Proton Capture Radiation from Ca^{40} in the Region of the Giant Resonance*†

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The 90° differential cross section for radiative proton capture to the ground state of Ca^{40} was measured for proton energies from 6 to 15 MeV, corresponding to Ca^{40} excitation energies of 14 to 23 MeV. A giant resonance near the excitation energy of 19 MeV with a width of about 3 MeV occurs in the $K^{39}(p,\gamma_0)Ca^{40}$ reaction. The giant resonance is split into eight resolved fine structure peaks between 18 and 22 MeV, and subsidiary peaks appear below the giant resonance at 15.2 and 16.2 MeV. This experiment extends the region of excitation energies studied in previous experiments, and the results are in agreement in the region of overlap. The pulse-height spectra from the gamma-ray spectrometer show a secondary gamma-ray peak with an energy corresponding to the energy of the radiation from transitions to one or more of the first four excited states of Ca^{40}. The gamma rays from the individual excited-state transitions were unresolved in this experiment. The area under the secondary peak is taken as the yield of gamma rays from the $K^{39}(p,\gamma_1+\gamma_2+\gamma_3+\gamma_4)Ca^{40*}$ reactions. The combined relative differential cross section for these reactions increases with energy by a factor of two over the range of excitation energies studied.

I. INTRODUCTION

RECENT shell-model calculations for the dipole states in doubly magic nuclei have contributed considerably to the understanding of the photonuclear effect in these nuclei. The general success of the calculations of Elliott and Flowers[1] for O^{16} has stimulated similar shell-model calculations for other nuclei,[2] particularly Ca^{40}. Brown *et al.*[3] have calculated the dipole states for O^{16} and Ca^{40} with a simplified procedure that uses a zero-range particle-hole interaction, and Balashov *et al.*[4] have performed similar calculations using finite range forces. Lee[5] has studied the specific effects of the spin-orbit force on the dipole states in O^{16} and Ca^{40}. All of these calculations for Ca^{40} agree in indicating a strong dipole resonance in the photonuclear cross section near 20 MeV.

Measurement of the cross section for radiative proton capture frequently offers a convenient means for studying the giant resonance in nuclei. The theorists working in this field are particularly interested in obtaining more information about gamma-ray transitions to low-lying excited states of nuclei,[6] for it appears that, in addition to the ordinary giant resonance for transitions to the ground state, there may also exist giant resonances built on excited states. Gove *et al.*[7] have separated the gamma-ray peaks for transitions to the first excited states of C^{12} and Si^{28}, and they found that the cross section for the $B^{11}(p,\gamma_1)C^{12*}$ reaction shows considerably more structure than that for the ground-state $B^{11}(p,\gamma_0)C^{12}$ reaction.

Tanner *et al.*[8] studied the $K^{39}(p,\gamma)Ca^{40}$ reaction and found that this reaction passes through a giant resonance corresponding to excited states of Ca^{40} in the region of 18 to 21 MeV. Their data suggest that the giant resonance in Ca^{40} is split into at least three fine structure peaks at 18.8, 19.6, and 20.0 MeV. Before the completion of the experiment described in this report, Feldman *et al.*[9] reported preliminary results of their (p,γ) experiments, and the final results[10] show the same fine structure as that found by Tanner *et al.* plus additional fine structure peaks at 19.2, 21.0, and 21.7 MeV. Neither of these experiments indicated transitions to low-lying excited states of Ca^{40}.

The experiment reported here was motivated by the desire to obtain more information about the cross sections for radiative proton capture transitions to both the ground and excited states of Ca^{40}. Past experience, however, has shown that radiative capture experiments of this type are seriously hampered by intense low-energy background radiation and that the energy resolution normally obtained is insufficient, in most cases, for separating the spectral peaks of the excited-state transitions from those due to the ground-state transitions. Consequently, a gamma-ray spectrometer with improved energy resolution was used. The 90° differential cross sections were measured by bombarding a thin,

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† This work is described in greater detail in a thesis submitted by one of the authors (J. C. H.) to the University of Illinois in partial fulfillment of the requirements of the Ph.D. degree.
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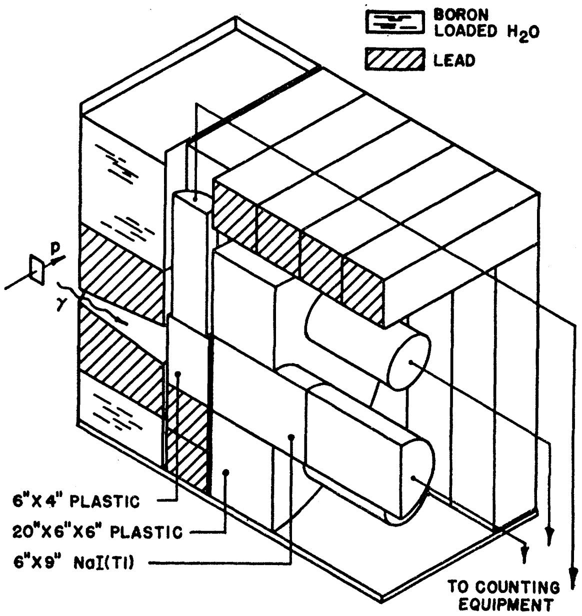

FIG. 1. Cut-away view of the gamma-ray spectrometer illustrating the relative positions for the scintillators and the shielding.

metallic potassium foil with 6- to 15-MeV protons, in steps of 0.2 MeV or less. In agreement with the previous experiments, the yield of gamma rays from transitions to the ground state of Ca^{40} was found to pass through a giant resonance for excitation energies between 18 and 22 MeV, and four more fine structure peaks were found at 15.2, 16.2, 18.2, and 20.3 MeV. In addition to gamma rays from transitions to the ground state of Ca^{40}, a secondary, lower energy spectral line was also found. The position of this secondary peak corresponds to the energy expected for transitions to one or more of the first four excited states of Ca^{40}. The area under this peak increases with excitation energy by about a factor of two over the region of excitation energies studied.

II. EXPERIMENTAL APPARATUS AND PROCEDURE

The experiment was performed with the University of Illinois variable energy cyclotron.[11,12] The energy of the proton beam was defined to within 1% by a 30° energy analyzing magnet with slits located at the exit of the cyclotron, at the entrance to the analyzing magnet, and three feet in front of the target. The beam was collected in a long, graphite-lined Faraday cage 7.5 ft from the target. The beam energy spread was normally less than 70 keV.

The target was a 99.9% chemically pure, self-supporting metallic potassium foil, which was formed by rolling under paraffin oil. The foil was dipped in benzene to remove the oil and was quickly transferred to the target chamber, which was then rapidly evacuated. The thickness of the target was found to be 4.3 ± 0.9 mg/cm^2, which corresponds to 120 keV for 12-MeV protons.

Gamma radiation from the target was detected with a scintillation spectrometer consisting of a 6-in.-diam ×9-in.-length NaI(Tl) crystal and two auxiliary plastic scintillators, arranged as shown in Fig. 1. This detector was operated in an anticoincidence mode, obtained by connecting the NaI(Tl) crystal in anticoincidence with both plastic scintillators, and a coincidence mode, obtained by leaving the annular scintillator in anticoincidence and connecting the front scintillator in coincidence. Foote and Koch[13] have shown that, for gamma-ray energies greater than about 10 MeV, the energy resolution normally obtained with scintillation spectrometers is primarily determined by the loss of radiation from the sides and ends of the scintillator. The anticoincidence mode improved the energy resolution by suppressing the analysis of gamma-ray interactions for which there were simultaneous losses of radiation from either the front end or from the sides of the NaI(Tl) crystal. For gamma-ray energies near 20 MeV, the energy resolution for this mode was typically 7% and the efficiency was estimated[14] to be between 10% and 30%.

The operating principle for the coincidence mode is similar to that for the scintillation pair spectrometer developed by Ziegler *et al.*[15] In this mode the system is set up to count gamma rays that produce the following sequence of events. After the primary gamma-ray enters the NaI(Tl) crystal, it converts to a positron-electron pair near the front face; then one of the 0.5-MeV annihilation quanta escapes back out the front face and is counted in the front scintillator with no radiation simultaneously counted in the annular scintillator. The coincidence mode gave better energy resolution than the anticoincidence mode, but the efficiency for gamma-ray energies near 20 MeV was only about 5% of the efficiency for the anticoincidence mode.

Pulses from the scintillators were amplified by double-delay-line amplifiers, and then fed to a commerical fast-slow multiple coincidence system of the cross-over pickoff type. The coincidence system gated a 1024-channel pulse-hight analyzer "on" when the conditions of either mode were satisfied. Both modes were recorded simultaneously, the coincidence spectrum going into one part of the analyzer memory, the anticoincidence spectrum into another part. Pulse rates from each of the scintillators were monitored during the experiment, and the beam current was kept low enough so that pulse pile-up and chance anticoincidence caused an error of less than 5% in the yield for the ground-state radiation.

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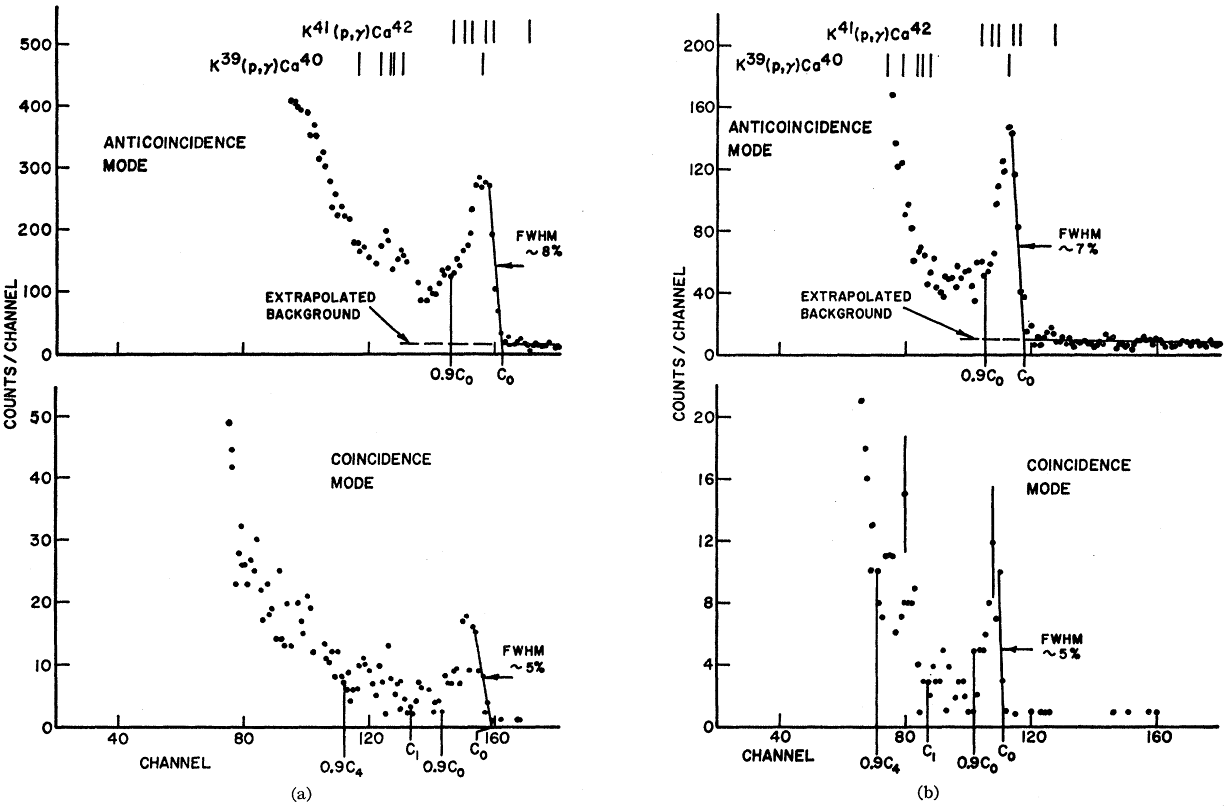

FIG. 2. High-energy region of the $K(p,\gamma)Ca$ spectra obtained with the coincidence and anticoincidence modes of operation of the spectrometer for proton energies of (a) 12.9 MeV and (b) 7.0 MeV. The channels labeled C_0, C_1, and C_4 were used in the determination of the yield as explained in the text. The two rows of vertical lines, labeled $K^{41}(p,\gamma)Ca^{42}$ and $K^{39}(p,\gamma)Ca^{40}$, indicate the expected positions for spectral peaks from these reactions.

Figure 2(a) shows a typical pulse-height spectrum from the upper region of the range of proton energies used. The yield of gamma rays from the $K^{39}(p,\gamma_0)Ca^{40}$ reaction was taken as the sum of the counts in the channels from $0.9C_0$ through C_0, where C_0 was defined by the high-energy edge of the main peak. A typically 10% background subtraction, which was determined by extrapolation of the higher energy cosmic-ray level under the peak, was necessary with the anticoincidence mode. The gamma-ray energy for the ground-state transitions was calculated by adding the Ca^{40} proton binding energy (8.33 MeV) to the center-of-mass energy of the incident protons. This energy and the corresponding value of C_0 established the energy scale that was used to predict the locations for other spectral peaks. The energy for the secondary, lower energy peak in Fig. 2(a) agrees with the value expected for gamma rays from transitions to one or more of the first four excited states of Ca^{40}. The spectrometer resolution was inadequate for the separation of the individual peaks from transitions to the first or to the second, etc., excited states.

Figure 2(b) shows a typical spectrum for lower proton energies. In this case, the secondary peak has disappeared in the anticoincidence spectrum, but remains apparent in the coincidence spectrum. Although the coincidence spectra suffered from lack of good statistical counts, they were relatively free of background from piled-up pulses and cosmic rays. Furthermore, the low-energy tail of the main peak was suppressed with the coincidence mode. The additional resolving power of the coincidence mode was essential for the extraction of the area under the secondary peak, particularly at lower proton energies where the secondary peak was generally buried in the rapidly rising background with the anticoincidence mode. The sum of the counts in the coincidence spectra from $0.9C_4$ through C_1, where C_1 and C_4 are the channels corresponding to the expected high-energy edges of the gamma-ray peaks from transitions to respectively the first and fourth excited states of Ca^{40}, was taken as the yield from the $K^{39}(p,\gamma_1+\gamma_2+\gamma_3+\gamma_4)Ca^{40*}$ reactions.

Although about 7% of the target was K^{41}, we found no unambiguous evidence for transitions to the ground state of Ca^{42}, which has a proton binding energy about 2 MeV greater than that for Ca^{40}. The two rows of vertical lines at the top of Fig. 2, labeled $K^{39}(p,\gamma)Ca^{40}$ and $K^{41}(p,\gamma)Ca^{42}$, show the expected positions for peaks in these pulse-height spectra resulting from radiative capture transitions to the ground and first few excited states of, respectively, Ca^{40} and Ca^{42}. These lines show that radiative capture transitions to the ground state of Ca^{42} should have caused another peak above the main ground-state peak for Ca^{40}, and that transitions to the first five excited states of Ca^{42} could contribute to the yield of the ground-state transitions of Ca^{40}. Although our results may be in error as a result of transitions to these excited states of Ca^{42}, a measurement of the magnitude of this error would require the use of an isotopically separated target of either K^{39} or K^{41}. An experiment with a separated target of K^{39} would be highly desirable because, in addition to the elimination of radiative capture transitions in K^{41}, the relatively high-energy neutrons from the $K^{41}(p,n)$ reaction, which has a threshold of 1.2 MeV, would also be eliminated.

III. RESULTS

The experimental excitation function for the $K^{39}(p,\gamma_0)Ca^{40}$ reaction obtained with the anticoincidence mode is presented in Fig. 3. When a yield point came out noticeably high or low during the experiment, a peak or valley was anticipated and an attempt was made to record at least one more nearby point to give additional confidence for the existence of the peak or valley; that is, "one point peaks" were avoided if possible. Since the accumulation of the data required about one month, there was some concern about possible target deterioration during the experiment. The data indicated by crosses, between 6 and 11 MeV, were taken at the beginning of the experiment; near the end of the experiment the cyclotron was returned to lower energies to fill in gaps. Since both the crosses and the dots lie on the same curve, deterioration of the target during the experiment must have been small. The triangles above 13 MeV show part of the results of some preliminary work using higher energies, but these data are not believed to be as accurate as the rest of the data. The indicated errors represent statistical fluctuations in the yields and in the corresponding cosmic-ray background levels. The horizontal bars at the top of Fig. 3 indicate the approximate amount of energy lost by the beam in traversing the target. The 90° differential cross section for this reaction is shown on the right side of Fig. 3; the uncertainty of $\pm 70\%$ is due mainly to the uncertainty in the efficiency of the spectrometer and the uncertainty in the thickness of the target.

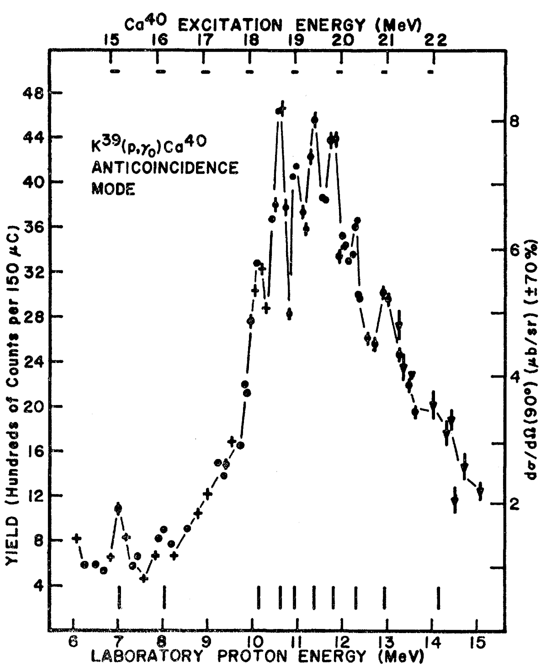

FIG. 3. Differential cross section at 90° for the $K^{39}(p,\gamma)Ca^{40}$ reaction measured with the anticoincidence mode. The ordinate on the left gives the relative cross section, and the ordinate on the right gives the estimated absolute cross section. The lengths of the horizontal bars at the top of the figure indicate the approximate energy lost by the proton beam in traversing the target. The ten vertical lines at the bottom of the figure indicate the energies, listed in Table I, for the fine structure peaks. The significance of the data points indicated by dots (●), by crosses (+), and by triangles (▼) is discussed in the text.

TABLE I. Comparison of the proton energies at which similar fine structure peaks occur in the $K^{39}(p,\gamma_0)Ca^{40}$ reaction. Corresponding Ca^{40} excitation energies are enclosed in parentheses. Energies are given in MeV.

This work	Tanner *et al.* (Ref. 8)	Baliga (Ref. 10)
7.05 (15.2)		
8.05 (16.2)		
10.15 (18.2)		
10.60 (18.7)	10.8 (18.8)	(18.7)
10.95 (19.0)		(19.2)
11.35 (19.4)	11.6 (19.6)	(19.5)
11.80 (19.8)	12.0 (20.0)	(20.0)
12.30 (20.3)		
12.95 (21.0)		(21.0)
14.1 (22)		(21.7)

The excitation function for the $K^{39}(p,\gamma_0)Ca^{40}$ reaction shows a considerable amount of fine structure, which appears to be superimposed on a broad giant resonance. Over the region of energies investigated, ten discernable fine structure peaks were found. The energies at which they occur are listed in Table I. In the region of overlap, the general shape of the fine structure found here is in excellent agreement with that found by Tanner *et al.*[8] and by Baliga,[10] whose results are also listed in Table I. Baliga indicates a maximum cross section of about 2.5 μb/sr, which is within the lower limit of the error assigned to the cross section at the maximum shown in Fig. 3.

The excitation function for the $K^{39}(p,\gamma_0)Ca^{40}$ reaction obtained with the coincidence mode is shown in Fig. 4(a). The structure found here is completely consistent with the structure shown in Fig. 3, although the statistical accuracy is somewhat inferior. This consistency between the data recorded with the anticoincidence and coincidence modes gives additional confidence in the results for the ground-state radiation.

The excitation function for radiative capture transitions to the first through the fourth excited states of Ca^{40}, as determined by the method described in the previous section, is shown in Fig. 4(b). The ordinates for the curves in Fig. 4(a) and Fig. 4(b) are correct relative to each other. However, the yield points shown in Fig. 4(b) may include a background contribution as large as 40%. Therefore, we can conclude only that the cross section for the $K^{39}(p,\gamma_1+\gamma_2+\gamma_3+\gamma_4)Ca^{40*}$ reactions increases with excitation energy by about a factor of two over the region of excitation energies

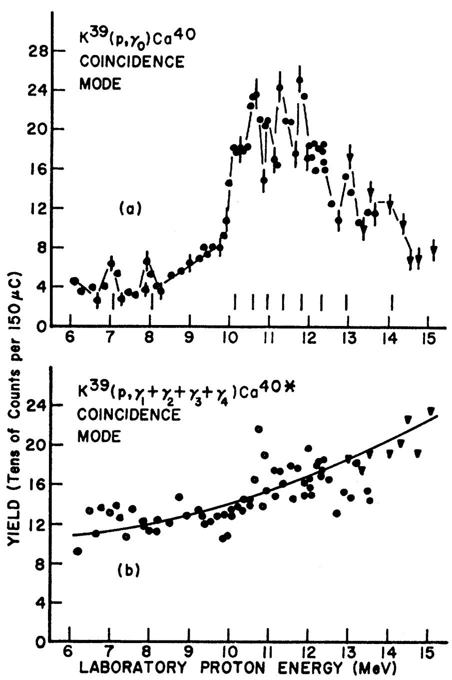

FIG. 4. Excitation curves obtained with the coincidence mode of operation for (a) the $K^{39}(p,\gamma_0)Ca^{40}$ reaction and (b) the combined $K^{39}(p,\gamma_1+\gamma_2+\gamma_3+\gamma_4)Ca^{40*}$ reactions. The ordinates are correct relative to each other. The ten vertical lines at the bottom of (a) correspond to the energies of the fine structure peaks obtained with the anticoincidence mode.

studied. Although there may be unresolved structure in the cross section for this reaction, we are not able to conclude anything definite about the presence of such structure. Nevertheless, the results are sufficiently interesting to warrant further investigation.

IV. DISCUSSION OF RESULTS AND CONCLUSIONS

The 90° differential cross section for the $Ca^{40}(\gamma,p_0)K^{39}$ reaction, which was derived from the $K^{39}(p,\gamma_0)Ca^{40}$ cross section of Fig. 3 by applying the principle of detailed balance, is shown as the upper curve in Fig. 5. The ordinate to the left of Fig. 5 applies only to this cross section. The $Ca^{40}(\gamma,p_0)K^{39}$ excitation function dis-

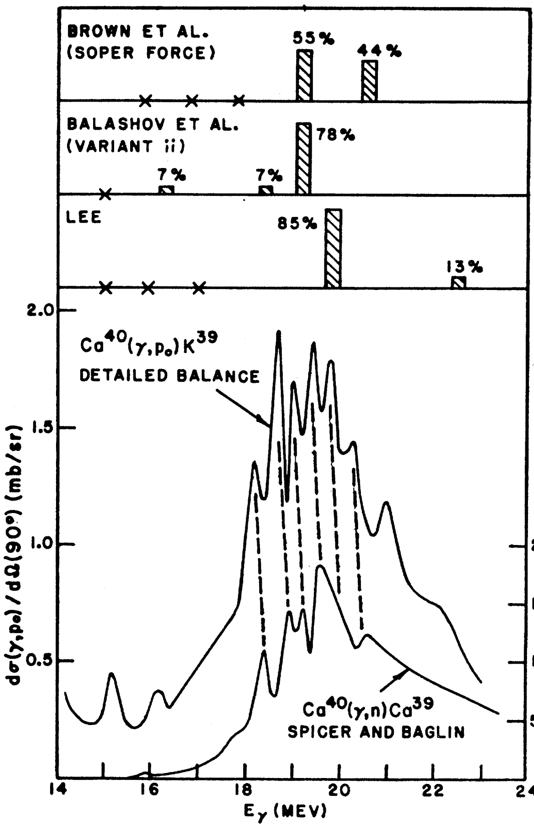

FIG. 5. Comparison of the $Ca^{40}(\gamma,p_0)K^{39}$ differential cross section at 90°, obtained from the inverse reaction by applying the principle of detailed balance, with the experimental $Ca^{40}(\gamma,n)Ca^{39}$ cross section and with theoretical energies and dipole strengths of the dipole states of Ca^{40}. The X's indicate energies for dipole states that carry less than 1% of the dipole strength.

plays, of course, the same fine structure peaks as those for the inverse reaction.

It is now becoming apparent[2] that considerable fine structure also exists in the photoneutron excitation function for Ca^{40}. An example of such structure is seen in the $Ca^{40}(\gamma,n)Ca^{39}$ cross section measured by Spicer and Baglin.[16] Their cross section is shown as the lower curve in Fig. 5, where the scale to the right is the appropriate ordinate. The dashed lines connecting similar fine structure peaks of the $Ca^{40}(\gamma,p_0)K^{39}$ differential cross section and the $Ca^{40}(\gamma,n)Ca^{39}$ cross section show the striking similarity in the fine structure for these two cross sections. Although the excitation energies for the maxima of the fine structure peaks are slightly displaced, the difference is within the combined uncertainties in the absolute energy calibration for both our measurement and the measurement of Spicer and Baglin. Noteworthy in this comparison, however, is the fact that photoneutron emission is limited by conservation of energy to emission to the ground state of Ca^{39} for Ca^{40} excitation energies less than 18.2 MeV

[16] B. M. Spicer and J. E. E. Baglin (private communication).

[$Ca^{40}(\gamma,n)$ threshold energy plus first excited-state energy of Ca^{39}]. Therefore, since the giant resonance occurs at excitation energies only slightly higher than this excited-state threshold energy, photoneutron emission to the ground state of Ca^{39} probably predominates throughout the giant resonance. Thus, it is very likely that the comparison between the (γ,p_0) and the (γ,n) excitation functions is in reality a comparison between the (γ,p_0) and the (γ,n_0) excitation functions.

Calculations of the dipole states that are effective in producing the giant dipole resonance are least complicated for the doubly magic nuclei, with filled shells of protons and neutrons. Photodisintegration in the region of the giant dipole resonance is believed to involve single-particle transitions between major shells,[17,18] and the excitation energies for these single-particle transitions are normally taken from the experimental values for the single-particle levels of neighboring isotopes and isotones.[19] Only transitions that produce $J^\pi = 1^-$ states are considered in the calculations. The particle-hole interaction is taken into account by using these single-particle states as basic states for perturbation theory computations.[20] This interaction causes a shift in the excitation energies for the dipole states and one or two of the highest energy perturbed states take nearly all the dipole strength. The excitation energies and the relative dipole strengths for the dipole states of Ca^{40} as found by Brown *et al.*,[3] by Balashov *et al.*,[4] and by Lee[5] are indicated by the shaded bars at the top of Fig. 5. The ×'s indicate the excitation energies for states that carry less than 1% of the dipole strength and that lie within the energy region of the abscissa. Gillet[21] has also calculated the dipole states of Ca^{40} and his results are similar to the results of the above mentioned authors.

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Figure 5 shows that the bulk of the giant resonance for both the (γ,p_0) and the (γ,n) cross sections is concentrated between 18 and 21 MeV, in good agreement with the calculated excitation energies for the strong dipole states of Ca^{40}. Balashov *et al.* also calculated the widths for the giant resonance in the $Ca^{40}(\gamma,p)$ and $Ca^{40}(\gamma,n)$ cross sections, and they obtained a value of about 3 MeV in each case. This value is in rather good agreement with the experimental width for the gross structure shown in Fig. 5. In the case of O^{16}, which like Ca^{40} is doubly magic, the measured width of the 22-MeV peak[22] in the $O^{16}(\gamma,n)$ cross section agrees with a theoretical calculation reported by Ferrell.[23] However, none of these calculations for either Ca^{40} or O^{16} offers an explanation for the fine structure in the giant resonance. More work, both experimental and theoretical, is clearly needed to shed some light onto this aspect of the giant resonance in Ca^{40}. Measurement of the angular distributions for each of the fine structure peaks found in the 90° differential cross section are imperative for an understanding of the nature of these resonances, and a calculation of the shape and the magnitude of the cross section specifically for photoproton emission to the ground state would allow a precise comparison between the results of experiment and the results of theory.

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