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Brief Reports

Brief Reports are short papers which report on completed research or are addenda to papers previously published in the **Physical Review**. *A Brief Report may be no longer than 3½ printed pages and must be accompanied by an abstract.*

^{40}Ca$(\gamma, p_0)^{39}$K reaction for $E_\gamma = 100$–300 MeV

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The differential cross section for the ^{40}Ca$(\gamma, p_0)^{39}$K process has been measured in the energy range $E_\gamma = 100$–300 MeV at laboratory angles of 45°, 90°, and 135°. The cross section for the (γ,p) reaction leaving ^{39}K in its ground state was extracted from the tip region of the proton spectra measured at a series of bremsstrahlung endpoint energies. The data are compared with a distorted-wave impulse-approximation calculation based on a direct, single-particle knockout mechanism.

Differential cross sections for the exclusive (γ,p) reaction, in which the residual nucleus is left in its ground or a low-lying excited state, have been measured for various nuclei with $A > 4$ at photon energies in the range between the giant dipole resonance and the pion production threshold.[1–6] These measurements have been extended to higher energies for ^{16}O (Refs. 7 and 8) and ^{40}Ca; the latter results are reported here.

Owing to the large mismatch between the momentum of the outgoing proton and incoming photon, it has long been thought unlikely that a simple single-particle quasifree knockout (QFK) mechanism could account for the magnitude of the (γ,p) cross section. These reactions might therefore exhibit sensitivity to two-particle effects such as nucleon-nucleon correlations or meson exchange currents. For several nuclei with $A \leq 16$, frequently cited experimental evidence for this point of view is found in the magnitudes of the (γ,n) cross sections[6,9] which are comparable to those of the corresponding (γ,p) cross sections. However, for photon energies up to ~ 100 MeV, the QFK mechanism has been shown[10] to reproduce the (γ,p) results. Moreover, when recoil effects[6,11] and final-state charge exchange interactions[12,13] are examined, they are found to play a non-negligible role in the (γ,n) process, so that the need to invoke two-nucleon mechanisms is less strong. It must be noted, however, that the QFK calculations are very sensitive to the nuclear potentials chosen, and a wide range of results can be obtained for "reasonable" choices.[10]

For higher photon energies, the situation is rather different. For ^{16}O, the only nucleus for which extensive (γ,p) data exist, the QFK prediction[10] falls increasingly below the measurement[7] above 100 MeV. [There are as yet no comparable (γ,n) data.] Two models which treat different two-particle effects, viz., meson exchange currents[14] and intermediate-state $\Delta(1232)$ excitation,[15] produce large enhancements in the (γ,p) cross section but fail to obtain quantitative agreement with the data (see Ref. 7). This suggests the study of the (γ,p) process in another nucleus for $E_\gamma > 100$ MeV, to see whether the same discrepancies between experiment and theory are observed.

At lower energies ($E_\gamma = 60$–100 MeV), a comparison of measured cross sections for the (γ,p) reaction to low-lying states with QFK calculations has been carried out[3,4] for a range of nuclei with masses between $A = 7$ and 93. In this work, it appears that the QFK calculation is more successful for some nuclei than for others, although this could be partly a result of the potentials and hole-state systematics employed. With the parameters chosen, the QFK calculation was found to underestimate the measured cross sections for ^{12}C, ^{16}O, and ^{27}Al while reproducing or actually overestimating the results for ^{7}Li, ^{40}Ca, ^{59}Co, and ^{93}Nb. Of the latter four nuclei ^{40}Ca is advantageous for further study. In the ^{40}Ca$(\gamma, p_0)^{39}$K reaction the initial and final states are well represented as a doubly closed shell and a single proton hole in the $1d_{3/2}$ shell. The relatively high energy (~ 2.5 MeV) of the first excited state in ^{39}K also facilitates the extraction of the (γ, p_0) cross section from the endpoint region of the bremsstrahlung-induced proton spectrum.

The experiment was performed at the MIT Bates linear accelerator laboratory. The apparatus, experimental method, and data analysis procedure were identical to those described in Ref. 7. A natural calcium metal target was irradiated with a bremsstrahlung beam produced by a tungsten radiator of thickness ~ 0.04 radiation lengths, and the emitted protons were detected using a magnetic spectrometer equipped with drift chambers and plastic scintillation

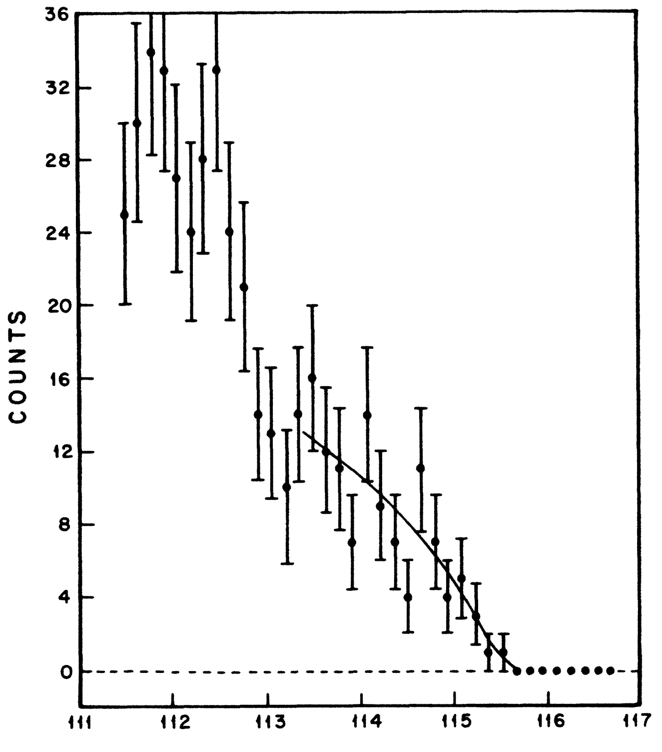

FIG. 1. Proton energy spectrum observed in the ^{40}Ca(γ,p)^{39}K reaction at $\theta_p=45°$ for a bremsstrahlung endpoint energy of 126 MeV. The solid line represents a fit to the data for final-state excitation energy $\lesssim 2.5$ MeV.

counters. The cross section for the ^{40}Ca(γ,p$_0$)^{39}K reaction was determined by fitting a calculated shape, determined principally by the incident bremsstrahlung spectrum, to the top ~ 2.5 MeV of the measured proton spectrum, as illustrated in Fig. 1.

The results are given in Table I and plotted in Fig. 2. The errors quoted are the statistical uncertainties combined with those systematic errors which vary from run to run. These include a 1%–5% uncertainty in the dead time correction and an energy dependent error, which varies from 1.7% for $E_\gamma \leq 151$ MeV to 5.4% at $E_\gamma = 301$ MeV, due to the uncertainty in the correction for nuclear interactions of the protons in the detector system. In addition, there is an overall systematic uncertainty of $\sim 4\%$ arising from the uncertainty in the incident photon flux.

TABLE I. Laboratory cross sections for the ^{40}Ca(γ,p$_0$)^{39}K reaction (nb/sr).

E_γ (MeV) \ θ_p	45°	90°	135°
101.5	349 ± 25	93 ± 11	10.2 ± 1.8
126.4	77 ± 9	35.9 ± 4.8	2.6 ± 0.7
151.3	63 ± 9	5.0 ± 1.4	0.77 ± 0.39
176.2	29.7 ± 4.4	1.3 ± 0.7	0.52 ± 0.26
201.2	27.7 ± 4.5	0.36 ± 0.36	0.13 ± 0.09
221.2	22.4 ± 3.7		< 0.035
241.2	8.6 ± 4.1	0.54 ± 0.46	
271.2	7.0 ± 1.8		
281.3		0.29 ± 0.24	
301.4	3.2 ± 1.2		

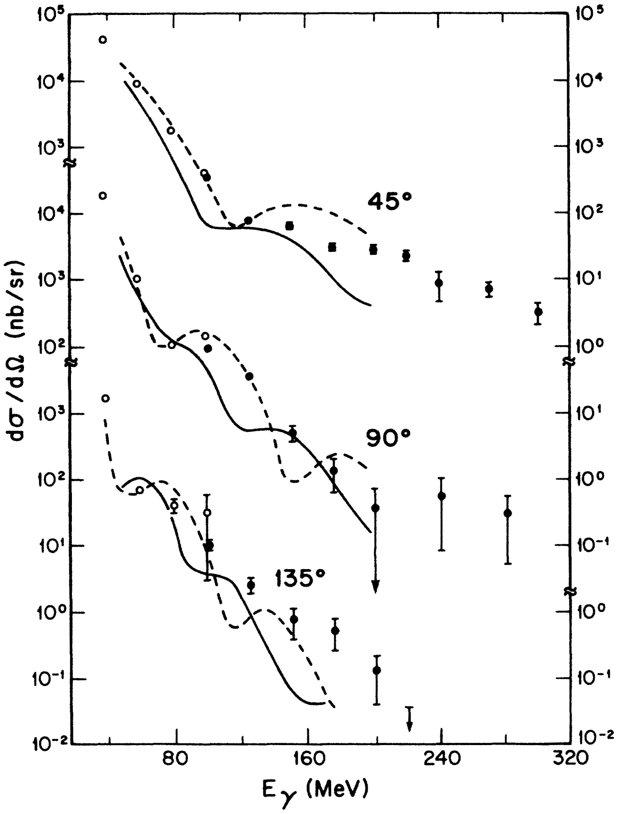

FIG. 2. Laboratory cross sections for the ^{40}Ca(γ,p$_0$)^{39}K reaction at $\theta_p=45°$, 90°, and 135° as a function of incident photon energy. The open circles are taken from Ref. 4; the solid circles are the results of the present experiment. The curves represent theoretical predictions of Boffi *et al.* (Ref. 10), using the bound state potentials of Ref. 17 (solid curves) or Ref. 18 (dashed curves) and the continuum state optical potential of Ref. 19.

The results of this experiment, together with some lower energy data,[4] are compared with a theoretical prediction in Fig. 2. The solid and dashed curves represent the QFK calculations of Boffi *et al.*,[10,16] obtained using the initial-state wave functions given by Negele[17] and Elton and Swift,[18] respectively. In both cases the final-state wave functions were determined by the optical potential of Nadasen *et al.*[19] The differences between these curves illustrate the rather large sensitivity of the QFK prediction to the form of the wave functions employed. However, both of these calculations are seen to provide a fairly good representation of the data at all three angles for $E_\gamma \lesssim 200$ MeV, the maximum photon energy for which the theoretical results were reported. This is in striking contrast to the QFK predictions of Boffi *et al.*[10] for ^{16}O, which fall well below the data at all but the most forward angle and lowest photon energies.

One criticism that has been made[14] of QFK calculations such as those in Ref. 10 is that orthogonality between the initial- and final-state wave functions has not been maintained, since these are calculated using different potentials. Boffi *et al.*[11] have estimated a correction for this effect, which they illustrate for the $^{12}C(\gamma,p_0)$ cross section at energies up to 100 MeV. For most of the angular range, the correction is small. Although it is not known what effect the orthogonality correction will have at higher photon energies, there is no evidence presently available that it will be large. Some further discussion of this problem may be found in Refs. 7 and 20.

The previously published results for the $^{16}O(\gamma,p)$ cross section[7,8] for $E_\gamma \geqslant 100$ MeV have demonstrated that we are far from a quantitative understanding of the intermediate energy photoproton knockout process. The data presented here for the $^{40}Ca(\gamma,p_0)$ reaction only serve to deepen the mystery. Whereas the results for ^{16}O seemed to indicate the presence of two-particle mechanisms, at least for photon energies above 100 MeV, the necessity of including such effects in the ^{40}Ca case is not evident from these data. Based on the comparison of the available calculations[10] for ^{40}Ca with the present results, one would conclude that the single-particle QFK mechanism provides an adequate explanation for the (γ,p) process.

Clearly, further theoretical and experimental work is needed. In particular, a study of the $^{40}Ca(\gamma,n_0)^{39}Ca$ reaction would be of great interest, since one of the strongest arguments for the importance of two-particle effects in the (γ,N) process is the near equality of the (γ,n) and (γ,p) cross sections [for $E_\gamma \lesssim 150$ MeV, where (γ,n) measurements have been made], and no (γ,n) measurements have been performed for $A > 16$.

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