Excited States of ^{40}Ar Observed in the Reaction ^{40}Ar $(\gamma,n_0)^{39}$Ar

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We identify 27 excited states of ^{40}Ar in the energy range 10.4–12.5 MeV from the photoneutron spectrum of ^{40}Ar irradiated with 12.5-MeV bremsstrahlung. These levels are probably associated with the promotion of one of the $1f_{7/2}$ valence neutrons into the continuum. The distribution of radiation strength in this region suggests the presence of a single-particle resonance in ^{40}Ar at ~ 10 MeV.

We wish to report 27 new[1] levels in ^{40}Ar between 10.4 and 12.5 MeV, observed in photoneutron spectra from liquid argon. The experiment was carried out at the National Research Council's electron linear accelerator laboratory using conventional nanosecond time-of-flight methods[2] with a resolution of 0.6–0.9 nsec/m (20 keV at a neutron energy of 1 MeV).[3] Bremsstrahlung from a 0.05-cm Ta radiator, swept clean of electrons by a dump magnet, was used to irradiate a 4-liter, 12-cm-diam Dewar of liquid Ar placed 1 m from the radiator. Photoneutrons from the target entered an evacuated flight tube with internal collimation which allowed a proton recoil detector placed 31.2 m away to view a 15-cm-diam region of the target. The detector consisted of a 30-cm-diam, 8-cm-thick cylinder of NE102 plastic scintillator viewed by four photomultipliers. A neutron event was defined by a fast (20 nsec) coincidence between any two of them.

Figure 1 shows the photoneutron time distribution obtained in an 18-h run at an end-point energy of 12.6 MeV. The open circles represent the background observed in a similar run when the Ar was exposed to 9.8-MeV bremsstrahlung. Most of this background was independent of time

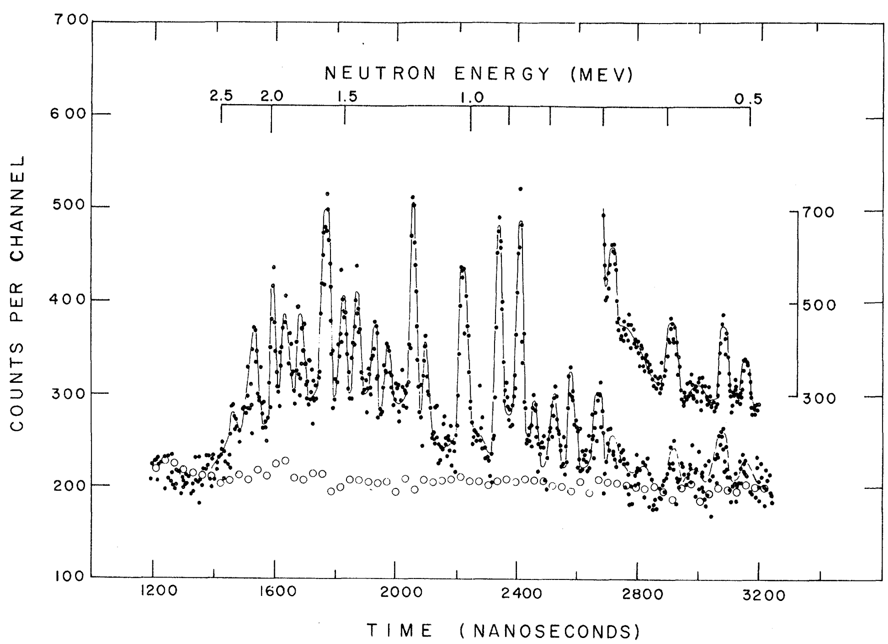

FIG. 1. Neutron time-of-flight spectra for the ^{40}Ar(γ,n_0) reaction. Closed circles, data taken at a bremsstrahlung end-point energy of 12.6 MeV. Open circles, ten-channel averages of data taken at 9.8 MeV, below the neutron threshold of Ar. Inset, data taken at 17.5 MeV. Only the neutron peaks at 1.02 and 1.60 MeV are significantly broader than the instrumental resolution (see text). Note suppressed zero.

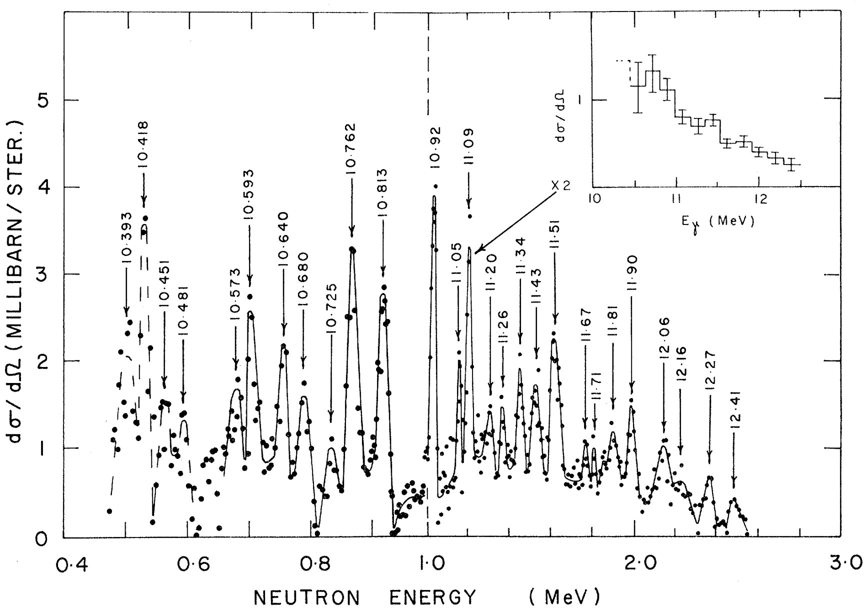

FIG. 2. Differential cross section at 90° for the reaction $^{40}Ar(\gamma, n_0)^{39}Ar$. Note the change of scale at a neutron energy of 1 MeV. The inset shows the same cross section plotted as a function of photon energy, and averaged over 200-keV intervals.

and arose from random scintillations in the large detector. The region from 2700–3200 nsec is also plotted for a 17.5-MeV run and shows the low-energy neutron groups more clearly. A bremsstrahlung distribution for 12.6-MeV electrons was obtained under the same operating conditions by measuring the photoneutron spectrum from a deuterium target (a 15-cm×4-cm cylinder of heavy water) and using the known[4] photodisintegration cross section of the deuteron to convert it to a photon distribution.

Figure 2 shows the differential cross section at 90° for the reaction $^{40}Ar(\gamma, n_0)^{39}Ar$ obtained by dividing the observed neutron spectrum by the measured photon distribution. Since the first excited state of ^{39}Ar lies at 1.27 MeV,[1] the outermost 1.27 MeV of the spectrum must consist of neutrons making transitions to the ground state of ^{39}Ar. A run at a bremsstrahlung end-point energy of 11.6 MeV confirmed that *all* neutron groups observed in the 12.6-MeV run represented transitions to the ground state of ^{39}Ar. A total of 27 neutron groups are evident in the spectrum at neutron energies between 0.5 and 2.5 MeV. The excitation energies given in the figure were obtained from the neutron energies by using the relationship $E_{ex} = \frac{40}{39}E_n + S_n$, where S_n, the neutron separation energy for ^{40}Ar, is 9.872 MeV.[5] The absolute cross-section scale was obtained by comparing the neutron yields from liquid Ar and heavy water contained in identical $\frac{1}{2}$-liter containers.

The energy dependence of the neutron detector was obtained by measuring the photoneutron distribution from deuterium irradiated with bremsstrahlung of end-point energy 19 MeV, and comparing it with the spectrum calculated from the known deuterium photodisintegration cross section[4] for a Schiff bremsstrahlung distribution.[6] It was found that the detector had a threshold of 300 keV and a relative efficiency which increased almost linearly with neutron energy between threshold and 2.5 MeV and remained fairly constant at higher energies. The cross section presented in Fig. 2 has been corrected for this detector efficiency.

The integrated cross section over the energy range 10.4–12.5 MeV is 15 MeV mb, under the assumptions (i) and (ii) below, and is quite large, representing about 2% of the exchange-augmented dipole sum.[7] The inset to Fig. 2 shows the cross section averaged over 200-keV intervals to illustrate the gross behavior of the absorption in this region. For the high-energy part of the spectrum ($\gtrsim$ 1 MeV) the errors shown in the inset were assigned from the estimated uncertainty in the background level. At lower energies the error is larger because of the increasing uncertainty in the estimated detector efficiency near threshold. We note that the cross section decreases with increasing photon energy and that its general shape suggests a resonance of some kind at 10–11 MeV. Similar concentrations in photon transition strength have been reported for other nuclei in photoneutron measurements near threshold,[8,9] in the study of the inverse radiative capture process,[10] and in measurements of the elastic photon scattering cross section below the photoneutron threshold.[11] In some cases where these display a typical intermediate structure width of a few hundred keV or less, they have been interpreted as "photon doorways" to the compound nucleus.[8] The present example does not appear to fit so readily into this category, however, as it is considerably broader. It is striking too, that neutrons are emitted exclusively to the ground state of ^{39}Ar from this region of excitation, even though transitions to the low excited states of ^{39}Ar are energetically possible. In runs at higher energies we observe an abrupt change in the character of the photoneutron emission, starting at a photon energy of ~14 MeV, where neutrons are emitted freely to several of the low-lying excited states of ^{39}Ar. A complete account of our measurements is in preparation.

We suggest that the present experiment examines photon interactions which promote into the continuum one of the two $(1f_{7/2})$ valence neutrons in ^{40}Ar, leaving the residual ^{39}Ar nucleus undisturbed in its ground state $(J^\pi = \frac{7}{2}^-)$. At higher energies we begin to excite the collective giant dipole resonance, and the residual nucleus is left with a hole in one of its closed shells—a higher-energy configuration than that of the ground state. In view of their strength most of the low-lying transitions which we observe are likely to be electric dipole in character, although a few of them may be due to $M1$ transitions, and should be excluded in estimating the $E1$ cross section. It is probable that the individual resonances share the strength of a single-particle transition, for which $(1f_{7/2} \rightarrow 1g_{9/2})$ is a likely candidate. Theoretical estimates[12] of ~10–12 MeV for the energy of $E1$ transitions out of this valence shell agree quite well with the observed energy. However, the two peaks at 1.02- and 1.60-MeV neutron energy, which are clearly broader than the instrumental resolution, might well be $1f \rightarrow 2d$ transitions.

We have evaluated the ground-state radiation width $\Gamma_{\gamma 0}$ for each of the observed resonances, using the relationship[13]

$$\int_0^{2\pi} d\varphi \int_0^{\pi} (d\sigma/d\Omega) \sin\theta \, d\theta = 2\pi^2(\lambda/2\pi)^2 g\Gamma_{\gamma 0}, \quad (1)$$

with these assumptions: (i) All transitions are electric dipole. Since the ground state of ^{40}Ar has zero spin $(I=0)$, the intermediate state has unit spin $(J=1)$, and the statistical factor $g=(2J+1)/2(2I+1)$ takes the value $\frac{3}{2}$. (ii) The angular distribution of the emitted photoneutrons is[14] $W(\theta) \sim 1 + \frac{5}{6}\sin^2\theta$, corresponding to the $1f_{7/2}$-$1g_{9/2}$ single-particle transition. The integrated cross section for each peak was defined as the total area between the minima on either side. While this includes contributions from the wings of neighboring resonances, this is largely compensated for by the omission of the wings of the resonance being evaluated. For this reason the total area presented in Table I is somewhat less than the full area of Fig. 2, since there are some regions which have not been included in indivi-

TABLE I. Transition strengths for excited states of ^{40}Ar.

Excitation Energy (MeV)	Area of Resonance (MeV-mb/ster)	$g\,\Gamma_{\gamma 0}$ [a] (eV)	$\Gamma_{\gamma 0}$ [b] (eV)
10.393	(0.075)	(11.3)	(7.5)
10.418	(0.064)	(9.6)	(6.4)
10.451	(0.033)	(5.0)	(3.3)
10.481	(0.033)	(5.0)	(3.4)
10.573	0.047	7.3	4.9
10.593	0.052	8.1	5.4
10.640	0.059	9.3	6.2
10.680	0.044	7.0	4.6
10.725	0.044	7.0	4.7
10.762	0.080	12.8	8.5
10.813	0.072	11.7	7.8
10.92	0.080	13.2	8.8
11.05	0.031	5.2	3.5
11.09	0.066	11.2	7.5
11.20	0.042	7.3	4.8
11.26	0.034	6.0	4.0
11.34	0.050	8.9	5.9
11.43	0.062	11.2	7.4
11.51	0.083	15.2	10.1
11.67	0.023	4.4	3.0
11.71	0.018	3.5	2.3
11.81	0.060	11.5	7.7
11.90	0.047	9.2	6.2
12.06	0.045	9.1	6.0
(12.16)	(0.042)	(8.7)	(5.8)
12.27	0.022	4.6	(3.1)
12.41	(0.02)	(4.5)	(3.0)

[a]Assuming angular distribution $1 + \frac{5}{6}\sin^2\theta$.
[b]Assuming $g = \frac{3}{2}$.

dual resonances. The results are presented in Table I, where it is seen that ground-state radiation widths lying between 2 and 10 eV prevail. For the region near the detector threshold and the region close to the bremsstrahlung tip, entries in Table I have been placed in parentheses.

Using an average level spacing D of 70 keV (27 levels are excited in an interval of 2 MeV), we obtain values for the ground-state $E1$ strength function lying between 2×10^{-5} and 1.5×10^{-4}, with an average value of $\langle\Gamma_{\gamma0}/D\rangle = 8\times10^{-5}$. Such a value of $\langle\Gamma_{\gamma0}/D\rangle$ accords well with $E1$ transition strengths in the inverse radiative capture process.[15] A similar value of 9.6×10^{-5} is quoted by Fultz *et al.*[16] for ^{26}Mg, and is also interpreted as representing radiative strength not associated with the giant dipole resonance. Axel[17] has proposed that, in general, the distribution of $E1$ strength near the neutron threshold should reflect the low-energy wing of the giant dipole resonance, and predicts that for a typical heavy nucleus the strength should vary as E^5. The energy dependence for ^{40}Ar is quite different, and suggests that the distribution of $E1$ strength near the photoneutron threshold is reflecting the high-energy wing of a local single-particle resonance.

[1]P. M. Endt and C. Van der Leun, Nucl. Phys. A105, 1 (1967).

[2]R. W. Gellie, K. H. Lokan, N. K. Sherman, R. G. Johnson, and J. I. Lodge, to be published.

[3]The overall energy resolution is affected by the uncertainty in path length due to the finite thicknesses of both target and detector.

[4]J. S. Levinger, Phys. Rev. 97, 970 (1955); A. Whetstone and J. Halpern, Phys. Rev. 109, 2072 (1958).

[5]J. H. E. Mattauch, W. Thiele, and A. H. Wapstra, Nucl. Phys. 67, 32 (1965).

[6]L. I. Schiff, Phys. Rev. 83, 252 (1951).

[7]J. S. Levinger and H. A. Bethe, Phys. Rev. 78, 115 (1950).

[8]R. J. Baglan, C. D. Bowman, and B. L. Berman, Phys. Rev. C 3, 2475 (1971); H. E. Jackson and E. N. Strait, Phys. Rev. Lett. 27, 1654 (1971).

[9]E. J. Winhold, E. M. Bowey, D. B. Gayther, and B. H. Patrick, Phys. Lett. 32B, 607 (1970).

[10]G. A. Bartholomew, in *Proceedings of the International Symposium on Neutron Capture Gamma-Ray Spectroscopy, Studsuik, Sweden, 1969* (International Atomic Energy Agency, Vienna, Austria, 1969), p. 553.

[11]P. Axel, K. Min, N. Stein, and D. C. Sutton, Phys. Rev. Lett. 10, 299 (1963).

[12]A. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, New York, 1969), Vol. I, p. 239.

[13]R. J. Baglan, C. D. Bowman, and B. L. Berman, Phys. Rev. C 3, 672 (1971).

[14]E. D. Courant, Phys. Rev. 82, 73 (1951).

[15]L. M. Bollinger, *Experimental Neutron Resonance Spectroscopy* (Academic, New York, 1970), p. 235; G. A. Bartholomew, Annu. Rev. Nucl. Sci. 11, 259 (1961).

[16]S. C. Fultz, R. A. Alvarez, B. L. Berman, M. A. Kelly, D. R. Lasher, T. W. Phillips, and J. McElhinney, Phys. Rev. C 4, 149 (1971).

[17]P. Axel, Phys. Rev. 126, 671 (1962).

Hole-Strength Variations in Neutron Pickup Reactions to Isobaric-Analog States in Mo Isotopes*

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We report a study of isobaric-analog states excited in the (p,d) and (d,t) reactions on ^{92,94,96}Mo and in the reaction ^{98}Mo$(p,d)^{97}$Mo. We observe a large decrease in $l=1$ hole strength with increasing mass number and fluctuations in the ratios $C^2S_n\,(p,d)/C^2S_n\,(d,t)$. The first effect is discussed in terms of mixing with the dense spectrum of $T_<$ levels in the region of the isobaric-analog states.

Isobaric-analog states (IAS) in the $A=90$ region have been studied extensively via proton scattering[1] and, more recently, in proton stripping reactions.[2-4] However, no extensive studies of $T_>$ hole states have been reported for this region. In the present work, we studied IAS excited in the (p,d) and (d,t) reactions on ^{92,94,96}Mo and in the reaction ^{98}Mo$(p,d)^{97}$Mo. A comparison of spectroscopic strengths deduced from these two reactions is presented, with further comparisons to the parent-state results of Ohnuma and Yntema,[5] who studied the $(d,{}^3$He$)$ reaction on the molybdenum isotopes.

Data were taken with 38.6-MeV protons and