothesis is supported by the result of averaging the data. Figure 7 shows long-counter data taken with an energy resolution of about 25 keV so that much of the fine structure is averaged out of the excitation function. The number of prominent peaks in this poor resolution data is 37. A number of the resonances observed have been assigned spins and parities based on analysis of proton elastic scattering data reported in the preceding paper.[6] Column 4 of Table I shows spin and parity assignments of that analysis for each of these levels. In the work of Ref. 6, a definite correspondence between the resonances observed and a particular level of ^{41}Ar has been made for most of the resonances and is displayed in Table I. The neutron widths for these states can be derived from the (p,n) cross sections and the resonance parameters determined from the elastic scattering analysis. These neutron widths are given in column 5 of the Table. Because of the large number of resonances observed, it is impossible to identify with certainty corresponding levels which are isobaric analogs above 4.06 MeV and the correspondence shown above this energy in Table I is tentative for all levels.

TABLE I. Prominent resonances observed in the ^{40}Ar$(p,n)^{40}$K reaction with a comparison to ^{40}Ar$(d,p)^{41}$Ar data.

E_p Lab MeV	$E'-0.52$ c.m. MeV	E_x[a] ^{41}Ar MeV	J^{π} [b]	Γ_n keV
2.44	1.86	1.871	$\frac{1}{2}^+$	<0.3
2.54	1.96	1.988		
2.63	2.05			
2.68	2.09			
2.74	2.12			
2.82	2.23			
2.92	2.33			
2.97	2.38			
3.06	2.46	(2.402)[c]		
3.13	2.54			
3.25	2.65			
3.35	2.75	2.701		
3.38	2.78	2.740	$\frac{3}{2}^-$	12
3.48	2.88		$\frac{1}{2}^-$	2
3.51	2.90			
3.55	2.94			
3.58	2.97	2.955	$\frac{3}{2}^-$	3
3.64	3.03	3.017	$\frac{1}{2}^-$	8
3.75	3.14	(3.12)	$\frac{1}{2}^+$	3
3.88	3.27	(3.293)	$(\frac{3}{2}^+)$	(6)
3.93	3.32	3.335	$\frac{3}{2}^-$	7
4.02	3.40	(3.393)	$\frac{1}{2}^+$	8
4.06	3.44	3.438	$\frac{3}{2}^-$	8
4.20	3.58	(3.577)		
4.28	3.66	(3.601)		
4.35	3.72	(3.705)		
4.40	3.77	(3.808)		
4.48	3.85	(3.847)		
4.52	3.89	(3.900)		
4.57	3.93			
4.62	3.98	(3.979)		
4.72	4.08	(4.108)		
4.76	4.13	(4.135)		
4.80	4.16	(4.163)		
4.83	4.20			
4.88	4.25	(4.280)		
4.96	4.33	(4.305)		

[a] From Kashy *et al.*, Ref. 12.
[b] From Scott *et al.*, Ref. 6.
[c] Parentheses denote uncertain correspondence as analog states.

[13] E. Kashy, A. M. Hoogenboom, and W. W. Buechner, Phys. Rev. **124**, 1917 (1961).
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[16] P. Richard, C. F. Moore, J. D. Fox, and D. Robson, Phys. Rev. Letters **13**, 343 (1964).

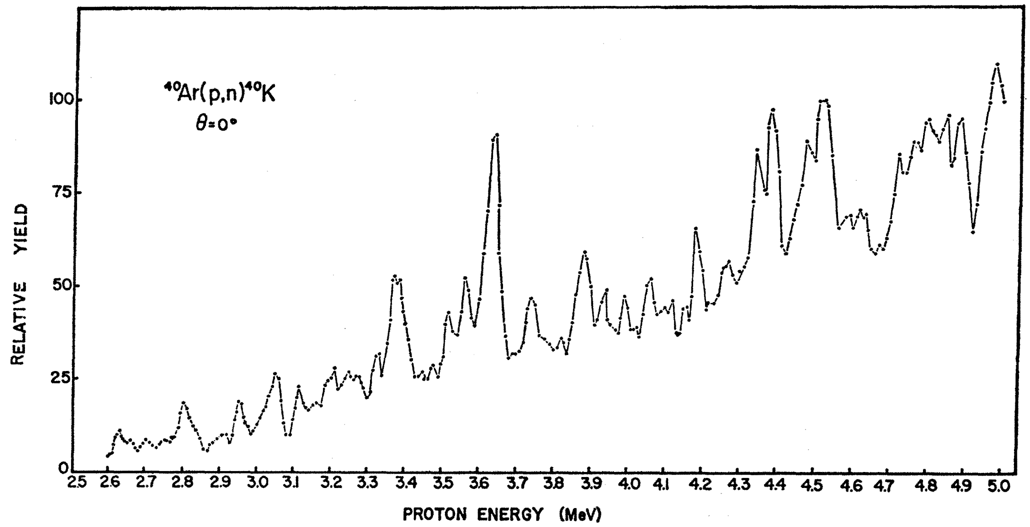

FIG. 7. Neutron yield data taken with an energy resolution of 25 keV, showing gross structure of the excitation function.

A significant feature of Fig. 7 is that almost every prominent structure observed can be associated with a known level of ^{41}Ar supporting the hypothesis of Ref. 6 that a very large majority of the proton strength of the ^{41}K states in this region of excitation is produced by the isobaric analog states ($T=\frac{5}{2}$) and their mixing[6,16] into the states of normal ($T=\frac{3}{2}$) isobaric spin.[17] Assuming that all of the proton-induced reactions in this energy range proceed by a compound nucleus mechanism, one would generally expect the proton strength to be shared between the normal states ($T=T_z$) and the isobaric analogs ($T=T_z+1$), with the excitation of the normal states forming a "background" upon which is superimposed the less dense and pronounced analog states.[18] For the case of the data of Fig. 7, a substantial fraction of the yield observed is expected to be due to this "background" cross section. In the elastic scattering[6] measurements on ^{40}Ar, this "background" cross section is much less important because of the relatively small fraction of the proton strength contained in it.

Although the strong enhancements of (p,n) cross sections near analog states contain much useful information, the large level density of analog states in ^{41}K makes the use of isobaric analog resonances for nuclear spectroscopy somewhat more complex than in nuclei in which the analog states are more widely separated relative to the spacing of states with normal ($T=T_z$) isobaric spin.

ACKNOWLEDGMENTS

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