for ^{33}S something other than a simple collective-rotational model will be required to explain the electromagnetic transitions. In fact, Van Middelkoop and Engelbertink[8] have recently reported very good agreement between measured transition rates in ^{33}S and shell-model calculations. Thus it may be that the shell-model approach is the best one for this nucleus.

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Beta Decay of ^{40}Cl and Levels of ^{40}Ar†

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Radioactive ^{40}Cl was produced by the reaction ^{40}Ar$(n, p)^{40}$Cl through bombardment of a liquid-argon target with 14.9-MeV neutrons. γ rays were observed with 6-, 15-, and 35-cc Ge(Li) crystal detectors, and with two NaI(Tl) crystal detectors in coincidence. Twenty-three γ rays with energies from 262 to 6334 keV were assigned to transitions in ^{40}Ar. The β-ray relative intensities were deduced from the relative intensities of the γ rays, and logft values were calculated. It was concluded that all levels in ^{40}Ar up to and including the 3518-keV level have even parity. Seven levels from 3681 to 6335 keV in ^{40}Ar have odd parity and spin of 1, 2, or 3. The ground energy level of ^{40}Cl has spin-parity 2^-, if in fact the 3681-keV level of ^{40}Ar has spin-parity 3^-.

I. INTRODUCTION

At the time that this study was started, relatively little was known about the energy levels of ^{40}Ar and their modes of decay. Of particular interest was the only known odd-parity level located at 3.689 MeV, which had been assigned spin-parity 3^- according to various data which could be interpreted as supporting this assignment; additional odd-parity levels were expected on the basis of comparisons with nearby even-even nuclei. Some other levels of ^{40}Ar at lower and higher energies did not have definite spin-parity assignments. The objectives of the present investigation were to determine the energies of ^{40}Ar levels; to assign spins and parities (or at least to limit the possibilities); and to determine logft values for the β decay of ^{40}Cl. Measurements were made on the γ rays from levels of ^{40}Ar following the 1.4-min β decay of ^{40}Cl. Many levels of ^{40}Ar can be populated by the β decay, since the β-decay energy is large (7.41 MeV), and the parity of some levels can be determined, since observed transitions from the 2^- ground-energy level of ^{40}Cl to low-lying even-parity levels will be first-forbidden β-decay transitions ($\Delta J = 0, \pm 1, \pm 2$; parity change) while generally only allowed transitions ($\Delta J = 0, \pm 1$; no parity change) will be observable for the higher-lying levels. Branching ratios for γ decay have been determined, and the ^{40}Ar level energies have been measured with greater accuracy than previously, with the use of Ge(Li) crystal detectors. A preliminary report of the present results was presented earlier.[1] This report complements the branching-ratio results of a recently completed angular-correlation study[2] of the ^{40}Ar$(p, p'\gamma)$ reaction, which involves some levels which are only weakly populated by the β decay.

Previous Studies

Radioactive ^{40}Cl was first produced and identified by Morinaga[3] through the ^{40}Ar$(n, p)^{40}$Cl reaction; he observed that the β-decay endpoint energy was approximately 7.5 MeV and that there were γ rays of energies 1.46, 2.75, and 6.0 MeV; he measured the half-life as 1.4 min. Subsequently, Robinson,[4] also at Purdue University, extended these measurements, utilizing coincidence measurements. His results are summarized in the previously unpublished tentative decay scheme of Fig. 1; he stated that no doubt there were other unresolved transitions. Robinson determined the half-life to be 1.38 (±0.02) min.

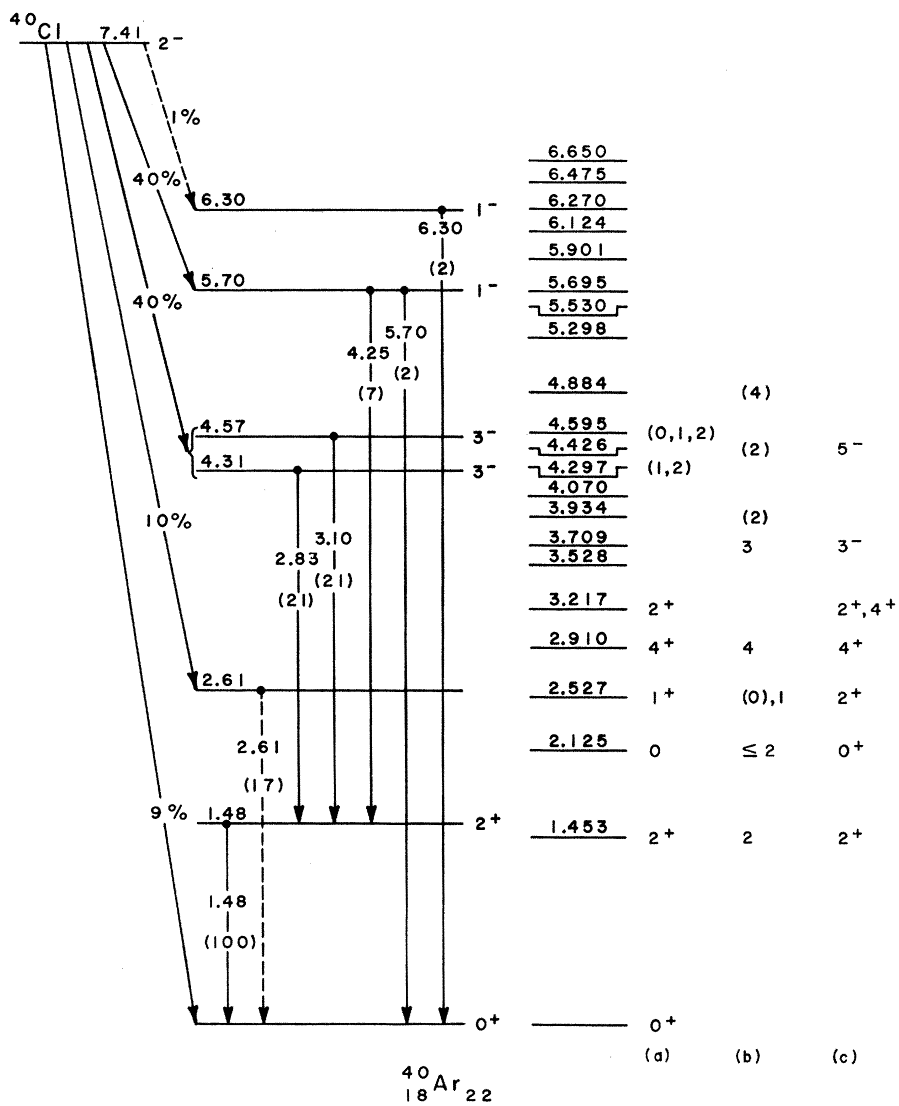

FIG. 1. Previously-known information about the β decay of ^{40}Cl and levels of ^{40}Ar. The decay diagram is from Ref. 4 and is printed here with the permission of Robinson. The level energies are from Ref. 9. References to spin-parity assignments are (a) 2, 10, and 12; (b) 11; and (c) 13–17.

During measurements of the cross sections for reactions caused by fast neutrons bombarding argon, Gray, Zander, and Ebrey[5] observed the ^{40}Cl β decay and confirmed the presence of the more intense radiations and the identification of contaminating radioactivities. Recently, Husain and Karras,[6] through Ge(Li) crystal spectroscopy, assigned γ-ray energies of 0.33 to 6.0 MeV to transitions following β decay of ^{40}Cl. From summed-pulse spectra in two NaI crystals, γ-γ cascades were deduced and a modification of Robinson's energy level diagram was described.

Proton and electron scattering data and studies of the decay of ^{40}K to ^{40}Ar had indicated[7] an ^{40}Ar first excited level with energy of about 1.5 MeV and a second level at approximately 2.4 MeV. Inelastic scattering of protons by van Heerden and Prowse[8] gave evidence for as many as nine levels in ^{40}Ar up to an energy of approximately 5 MeV. Benveniste, Booth, and Mitchell[9] reported the identification of twenty-one levels up to excitation energy of 6.65 MeV from study of the ^{40}Ar(p,p') reaction at bombarding energies of 7.32 and 9.39 MeV. Their energy assignments are given in the diagram of Fig. 1. Spin-parity assignments for a number of these levels have been made from the analysis of angular distributions of inelastically scattered protons,[10–13] inelastically scattered α particles,[14,15] γ rays from the $(n,n'\gamma)$ reaction,[16] and inelastically scattered deuterons.[17] Some of these assignments are shown in Fig. 1.

II. EXPERIMENTAL DETAILS

Radioactive ^{40}Cl sources were prepared by the ^{40}Ar$(n,p)^{40}$Cl reaction, using 14.9 ± 0.1-MeV neutrons produced through the ^{3}H$(d,n)^{4}$He reaction with the University of Kentucky neutron generator. Liquid-argon samples were made by condensing commerical grade argon gas in a Pyrex container which was cooled by a liquid-nitrogen bath. Samples of 90 to 110 cc were irradiated in a typical neutron flux density of 5×10^{8} n/cm^{2} sec, as measured with a BF_3 monitor counter which had been calibrated previously by the radiochemistry group.

In a typical source preparation, a sample of liquid argon was irradiated for one minute; then during an elapsed time of about one minute it was carried to the γ-ray detector system and enroute was poured into a nonradioactive Pyrex container. This container was immersed in liquid nitrogen during the counting period. In all, more than 125 samples were irradiated and counted.[18]

Preliminary γ-ray spectra were obtained with use of (a) a 7.62×7.62-cm-diam NaI(Tl) crystal detector; (b) a Raboy-Trail anticoincidence spectrometer[19,20] which utilized NaI(Tl) crystals; and (c) a 6-cc Ge(Li) crystal detector to obtain spectra of higher resolution. Finally, at later dates, 15- and 35-cc Ge(Li) crystal detectors provided still better resolution for recording the γ-ray spectra. Comparisons of the outputs of these different types of detectors aided in the interpretation of the spectra.

No chemical separations were attempted, as the earlier work of Robinson[4] provided the desired information concerning contaminants. The short bombarding time of one minute suppressed the production of ^{37}S, which with its half-life of 5.1 min was a troublesome contaminant. In checking for contaminants, a typical counting sequence was to record the spectrum for a two-minute interval starting from one minute after the end of the irradiation, then to record the spectrum from the same source for a three-minute interval, and then to record similarly for a ten-minute interval. In this way, it was possible to identify radioactivities of shorter or longer half-lives than that of ^{40}Cl. Variation of these time intervals through many observations confirmed that the contaminants were those produced by the reactions ^{40}Ar$(n,d)^{39}$Cl, ^{40}Ar$(n,\gamma)^{41}$Ar, and ^{40}Ar $(n,\alpha)^{37}$S. The γ rays which followed the β decay were identified by their known energies and half-lives.

γ-γ coincidence spectra were obtained with two 7.62×7.62-cm-diam NaI(Tl) crystals. The two detectors were contained in cylindrical lead shields, with their axes intersecting at a 90° angle, and with appropriate lead shielding placed between the two to prevent detection of scattered photons. Conventional slow-fast coincidence circuitry was used with resolving time $2\tau = 100$ nsec; a single-channel analyzer was used with one detector to permit selection of a narrow range of size of the triggering pulses.

Calibration of the Ge(Li) Crystal Detectors

Energy calibrations of the Ge(Li) crystal detectors were made with use of known γ-ray lines from radioactive sources.[21–24] The 35-cc detector was used for the final-energy determinations; its resolution was 3.8 keV at 1332 keV (full width at half maximum). Typical spectra were taken at a dispersion of 1 keV/channel, and a biased amplifier was used in covering the higher-energy range.

Efficiency calibrations of the detectors were made with use of U. S. National Bureau of Standards calibrated-intensity sources. The sources were supported at a distance of 4.6 cm from the detector surface, in air, without shielding. An extrapolation of the efficiency curve was made through use of the two γ rays of ^{24}Na. The efficiency curves were estimated to be accurate to better than 10% (above 4 MeV, 20%). In use with the ^{40}Cl sources, an efficiency correction was made for the absorption of γ rays by the Pyrex container. For the 4- to 6-MeV region, the annihilation-photon escape peaks were used, taking advantage of the fact that the efficiency changes very slowly with γ-ray energy, from 4 to 7 MeV, as is illustrated by the curves of Ref. 22. The 15-cc-detector data were used for this energy region.

III. RESULTS AND DISCUSSION

Preliminary spectral measurements were made with a NaI(Tl) crystal detector; the γ rays which had been observed previously by others were identified. Previously unreported γ rays were observed in spectra obtained with the anticoincidence shielded NaI(Tl) crystal spectrometer. The full complexity of the spectrum was not realized until the 6- and 15-cc Ge(Li) crystal detectors were used. Later, spectra were obtained with a 35-cc Ge(Li) crystal detector with the same results but with reduced statistical uncertainty.

With the 15-cc detector, spectra were obtained with overlapping energy ranges from 0 to 3.2 MeV, and from 2.7 to 6.0 MeV. With the 35-cc detector, a typical spectrum covered up to 4.03 MeV in 4096 channels, as shown in Fig. 2. For this spectrum three ^{40}Cl samples were used, with each one being counted for two minutes. In Fig. 3 is shown a portion of a typical spectrum acquired with the 15-cc detector, in which are seen the peaks due to the higher-energy γ rays.

Early in the study, a measurement was made of the half-life for decay of ^{40}Cl through observation of the 1461-keV line of the γ-ray spectra, with the result that $T = 1.44 \pm 0.08$ min, in reasonable accord with 1.4 and 1.38 ± 0.02 min, as reported by others.[3,4]

It was pointed out by Robinson[4] that one of the γ rays of ^{40}Ar has nearly the same energy as the 3103-keV γ ray of ^{37}Cl which is due to the ^{40}Ar$(n, \alpha)^{37}$S $\xrightarrow{\beta}$ ^{37}Cl reactions. The presence of this γ ray was shown in the present study by the γ-γ coincidence data (next subsection). In order to minimize the contribution of the ^{37}S decay, samples

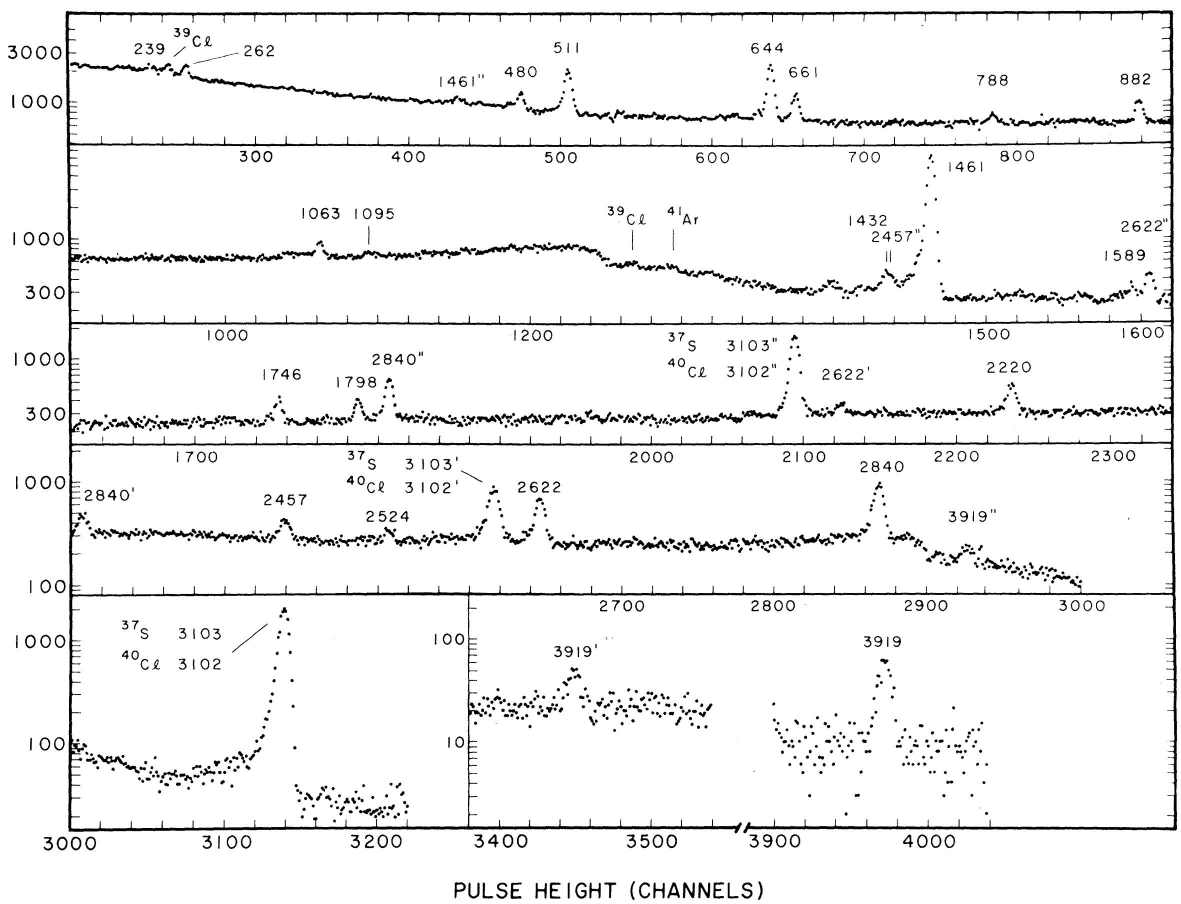

FIG. 2. Ge(Li) crystal detector (35-cc) spectrum of the γ rays emitted by ^{40}Ar following the β decay of ^{40}Cl.

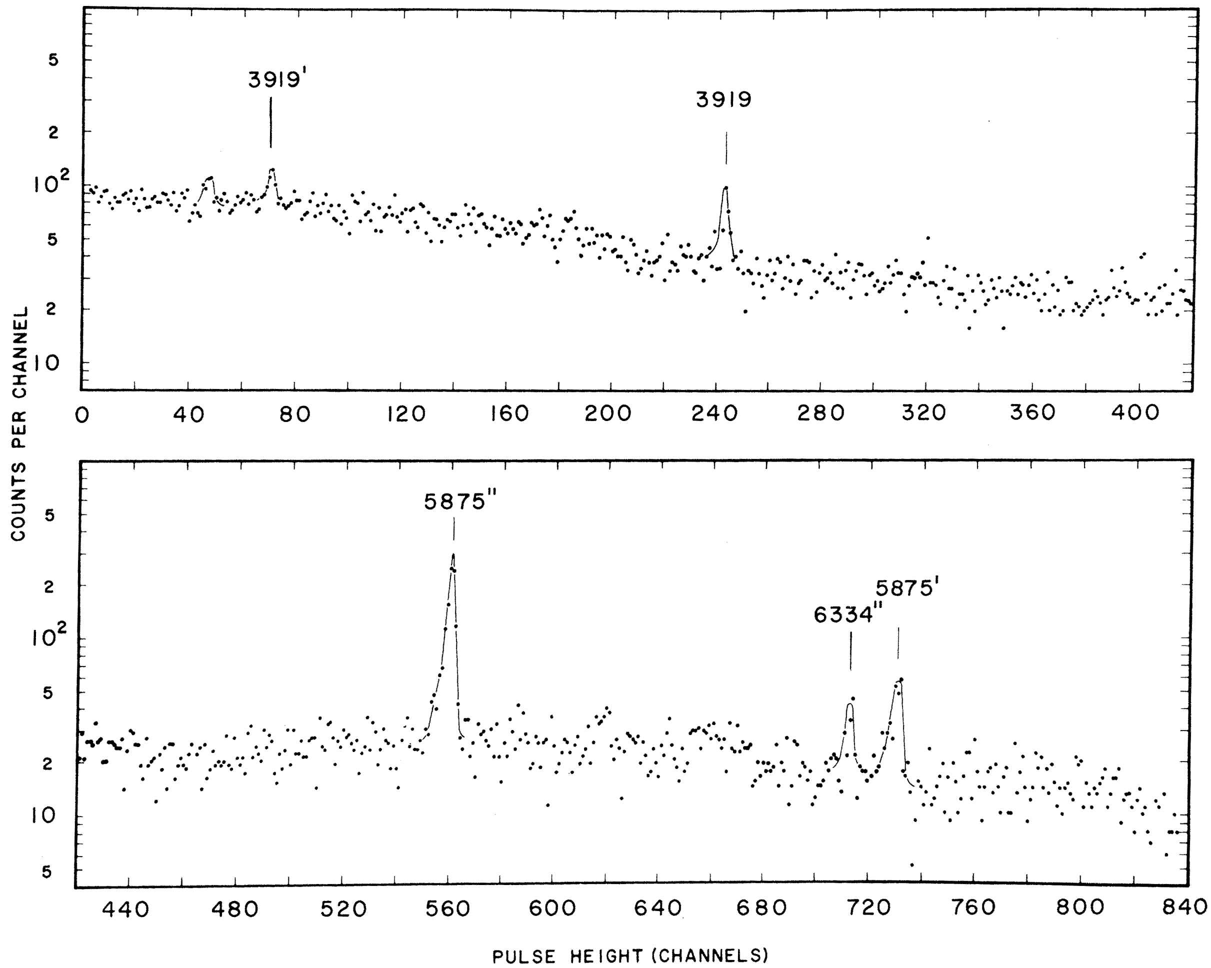

FIG. 3. Ge(Li) crystal detector (15-cc) spectrum of the higher-energy γ rays emitted by ^{40}Ar following the β decay of ^{40}Cl. The peak at channel 45 is due to a contaminant.

were prepared with a short irradiation time, counted as quickly as possible for a short time, and then counted later after six ^{40}Cl half-lives in order to determine the ^{37}S contribution to the γ-ray line, which was typically about 95%. Thus the intensity determination was difficult and uncertain; the yield of the ^{40}Cl 3102-keV line relative to the 1461-keV line was finally set at $5 \pm 3\%$. The energy of this line is taken as the difference of two energy levels; $4562.5 - 1460.7 = 3101.8$ keV. The energy of the ^{37}S line is now set at 3102.7 ± 0.3 keV, approximately 4 keV lower than the earlier determination.[20]

It is known that some low-intensity γ rays were not resolved. For example, the p'-γ coincidence data of Ref. 2 show a 84–12% branching from the 3207-keV level, whereas in this work only the stronger 84% transition was detectable.

A. γ-γ Coincidence Spectra

γ-γ coincidence spectra, which were gated by pulses associated with selected γ-ray lines at 1461, 2622, 2840, 3102, 3919, 5875, and 6334 keV, were recorded; all except the first are shown in Fig. 4. The coincidence spectrum which was gated by the very intense 1461-keV line was complicated, with coincidence peaks at 882, 1063, 1432 and/or 1461, 1798, 2622, 2840, and 3102 keV [these energies are taken from the Ge(Li) determinations]. At least seven γ rays appeared in coincidence with the 1461-keV line, but none of higher energy than 3102 keV. At this point reference to the energy-level diagram of Fig. 5 will aid the reader.

The spectrum of Fig. 4(a) was obtained with the single-channel-analyzer gate set to include the 5875″, 6334″, and 5875′ lines. The coincident 511-keV annihilation peak is due to those events in which the photons escaping from one crystal reached the other crystal around the end of the shield. Therefore, both transitions go directly to the ground energy level.

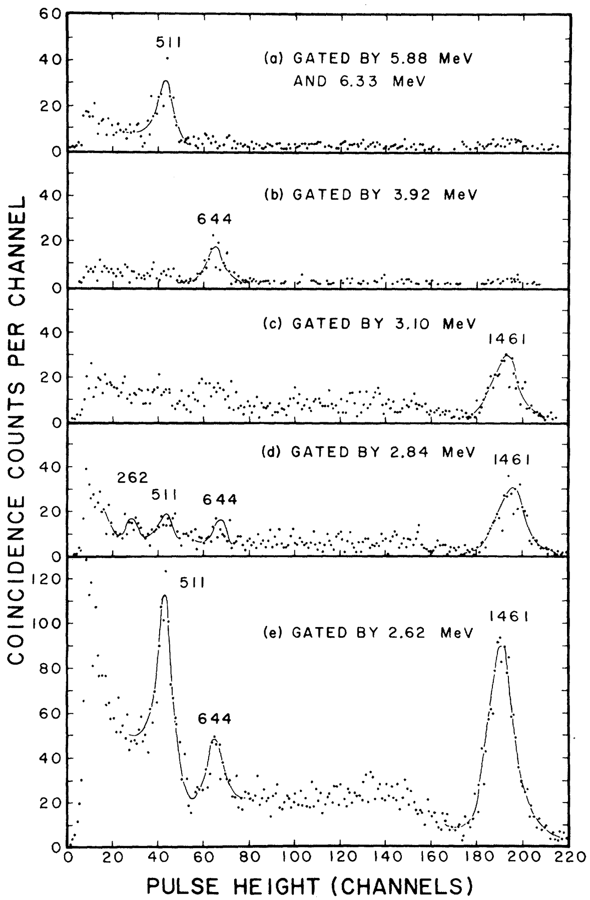

FIG. 4. γ-γ coincidence spectra, taken with two NaI(Tl) crystal detectors.

The spectrum gated by the 3919-keV line [Fig. 4(b)] shows one peak to which is assigned the energy 644 keV; in this coincidence spectrum the uncertainty in energy would permit 661 keV, but such a coincidence would necessarily require the presence of the 1461-keV peak also. The interpretation is that of a 3919-keV transition to the ground state, preceded by a 644-keV γ ray from a level at 4563 keV.

The spectrum gated by the 3102-keV line [Fig. 4(c)] shows only the 1461-keV peak in coincidence. Thus the 3102-keV γ ray is a cascade transition from a level at 4563 keV. The 3103-keV radiation from the contaminant ^{37}S did not interfere, since it is purely a transition to the ground level.

The spectrum gated by the 2840-keV line [Fig. 4(d)] shows a 1461-keV peak; evidently the 2840-keV γ ray is a cascade through the 1461-keV level from a level at 4301 keV. The weak 262-keV peak is from a 4563 → 4301 transition preceding the 2840-keV line. The 644-keV peak was due to gating by the 3919″ line at 2998 keV.

The spectrum gated by the 2622-keV peak shows a strong 1461-keV line [Fig. 4(e)]; thus, a cascade through the 1461-keV level from a level at 4082 keV is indicated. The 644-keV peak is due to the inclusion, within the lower-energy side of the gate, of pulses from the 2457-keV peak. An expected 480-keV peak is concealed by the 511-keV line.

B. Energy of the First Excited Level of ^{40}Ar

A separate measurement was made of the energy of the γ ray which is emitted following the decay of ^{40}K (by electron capture) to the first excited level of ^{40}Ar. The source consisted of the potassium occurring naturally in the concrete structure of the laboratory, and in several kg of available potassium compounds. Suitable statistical accuracy was obtained in 8-h counting periods. Standard sources of ^{60}Co and ^{228}Th were counted at the same time to provide lines which bracketted the ^{40}Ar line. The 35-cc Ge(Li) crystal detector was used. The average of several determinations was 1460.71 ± 0.05 keV. The present result is a needed confirmation of the previously reported value[25] of 1460.75 ± 0.06 keV. The average of the two is 1460.73 ± 0.05 keV. This γ ray can be used to fill a gap in the sequence of known standard energies, although naturally occurring sources of ^{40}K are extremely weak, and the short half-life of ^{40}Cl makes the use of this radioisotope inconvenient.

Assuming that the emitting nucleus is free to recoil, the recoil energy of 0.03 keV added to the γ-ray energy gives the level energy as 1460.76 ± 0.05 keV.

C. Energy Levels of ^{40}Ar

Table I gives the energies and the relative intensities of γ rays which have been assigned to transitions in ^{40}Ar. In the energy-level diagram of Fig. 5 is shown the result of assigning the 23 observed γ rays to particular transitions. Assignments have been made according to one or more of the following criteria: (a) agreement with γ-γ coincidence data; (b) existence of levels known from the ^{40}Ar(p, p') reaction; (c) the matching of the γ-ray energy to an energy interval between known levels; and (d) agreement with β-γ coincidence data of Ref. 4 to a limited extent. For several of the lower levels, very low-intensity γ rays were not detected in this work, but are known from Ref. 2; for completeness, they are shown on the diagram and are marked with an asterisk.

In the diagram, level energies are weighted averages which have been determined from the γ-ray measurements either from a direct transition to the ground-energy level, or through making a sum

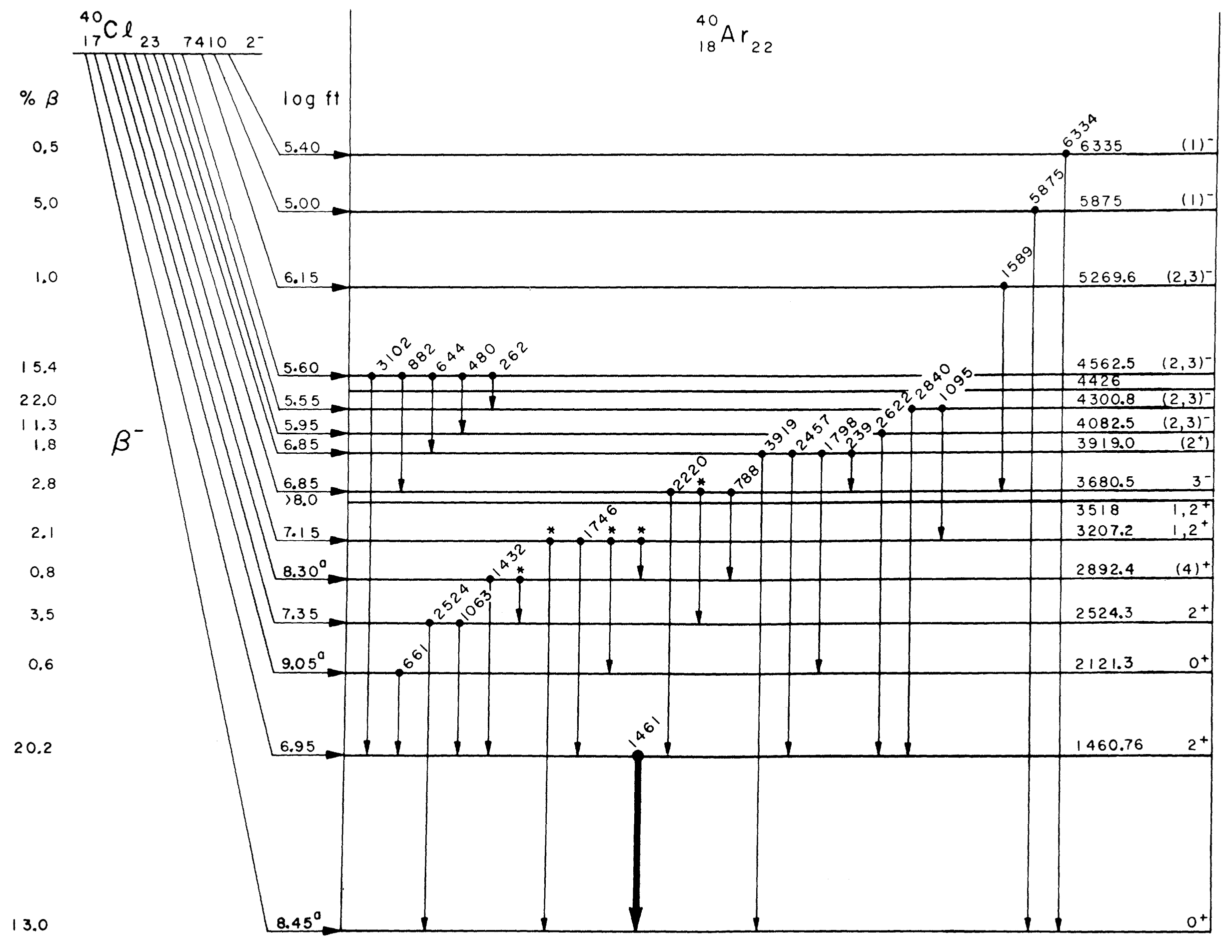

FIG. 5. Energy-level diagram for ^{40}Ar. Transitions marked with (*) are based on data from Ref. 2. The $\log f_0 t$ values were calculated from intensities deduced from the γ-ray data, as discussed in the text. Those which are marked (a) are "unique" first-forbidden $\log f_1 t$.

of energies of cascading γ rays, or both. Internal consistency is good, with the sum of cascading γ-ray energies typically adding to a crossover energy within two standard deviations. The largest discrepancy is 0.9 keV, at the 3919-keV level. It is to be noted that the levels of Fig. 5 which are populated by β decay are evidently ones which were previously observed in the (p,p') reaction,[9] with the possible exception of the 6335-keV level, which is 65 keV higher than the closest (p,p') level. Mostly, the (p,p') levels are slightly higher than those presently determined, with a maximum disagreement of 33 keV at the 4563-keV level. The level assignment at 5269.6 keV is tentative. It is located in energy by the sum 3680.5 + 1589.1 keV which places it 29 keV lower than a level known from the (p,p') reaction. There is no supporting coincidence data.

The level energies of Table I have been adjusted where necessary through the adding of the nuclear recoil energy, $E_\gamma^2/2Mc^2$, which is typically less than the statistical uncertainty in level energy but is 0.6 keV for the highest energy level.

Table I gives a summary of the branching ratios for the γ deexcitation of the levels of ^{40}Ar. The uncertainty in the γ-ray yields due to counting statistics was typically less than ±5%. The listed uncertainties in the γ-ray relative intensities include a contribution from the relative-efficiency determination. For the 4301-keV level, the coincidence data yield a ratio of intensities, $I(265)/I(1461)$, which is in agreement with the proposed decay diagram.

The ^{40}Cl β-ray branching was deduced through consideration of the γ-ray relative intensities. The beta intensities thus deduced were normalized to parts per 100 β decays – excluding the β-ray transitions to the ground level – and the results are given in column 2 of Table II. The β-γ coincidence data of Robinson[4] showed that the β rays in coinci-

TABLE I. ^{40}Ar level energies, γ-ray transitions, branching ratios, and γ-ray energies. T, ′, and ″ indicate observation of total energy, one-annihilation-photon escape, and two-annihilation-photon escape peaks. The nuclear recoil energy, where significant, has been added in deducing the level energy.

Level in ^{40}Ar (keV) E_i	Transition (keV) $\to E_f$	Branching ratio (%)	γ-ray energy (keV)	Observed (T,′,″)	Intensity relative to the 1461-keV line
1460.76 ±0.05	→0	100	1460.71 ±0.05	T,″	100.0
2121.3 ±0.2	→1460.8	100	660.5 ±0.2	T	3.2 ±0.3
2524.3 ±0.2	→0	45	2524.2 ±0.4	T	2.3 ±0.3
	→1460.8	55	1063.4 ±0.3	T	2.8 ±0.3
2892.4 ±0.4	→1460.8	98[a]	1432.0 ±1.5	T	2.1 ±0.3
	→2524.3	2[a,b]	···	···	···
3207.2 ±0.3	→0	12[a,b]	···	···	···
	→1460.8	84[a]	1746.4 ±0.3	T	3.0 ±0.3
	→2121.3	2[a,b]	···	···	···
	→2892.4	2[a,b]	···	···	···
3680.5 ±0.4	→1460.8	82	2219.5 ±0.4	T	7.1 ±1.0
	→2524.3	6[a,b]	···	···	···
	→2892.4	12	788.2 ±0.3	T	1.0 ±0.1
3919.0 ±0.5	→0	36	3918.7 ±0.4	T,′,″	4.2 ±0.8
	→1460.8	39	2457.0 ±0.4	T,″	4.5 ±0.8
	→2121.3	21	1797.8 ±0.3	T	2.4 ±0.3
	→3680.5	4	239.0 ±0.3	T	0.5 ±0.1
4082.5 ±0.4	→1460.8	100	2621.6 ±0.2	T,′,″	16.6 ±1.7
4300.8 ±0.4	→1460.8	98	2839.8 ±0.4	T,′,″	29.2 ±2.9
	→3207.2	2	1094.6 ±1.0	T	0.5 ±0.1
4562.5 ±0.4	→1460.8	25	3101.8 ±0.4	indirect	5 ±3
	→3680.5	15	881.6 ±0.3	T	3.1 ±0.3
	→3919.0	46	643.8 ±0.2	T	9.3 ±1.0
	→4082.5	9	480.2 ±0.3	T	1.8 ±0.3
	→4300.8	5	261.6 ±0.3	T	1.0 ±0.1
5269.6 ±0.5	→3680.5	100	1589.1 ±0.3	T	1.3 ±0.2
5875 ±3	→0	100	5875 ±3	′,″	6.5 ±1.3
6335 ±3	→0	100	6334 ±3	″	0.7 ±0.2

[a] From Ref. 2.
[b] These very low-intensity transitions were not observed in the present study.

dence with the 1461-keV γ rays had lower endpoint energies than the noncoincident β rays, and hence that the observed 7410-keV β group was undoubtedly due to a transition to the ^{40}Ar ground level. In order to obtain logft values, a fraction of the β decays must be assigned to the ground-level transition; about this the present data give no information. The only available data are that of Robinson,[4] who found that 9% of the β-decay transitions go to the ground level. However, Robinson also found that the ratio of the ground-transition group to the first-excited-level group was approximately 1:1 in intensity. Use of this ratio with the present data gives the result that the ground-transition group comprises 18% of all β transitions. It appears that the true value is between 9 and 18%; 13% was used in the calculation of the percentages of column 3 of Table II. Then, comparative half-lives were evaluated using the appropriate curves and nomograph,[26] and using 1.38 min as the half-life; the resulting $\log f_0 t$ are listed in column 4. The $\log f_0 t$ do not depend critically on the assumed 13%; e.g., ignoring the ground-level transition altogether would decrease the $\log f_0 t$ by only 0.06.

The present results can be used to argue that the spin-parity of the ground level of ^{40}Cl is 2^-. The known β decay to the 0^+ ground level of ^{40}Ar, and the deduced β decay to the 2^+ and 0^+ excited levels, are interpreted as first-forbidden transitions because of the large $\log f_0 t$. Thus the spin-parity of ^{40}Cl could only be 0^-, 1^-, or 2^-. Then the deduced β decay to the known 3^- level at 3681 keV could only be an allowed transition with $\Delta J = +1$, with 2^- as the only possible choice as the spin parity of the ^{40}Cl ground level, if, in fact, the 3681-keV level of ^{40}Ar has spin-parity 3^-. This is analogous to ^{38}Cl, which is known to have spin-parity 2^-. Also, the spin is in accord with Nordheim's strong rule[27] for odd-odd nuclei, which is that J equals the minimum of the sum over the spins j_i of the odd proton and neutron. Here, the odd $d_{3/2}$ proton and the odd $f_{7/2}$ neutron contribute to

TABLE II. The $\log f_0 t$ values. The β decay percentages in column (2) have been deduced from the γ-ray relative intensities. The ground-level β decay is discussed in the text.

Level in ^{40}Ar (keV)	% of ^{40}Cl β decay to each level: Excluding the ground level	Including the ground level	$\log f_0 t$
0	...	13.0	7.45 (8.45)[a]
1460.8	23.2	20.2	6.95
2121.3	0.7	0.6	8.25 (9.05)[a]
2524.3	4.0	3.5	7.35
2892.4	1.0	0.8	7.65 (8.30)[a]
3207.2	2.5	2.1	7.15
3518	...	<0.3	>8.0
3680.5	3.3	2.8	6.85
3919.0	2.0	1.8	6.85
4082.5	13.0	11.3	5.95
4300.8	25.2	22.0	5.55
4562.5	17.7	15.4	5.60
5269.6	1.1	1.0	6.15
5875	5.7	5.0	5.00
6335	0.6	0.5	5.40

[a] $\text{Log} f_1 t$; "unique" first-forbidden transitions with $\Delta J = \pm 2$.

$J = \frac{7}{2} - \frac{3}{2} = 2$.

As a consequence of the 2^- assignment to ^{40}Cl, the $\log f_1 t$ were calculated[26] for the unique first-forbidden transitions to the two 0^+ levels and the probable 4^+ level. They fall within the frequency-versus-$\log f_1 t$ distribution of Lipnik and Sunier,[28] which shows that the $\log f_1 t$ for known $\Delta J = \pm 2$ transitions are grouped closely around 8.3, with a lower limit at approximately 8.

The spins given in Fig. 5 are supported by data of Ref. 2, up to and including the 3681-keV level. The parity of the 3207-keV level is uncertain, since the $\log f_0 t$ permits either a first-forbidden $\Delta J = 0, \pm 1$, or an unfavored allowed transition. The inelastic α-particle scattering results[14] indicate odd parity, hence an allowed decay; on the other hand the systematic trend of $\log ft$ predicts 7 to 7.5 for a $\Delta J = 0$ first-forbidden decay.

The 3518-keV level is known[2] to have $J = 1$ or 2 and to decay to the 1461-keV level (84%) and to the ground level (12%). Neither γ ray was seen. However, a $\log f_0 t$ value of approximately 8.0 would reduce the relative intensity of the 3518 $\rightarrow$ 1461-keV transition to about 0.3% and it would not have been detectable. Therefore a first-forbidden transition is assumed, and even parity is assigned to this level. The probability of the 3207- and 3518-keV levels having even parity is favored by the systematic behavior of nuclei in this mass region, wherein the lowest-energy odd-parity level is always 3^-. Lassen and Larson[15] have assigned spin-parity 3^- to the 3681-keV and 5^- to the 4426-keV level on the comparison of analogous features of the inelastically-scattered α-particle yields from ^{40}Ar and ^{40}Ca targets. They found that these two levels were excited strongly and with the same angular distributions as the well-known 3^- and 5^- levels of ^{40}Ca at 3730 and 4480 keV. Wakatsuki *et al.*[14] give the 3681-keV level a definite 3^- assignment. The present results are consistent with these assignments, since of the two levels only the 3^- level is populated by β decay from the 2^- parent, as expected. The parity of the 3919-keV level is uncertain for the same reason that applies to the 3207-keV level; however, the γ-decay modes suggest even parity and $J = 2$. Higher-energy levels are given odd parity, since they are evidently populated by allowed β-decay transitions; each level could have spin of 1, 2, or 3, but some limits have been placed on the spin on the basis of the γ-decay modes. That is, levels which decay to 0^+ probably do not have spin-parity 3^-, and those which do not decay to 0^+ probably do not have 1^-. The low-energy decay modes of several of the higher energy levels, especially the 4563-keV level, are similar to those observed[29] in ^{36}Ar and ^{38}Ar, and are probably to be attributed to $M1$ transitions between odd-parity levels.

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Production of ^{32}P and ^{33}P from Various Targets with 550-MeV Protons*

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Cross sections for the production of ^{32}P and ^{33}P have been determined with 550-MeV protons on 19 target elements ranging from titanium to uranium. The main features of the results are an exponential decrease of the cross sections with increasing target mass up to zinc, a broad maximum between zirconium and tin, and an increase in cross section with increasing target mass between tantalum and uranium. All of the features have been correlated with similar results for ^{22}Na and ^{24}Na. In addition, an analytic function has been used to represent the experimental results in the region where ^{32}P and ^{33}P are produced primarily as spallation products.

INTRODUCTION

Studies of high-energy proton reactions ($Ep > 100$ MeV) in which the products have mass numbers approximately between 15 and 40 are becoming more frequent. When the target mass number is less than about 60 the production is generally explained on the basis of the cascade-evaporation mechanism in which these products are the end result of a long chain of nucleon emissions. The production cross sections for these products are predicted by such a mechanism to decrease exponentially with