(γ,p) Reaction in Argon-40*

B. M. SPICER†
Physics Research Laboratory, University of Illinois, Champaign, Illinois
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The energy distribution and angular distribution of photoprotons from argon irradiated with 22.5-Mev bremsstrahlung have been measured. The yield of protons was found to be 6.6×10^5 protons per mole per r, in good agreement with Saskatoon results. The angular distribution of protons indicated that the absorption was predominantly electric dipole, as expected. The energy distribution peaked at 2.6 Mev, and, from its characteristics, it was inferred that the Coulomb barrier for protons plus Cl^{39} was only about 2.5 Mev, and that the level density in Cl^{39} increased with energy approximately as $\exp(E)$. These result are discussed in terms of the compound nucleus model and the direct photoeffect model.

INTRODUCTION

THE abnormally high (γ,p) cross sections in middle-weight nuclei excited with 17.6-Mev γ radiation[1] raised doubts as to the validity of the statistical theory of nuclear reactions, as applied to the nuclear photo-effect. The most successful hypothesis proposed to explain these data was that of Courant,[2] who postulated that a compound nucleus was not formed in all of the cases where a photon was absorbed by the nucleus. In these exceptional cases, the proton was ejected before it could interact with the other nucleons to form a compound nucleus.

In the light nuclei, where the surface-to-volume ratio is large, it might be expected that the direct effect will be emphasised. To test this hypothesis, Wilkinson and Carver[3] used the γ rays from the $Li^7(p,\gamma)Be^8$ reaction to irradiate an argon gas target. The gas was contained in a proportional counter, and the energy spectrum of the emitted protons was obtained by pulse-height analysis with a 99-channel kick-sorter. The energy distribution of the emitted charged particles had the following characteristics: (a) A large peak was present which was of the same type predicted by the statistical theory of nuclear reactions. This peak occurred at a proton energy of 2.5 Mev, and this energy is lower than is expected on a statistical model, using an exponentially increasing level density in the residual nucleus, and assuming a constant characteristic temperature of 1 Mev. (b) Two small, high-energy peaks were found at proton energies of 6.8 and 5.7 Mev. These were interpreted as being due to transitions to the ground state and the first excited state of Cl^{39}, respectively. However, since the threshold for the reaction, as inferred from these proton energies, is in disagreement with the evidence from other sources, the implications of the existence of these two peaks will not be considered.

Wilkinson and Carver concluded that the reaction did not proceed with any great probability via a surface photoelectric effect since this would have given the main group at high energy. They found a ratio of (γ,p) to (γ,n) cross sections of about $\frac{1}{3}$, instead of 1/25 as expected from the statistical theory.

This abnormally high (γ,p) to (γ,n) cross-section ratio was also found by McPherson, Pederson, and Katz.[4] They measured the activation curves for the $A^{40}(\gamma,n)A^{39}$ and $A^{40}(\gamma,p)Cl^{39}$ reactions by counting the neutrons and measuring the Cl^{39} activity, respectively. The characteristics of the cross-section curves for these two reactions are shown in Table I. The values of the maximum cross sections are even more striking evidence for the abnormally high $\sigma(\gamma,p)/\sigma(\gamma,n)$ ratio. This high ratio is all the more surprising when it is considered that the (γ,p) threshold in argon is 2.5 Mev higher than the (γ,n) threshold. This would lead one to expect that the neutron emission to be energetically favored over proton emission, and that the emission of protons would be further restricted by the Coulomb barrier.

In view of this surprising behavior, it was considered that further investigation of these reactions would be of interest. This paper reports on measurements of the energy distribution and the angular distribution of the protons emitted from argon gas which was irradiated with 22.5-Mev bremsstrahlung.

EXPERIMENTAL PROCEDURE AND TREATMENT OF DATA

The experimental technique used in this experiment was the same as was used in a previously reported

TABLE I. Characteristics of photonuclear cross sections in A^{40}.

Reaction	Energy of peak (Mev)	σ maximum (millibarn)	$\int_0^{25}\sigma dE$ (Mev-millibarn)	Yield at 22 Mev
$A^{40}(\gamma,p)$	$\geqslant 25$	$\geqslant 120$	540	5×10^5
$A^{40}(\gamma,n)$	20	38	350	10^6

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† Fulbright Fellow, on leave from the Physics Department, University of Melbourne, Melbourne, Australia.
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[2] E. D. Courant, Phys. Rev. 82, 703 (1951).
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[4] McPherson, Pederson, and Katz, Can. J. Phys. 32, 593 (1954).

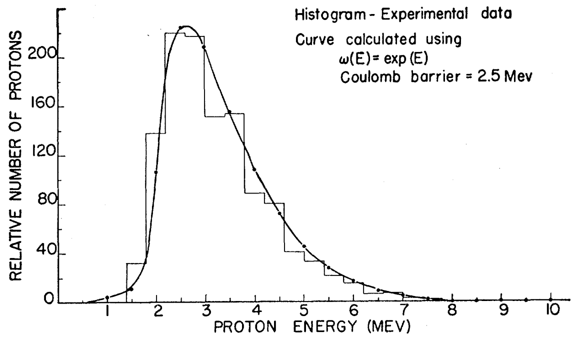

FIG. 1. Energy distribution of photoprotons from argon.

study of the photoprotons from oxygen.[5] An argon gas target, at a pressure of 1.19 atmospheres, was exposed to a collimated 22.5-Mev bremsstrahlung beam from the University of Illinois betatron. The protons emitted were detected in a pair of Ilford E1 emulsions, 100 microns thick.

Background tracks were due almost entirely to neutrons produced in the lead collimator giving rise to recoil protons in the emulsion. This background was estimated as described in reference 5. Background due to the $A^{40}(n,p)Cl^{40}$ reaction is negligible since its threshold, as calculated from the semiempirical mass formula is 8.1 Mev. The background was about 10% of the total number of tracks.

The energy of the proton at the surface of the emulsion was obtained from the range-energy data for Ilford emulsions given by Wilkins.[6] The energy lost by the proton in the gas between target and emulsion was calculated as described in reference 5. In the present experiment, the energy loss formula for argon (at 1.19 standard atmospheres pressure) was approximated by

$$-dE/dx=(0.1361/E)(\ln E+2.2239) \text{ Mev/cm}.$$

RESULTS AND DISCUSSION

(a) Proton Yield

In an area of 1.56 cm² which was scanned, 1350 proton tracks were found and measured. These numbers were substituted into the formula $Y=(4\pi N/d\Omega\cdot R)\times(1/MV)$, where Y is the yield in protons per mole per roentgen, R is the total dose given, in roentgens, as measured by a Victoreen thimble at the center of an 8-cm cube of Lucite, V is the effective volume of the gas target in cm³, N is the number of tracks found per unit area of the emulsion, M is the number of moles per cm³ of argon at the gas pressure used, and $d\Omega$ is the mean solid angle at the target subtended by unit area on the emulsion. The figure obtained for the yield of protons at 22.5 Mev was 6.6×10^5 protons per mole per roentgen. This is in very good agreement with McPherson *et al.*'s value of 7.3×10^5 protons per mole per roentgen.[4]

(b) Energy Distribution of Photoprotons

The measured energy distribution is shown in Fig. 1. This distribution has its peak at 2.6 Mev, and there are very few protons having energy greater than 5 Mev. This first statement is in good agreement with the findings of Wilkinson and Carver,[3] who found the peak at 2.5 Mev in their experiment with the Li γ rays. It is perhaps surprising that the energy of the peak is so nearly the same in the two experiments. The Wilkinson-Carver experiment was done at a single energy, 5 Mev above the (γ,p) threshold, whereas the present experiment, although it was done with a continuum of γ-ray energies, detected events which were produced chiefly in the energy range 20±2 Mev.

For comparison, energy distributions were calculated using the statistical theory of nuclear reactions. Now one would not expect a statistical theory to be applicable to a nucleus of only 39 nucleons. However, the results of Diven and Almy[7] on the energy spectrum of photoprotons from aluminum indicated that the statistical theory calculation could reproduce the general features of the observed energy distribution, and lent confidence to the use of the statistical theory to the present case.

The calculations made used the Coulomb barrier penetrabilities given by Feshbach, Shapiro, and Weisskopf,[8] and the cross section for the (γ,p) reaction was taken to be that measured by McPherson *et al.*[4] Three different forms were assumed for the level density in Cl^{39}. Writing the level density as $\omega(E)=\exp(E^n)$, the calculations were done for $n=0, \frac{1}{2}, 1$. The case $n=0$ was used because Diven and Almy[7] had some success with a level density of this form in predicting the energy distribution of photoprotons from aluminum. $n=\frac{1}{2}$ represents a simplification of the usually accepted form of

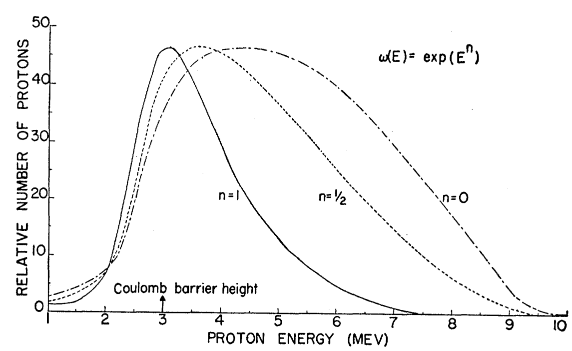

FIG. 2. Energy distribution of photoprotons, calculated using Coulomb barrier height of 3 Mev, level density$=\exp(E^n)$, and McPherson *et al.* measured (γ,p) cross section.[4]

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[8] Feshbach, Shapiro, and Weisskopf, Nuclear Development Association Report NYO 3077, 1953 (unpublished).

the level density in the statistical theory of nuclear reactions.

The probability of proton emission depends very strongly on the height of the Coulomb barrier. This would not normally be discussed, but Bethe has shown[9] that the peak in the energy distribution should approximate the height of the Coulomb barrier. The classical height for the Coulomb barrier ($Z/A^{\frac{1}{3}}$) is about 5 Mev. Therefore calculations were done for this case and also for the case of the Coulomb barrier being 3 Mev high. This value was suggested by the work of Scott,[10] who discussed the effects arising from consideration of the fact that the nuclear surface is not sharp. He concluded that the effect of a fuzzy surface would be to lower the height of the Coulomb barrier by about 40%.

The results of the calculations for the case of a Coulomb barrier height of 3 Mev are shown in Fig. 2. From the calculations we can draw two conclusions. First, the position of the peak in the energy distribution is controlled primarily by the height of the Coulomb barrier. The peak of the distribution shifts only 0.75 Mev between the two extreme level densities assumed (i.e., $n=0$ and 1). Second, the width at half-maximum of the peak in the energy distribution is determined chiefly by the value of "n" in the level density formula $\omega(E)=\exp(E^n)$. That is, it is determined by the rate of rise of the level density of the residual nucleus. The result of another calculation, using a Coulomb barrier height of 2.5 Mev, and a level density of the form $\omega(E)=\exp(E)$, is shown as the solid line in Fig. 1.

Therefore we conclude that the level density of Cl^{39} rises approximately as fast as $\exp(E)$, and that the effective height of the Coulomb barrier is only about 2.5 Mev instead of the classical value of 5 Mev.

The conclusions of this section support those of Wilkinson and Carver,[3] who noted that the explanation of the low energy of the peak in the energy distribution would require either a drastic modification of the Coulomb barrier or a level density which rises faster than $\exp(E)$. The present experiment apparently demands both of these possibilities.

(c) Angular Distributions

The angular distributions were plotted by grouping the tracks into 20° angular intervals, according to the angle the tracks made with the x-ray beam in the laboratory system. The plot was then corrected for the solid angle subtended by each interval at the position of the track. The solid angle correction factor is very closely $\langle\sin\theta\rangle_{Av}$, where $\langle\sin\theta\rangle_{Av}$ is the average value of $(\sin\theta)$ over the 20° interval.

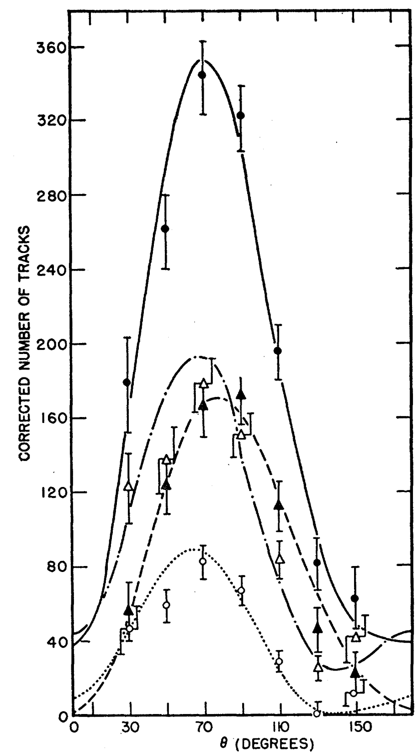

FIG. 3. Angular distributions of photoprotons from argon. ——— all protons, - - - - - - - protons of energy less than 3 Mev, —·—·—·— protons of energy greater than 3 Mev, ... protons of energy greater than 4 Mev.

The angular distributions obtained in this way are shown in Fig. 3. The distributions shown are for all protons, for protons having energy less than 3 Mev, protons having energy greater than 3 Mev, and greater than 4 Mev.

In all cases, the observed distributions could be fitted with curves of the form $a+b\sin^2\theta(1+c\cos\theta)$. This form was suggested by the large anisotropy which was present in all the angular distributions. The constants were determined by making least squares fits to the data. The least squares fits for the four cases are shown on Fig. 3, and the constants as determined are summarized in Table II. In the cases of the high energy protons, the lines have minima at about 130°, as well as the maxima between 60° and 70°. These minima are not to be taken seriously, since the statistics of the measurements at angles greater than 120° are very poor.

The "direct photoelectric effect" models put forward by Courant[2] and Wilkinson[11] predict, for the case of electric dipole absorption, an "$a+b\sin^2\theta$" form for the an-

TABLE II. Values of a, b, and c for the angular distributions.

Distributions	a	b	c
All protons	39	266	1
Protons $e_p<3$ Mev	2	160	0.5
Protons $e_p>3$ Mev	45	96	2
Protons $e_p>4$ Mev	10	52	2

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[11] D. H. Wilkinson, Proceedings of the Photonuclear Conference, Philadelphia, May, 1954 (unpublished).

TABLE III. Computed angular distributions for $A^{40}(\gamma,p)$ photoprotons.

$$A^{40}+\gamma\rightarrow A^{40*}\rightarrow Cl^{39}+p.$$

$$\mathbf{J}_A+\mathbf{l}_\gamma\rightarrow\mathbf{J}_B\rightarrow\mathbf{J}_c+\mathbf{l}_p.$$

$J_A=0^+$, $l_\gamma=1$, $J_B=1^-$ for all cases given here.

l_p	Jc	J of residual state	$N(^b)$
1	0	$\frac{1}{2}^+$	$3\sin^2\theta$
0	1	$\frac{1}{2}^-, \frac{3}{2}^-$	constant
2	1	$\frac{1}{2}^-, \frac{3}{2}^-$	$3\sin^2\theta+2$
1	1	$\frac{1}{2}^+, \frac{3}{2}^+$	$1+\cos^2\theta$
1	2	$\frac{3}{2}^+, 5/2^+$	$6+\sin^2\theta$
2	2	$\frac{3}{2}^-, 5/2^-$	$1+\cos^2\theta$
3	2	$\frac{3}{2}^+, 5/2^+$	$1+\sin^2\theta$
2	3	$5/2^-, 7/2^-$	$4+\sin^2\theta$

gular distribution. In particular, Courant's model gives, for the case of $E1$ absorption, distributions of the form:

for the $l\rightarrow l+1$ transition: $N(\theta)=l+\frac{1}{2}(l+2)\sin^2\theta$.

for the $l\rightarrow l-1$ transition: $N(\theta)=(l+1)+\frac{1}{2}(l-1)\sin^2\theta$.

l is the orbital angular momentum carried within the nucleus by the proton which was ejected. Wilkinson's model involves only the transition $l\rightarrow l+1$. If this picture is correct, the forms found for the angular distributions demand that the protons emitted from the A^{40} nucleus are predominantly these which have zero orbital angular momentum within the nucleus. This condition is then difficult to reconcile with the shell model of the nucleus, which is surely correct when applied to the ground states of the nuclei in this region of Z. The last-filled proton shell in A^{40} is indeed a $2s_{\frac{1}{2}}$ shell, but there is also a partially filled $1d_{\frac{3}{2}}$ shell on the proton side. One may then ask, if the protons in the $2s_{\frac{1}{2}}$ shell participate so strongly, why the protons in the $1d_{\frac{3}{2}}$ shell do not participate to any great extent? Courant's model has no answer to this query, but Wilkinson's model gives the result that specially strong transitions occur if the emitted particle was initially in a closed shell, although the increase is not great for an s-shell. If this argument is correct, then one has a case in which a very few particles in the nucleus are responsible for about half of the dipole sum.

Using the method of reference 5, which means using the assumption that a compound nucleus of definite J is formed in the reaction, angular distributions were calculated for the case of electric dipole absorption of photons by the A^{40} nucleus. The results of the calculations are shown in Table III. J_C is the final channel spin, which is obtained by adding vectorially the total angular momentum of the residual state and the intrinsic spin of the outgoing particle. The first impression of the results in Table III is that, even allowing that a compound nucleus theory does apply, and that direct interaction effects are negligible, the experimental results are difficult to explain unless very special conditions are satisfied. One could get an angular distribution of the form "$a+b\sin^2\theta$" quite readily, but to obtain a ratio of "b" to "a" as large as is observed is a much more difficult problem.

The presence of an asymmetry about 90° implies that there must be interference between electric dipole and electric quadrupole absorption of photons. Unfortunately, there is no way of estimating their relative contributions. It should be noted that this interference can occur only if a number of levels of spins 1^- and 2^+ overlap at the excitations in A^{40} which are being considered.

DISCUSSION

McPherson *et al.*'s[4] measurement of the (γ,n) and (γ,p) cross sections showed that the (γ,p) cross section was rising in a region where the (γ,n) cross section was falling. This was not expected on the basis of a simple evaporation theory. Both the experiment of Wilkinson and Carver[3] and the present experiment show that the energy distribution of photoprotons produced in this reaction has its peak at an unexpectedly low energy. Also, this peak is unusually narrow. The angular distributions show a large anisotropy which is difficult to explain. It is the purpose of this section to examine the explanations for these anomalies which are offered by the two models for photonuclear reactions which have been discussed.

(a) The Direct Photoelectric Effect

On this model, the nucleon which absorbs the photon is the one emitted. Thus, there is no competition between neutron and proton emission in the same way as there is on the compound nucleus picture.

The explanation on this model for the energy and angular distributions of the protons is not at all satisfactory quantitatively, but it is certainly plausible qualitatively. It would have to go somewhat as follows: On Wilkinson's model,[11] the emission of protons from the $1d_{\frac{3}{2}}$ shell requires that the outgoing proton have three units of orbital angular momentum. The Coulomb barrier penetration factor for such protons is small even when the protons have several Mev energy. From a photon energy where the direct photoelectric effect is possible on the protons in the closed $2s_{\frac{1}{2}}$ shell, these protons may be the ones which have the greater interaction with the photons and are therefore predominantly emitted. The Coulomb barrier penetration factor would be larger for them. Also the interaction with the protons in the closed $2s_{\frac{1}{2}}$ shell is enhanced by the amount given by the "encouragement factors" discussed by Wilkinson.[11] This then would be a plausible explanation for the relatively sudden upturn of the cross section for the (γ,p) reaction at about 18 Mev. Since most of the events observed in this experiment are induced by photons of energy 20±2 Mev, it would also explain why the peak in the energy distribution appeared at an energy as low as 2.6 Mev for the 22.6-Mev bremsstrahlung irradiation. Thus, we are postulating that the protons in the $2s_{\frac{1}{2}}$ shell are bound by about 16 Mev. Allowing that the $2s_{\frac{1}{2}}$ proton shell plays the greatest part in the reaction would also mean that the large anisotropy in the angular distributions is also explained. There still remains the difficulty of explaining the steep rise of the cross section between 18 and 23 Mev.

One way of deciding between this picture and the compound nucleus picture would be to repeat the present experiment using bremsstrahlung energies of, say, 16, 18, and 20 Mev. If the model just described is correct, then at the 16- and 18- Mev bremmstrahlung irradiations, the proton angular distribution should have the form of $N(\theta)=1+\sin^2\theta$, since this is the angular distribution characteristic of a $d\rightarrow f$ transition made by the emitted particle. At these energies, it is supposed that a direct photoelectric effect on the protons in the $2s_{\frac{1}{2}}$ shell is energetically impossible. In the 20-Mev irradiation, the contribution of the protons from the direct effect in the $2s_{\frac{1}{2}}$ shell should be becoming important, and its effect on the angular distribution should be observable.

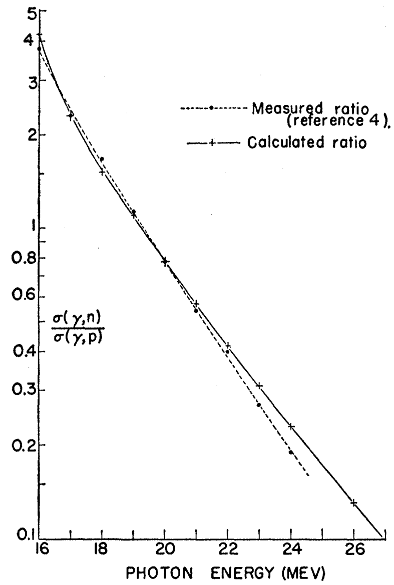

FIG. 4. Comparison with experiment of a rough calculation of the variation with energy of $\sigma(\gamma,n)/\sigma(\gamma,p)$.

(b) Compound Nucleus Theory

Using what was effectively a statistical theory, it was concluded earlier that to produce the observed shape of the energy distribution function, the level density of the residual nucleus, Cl^{39}, must increase with energy approximately as $\exp(E)$.

To get a clue as to the effect that this conclusion has on the ratio of (γ,p) to (γ,n) cross sections, we write down the expression for the ratio, on the statistical theory, of the two cross sections by integrating over the energy distributions. This gives

$$\frac{\sigma(\gamma,n)}{\sigma(\gamma,p)}=\frac{\int_0^{\epsilon_{n\,\max}}\epsilon_n\sigma_c(\epsilon_n)\omega(\epsilon_{n\,\max}-\epsilon_n)d\epsilon_n}{\int_0^{e\,\max}e\sigma_c(e)\omega(e_{\max}-e)de}.$$

Since the (γ,n) threshold is lower than the (γ,p) threshold in A^{40}, and the barrier penetrability for neutrons is always larger than the penetrability for protons of the same energy, there is only one factor in this equation which could be adjusted to allow the ratio of cross sections as given in the equation to become less than unity. This then would say that the energy dependence of the $\sigma(\gamma,n)/\sigma(\gamma,p)$ ratio is due to there being increasingly more proton exit channels than exit channels for neutron emission. This hypothesis was tested very crudely by the following calculation. In the formula given above, put

$$\omega(\epsilon_{n\,\max}-\epsilon_n)=A\exp[B(\epsilon_{n\,\max}-\epsilon_n)],$$
$$\omega(e_{\max}-e)=C\exp[D(e_{\max}-e)].$$

Replace the proton barrier penetration function by a step function at 2.5 Mev, in accordance with the conclusion drawn from the shape of the experimental energy distribution. Replace the neutron barrier penetration function by a step function at 0.2 Mev. The integrations may then be performed analytically, giving the result

$$\frac{\sigma(\gamma,n)}{\sigma(\gamma,p)}=\frac{A\left[\left(\frac{1}{B^2}+\frac{0.2}{B}\right)\exp\{B(\epsilon_{n\,\max}-\epsilon_n)\}-\left(\frac{1}{B^2}+\frac{\epsilon_{n\,\max}}{B}\right)\right]}{C\left[\left(\frac{1}{D^2}+\frac{2.5}{D}\right)\exp\{D(e_{\max}-e)\}-\left(\frac{1}{D^2}+\frac{e_{\max}}{D}\right)\right]}.$$

From this equation it is apparent that, to get any case where the ratio $\sigma(\gamma,n)/\sigma(\gamma,p)<1$, the condition that D be greater than B must be fulfilled. In Fig. 4, the results for $D=1$, $B=0.7$, $A=0.17C$ are shown. The relation between A and C was obtained by normalizing the calculated ratio to the experimental ratio at an energy of 20 Mev.

This rough calculation gives results which are in satisfactory agreement with experiment. It should not be taken as the final answer, however, since it was done merely to show that the existence of more exit channels for protons then for neutrons could explain the observed $\sigma(\gamma,n)/\sigma(\gamma,p)$ cross-section ratio.

This explanation rests explicitly on the assumption that, in this region of Z, the level density function for a given nucleus is a function of $(N-Z)$ as well as of A. In this case, it was assumed that

$$\omega(E) \text{ for } A^{39}(N-Z=3,\ J=7/2^-)$$

varied as $\exp(0.07E)$, while

$$\omega(E) \text{ for } Cl^{39}(N-Z=5,\ J=\tfrac{3}{2})$$

varied as $\exp(E)$. There is evidence supporting this assumption in the work of Gugelot[12] on the nuclear level densities as determined from (p,n) reactions in medium weight nuclei. In the more recent work of Miller, Friedlander, and Markowitz,[13] who investigated the competition between the (α,pn) and $(\alpha,2n)$ reactions in Cr^{50}, this same assumption must be used to explain their results, while still keeping the compound nucleus picture of nuclear reactions. The work of Cohen and Newman[14] on the ratio of the (p,pn) to $(p,2n)$ cross sections in nuclei of mass between 48 and 71 indicated that the ratio of probabilities of proton to neutron emission was much larger than expected on the usual statistical theory of nuclear reactions. These authors considered the explanation that the level density of odd-odd nuclei was very different from that of even-even nuclei of the same mass, which was advanced by Miller *et al.*[13] to explain their results. Cohen and Newman commented that this explanation would introduce difficulties into the explanation of certain results described in their paper. However, the idea is presented here because it does fit the observed facts in the case of the $A^{40}(\gamma,p)$ reaction.

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Disintegration Schemes of the Te^{127} and Te^{129} Ground States*†

M. C. DAY, JR., G. W. EAKINS, AND A. F. VOIGT
Institute for Atomic Research, and Departments of Chemistry and Physics, Iowa State College, Ames, Iowa
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A coincidence scintillation spectrometer was used to study the decay of the 9.3-hour Te^{127} isomer and the 72-minute Te^{129} isomer. The Te^{127} isomer was found to decay by a simple beta ray with an end-point energy of 0.683 ± 0.010 Mev. The beta-ray spectrum of the Te^{129} isomer consists of two beta groups with end-point energies of 1.46 ± 0.01 and 1.01 ± 0.02 Mev. Two gamma rays with energies of 0.450 ± 0.005 and 0.035 Mev were observed, and they were found to be in coincidence. The 0.450-Mev gamma ray was shown to be in coincidence with the 1.01-Mev beta ray, and the 0.035-Mev gamma ray was shown to be in coincidence with the 1.46-Mev beta ray. The results are consistent with level assignments based on the shell model of the nucleus.

INTRODUCTION

THE 9.3 hour isomer of Te^{127} was first studied by Seaborg, Livingood, and Kennedy.[1] Using absorption techniques, they were able to show that it decayed by a simple beta-ray group of ~0.8 Mev. A value of 0.7 Mev. was reported later.[2]

Absorption measurements on the 72-minute isomer of Te^{129} indicated that the radiations consist of two gamma-rays of ~0.3 and ~0.8 Mev and a beta ray of 1.75 Mev.[2] Wilkinson and Rall later reported a beta ray end point of 1.8 Mev as a result of spectrometer studies.[3] Since no coincidence studies on the Te^{129} isomer and no spectrometer measurements of the beta rays from the Te^{127} isomer have been reported, it was felt that further investigation was necessary.

SOURCE PREPARATION

A solution of $H_2TeO_4\cdot 2H_2O$ in 2.4*f* HCl and 1.25*f* HNO_3 was irradiated in the Iowa State College synchrotron. As a result of recoil following the (γ,n) reaction, essentially all of the active tellurium is reduced from the +6 valence state to lower valence states. Since there is no significant electron exchange between tellurate and these lower valence states under ordinary

* Based on a thesis submitted by one of the authors (M.C.D.) to Iowa State College in partial fulfillment of the requirements for a PhD. degree.
† Contribution No. 404. Work was performed in the Ames Laboratory of the U. S. Atomic Energy Commission.
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