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CAPTURE REACTION K^{39} (p, γ) CA^{40} IN THE GIANT RESONANCE REGION

(2,c)

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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 Elliot and Flowers for O^{16} (Fuller, 1962; Hayward, 1963) has stimulated similar shell model calculations for other nuclei, particularly Ca^{40}. Brown et al. (Brown, 1961) 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. (Balashov, 1961) have performed similar calculations using finite range forces. Lee (Lee, 1963) 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 (Ferrel, 1962a), 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. (Gove, 1961) have separated the gamma-ray

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peaks for transitio to t irst ex ted states of C^{12} and Si^{28}, and they four that cross s ion for the $B^{11}(p,\gamma_1)C^{12*}$ reaction shows co derabl re stru re than that for the ground state B^{11} $\gamma_0)C^{1}$ action.

Tanner e (Tan 1961) studie he $K^{39}(p,\gamma)Ca^{40}$ reaction and that is reaction pass through a giant resonance corr on ing o excited states of 40 in the region of 18 to 21 M nei a suggest that the iant resonance in Ca^{40} is sp nto least three fine str ture peaks at 18.8, 19.6 a 20.0 M Before the completion of the experiment describ n th report, Feldman et al. (Feldman, 1963; Baliga, 196 repor the results of their experiment which showed t ame fi structure found by Tanner et al. plus additi fine st ture 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 motiviated 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, 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 (Allen, 1960; Brussel, 1962). 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 at 3 feet in front of the target. The beam was collected in a long, graphite-lined Faraday cage 7.5 feet 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 $\pm$ 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"DX9"L NaI(Tl) crystal and two auxiliary plastic scintillators, arranged as shown in Figure 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 (Foote, 1954) 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. The

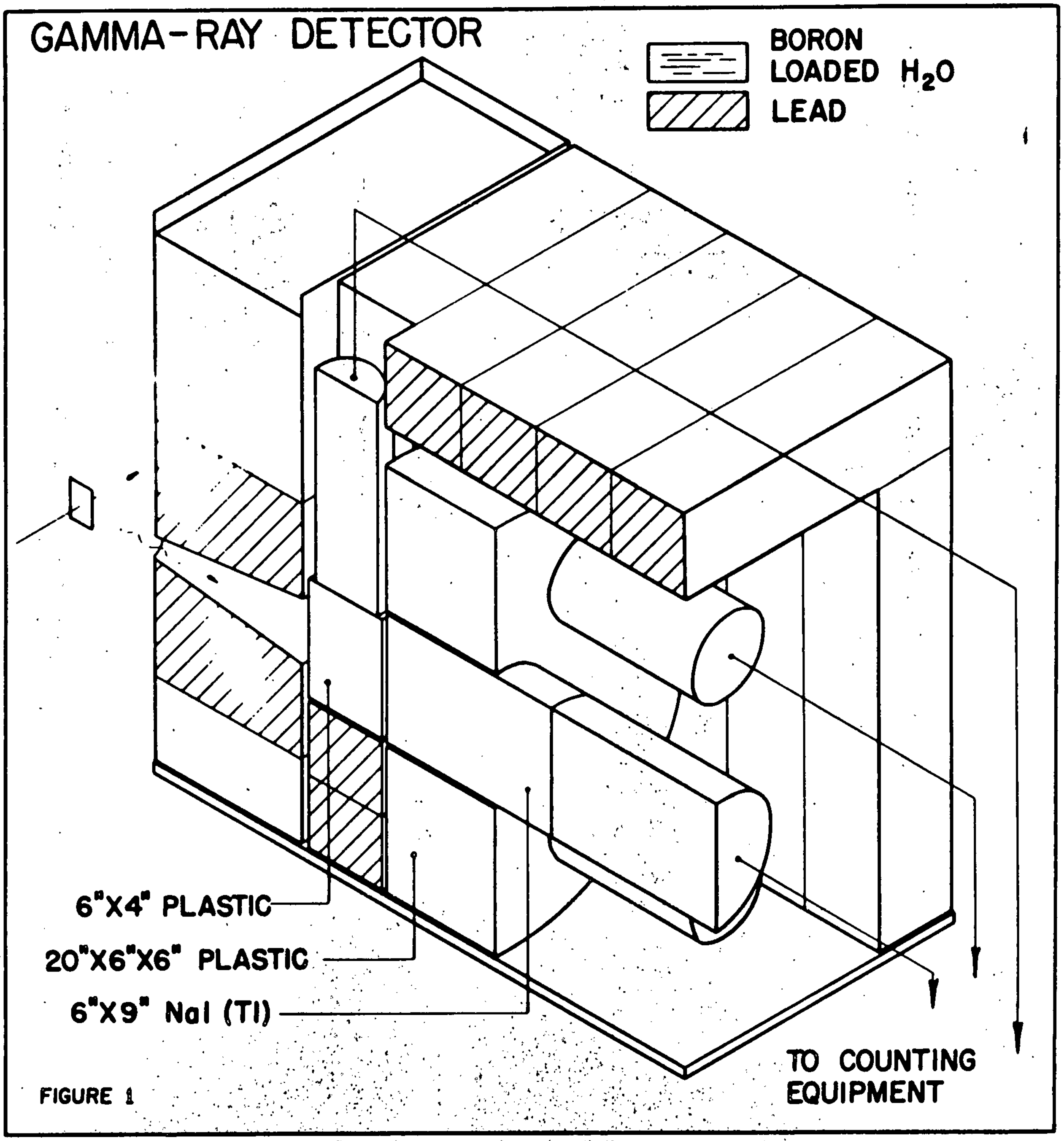

GAMMA-RAY DETECTOR
BORON LOADED H_2O
LEAD
6"X4" PLASTIC
20"X6"X6" PLASTIC
6"X9" NaI (Tl)
TO COUNTING EQUIPMENT

FIGURE 1

energy resolution for this mode was typically 7% and the efficiency, which is the ratio of the yield of monoenergetic gamma rays with an energy near 20 MeV to the number of these gamma rays that enter the solid angle subtended by the lead collimator, was estimated to be (20 $\pm$ 10)%. The operating prinicple for the coincidence mode is similar to that for the scintillation pair spectrometer developed by Ziegler et al. (Ziegler, 1963). The principle of operation is based on the realization of the following sequence of events. The primary gamma-ray enters the NaI(Tl) crystal and 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 absorbed in the front scintillator, and no other radiation escapes into the annular scintillator. The coincidence mode gave better energy resolution than the anticoincidence mode, but the efficiency 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 commercial fast-slow multiple coincidence system of the cross-over-pick-off type. The coincidence system gated a 1024 channel pulse height 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 cach 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.

Figure 2(a) shows a typical pulse height spectrum from the upper region of the range of proton energies used. The yeild 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 Figure 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

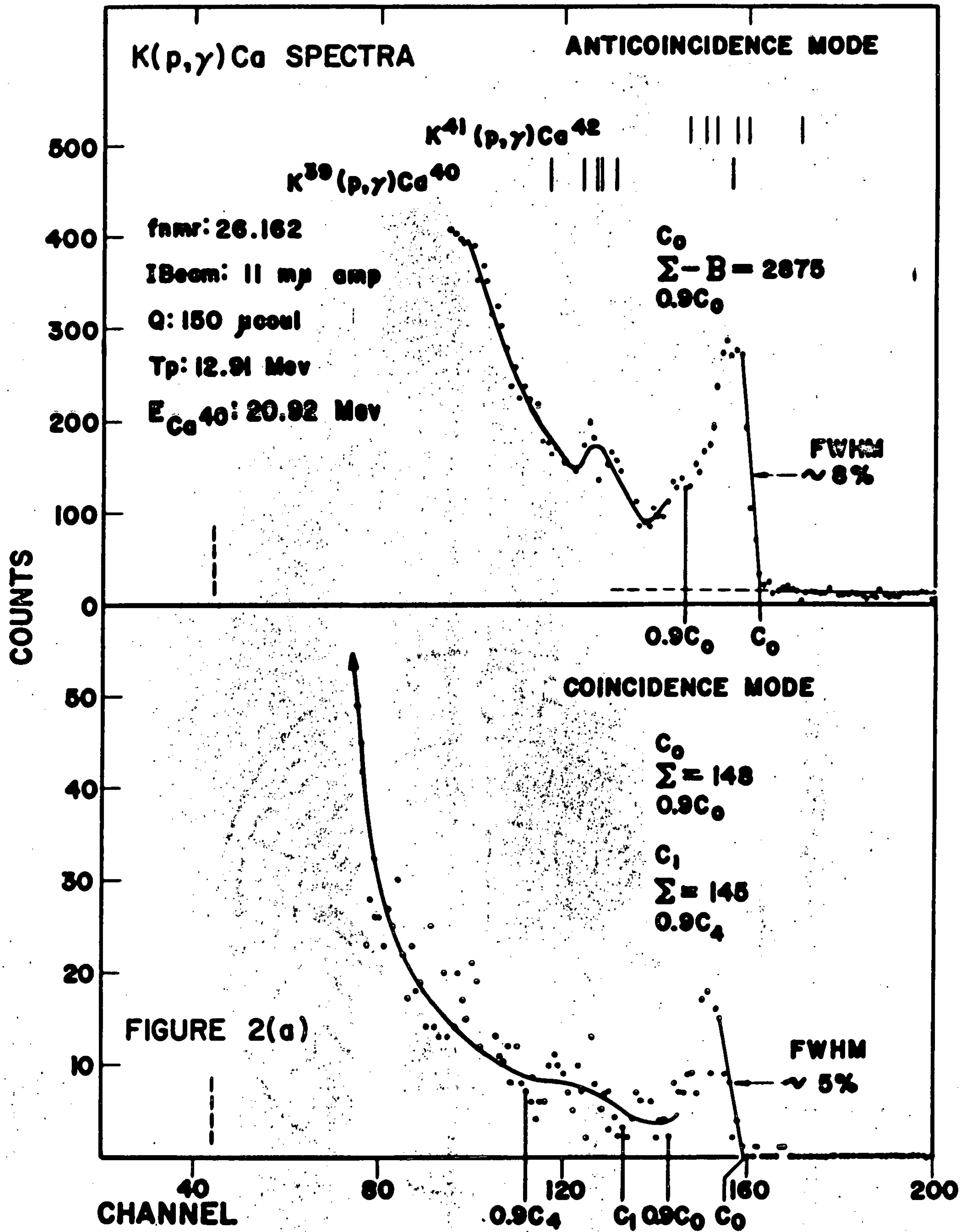
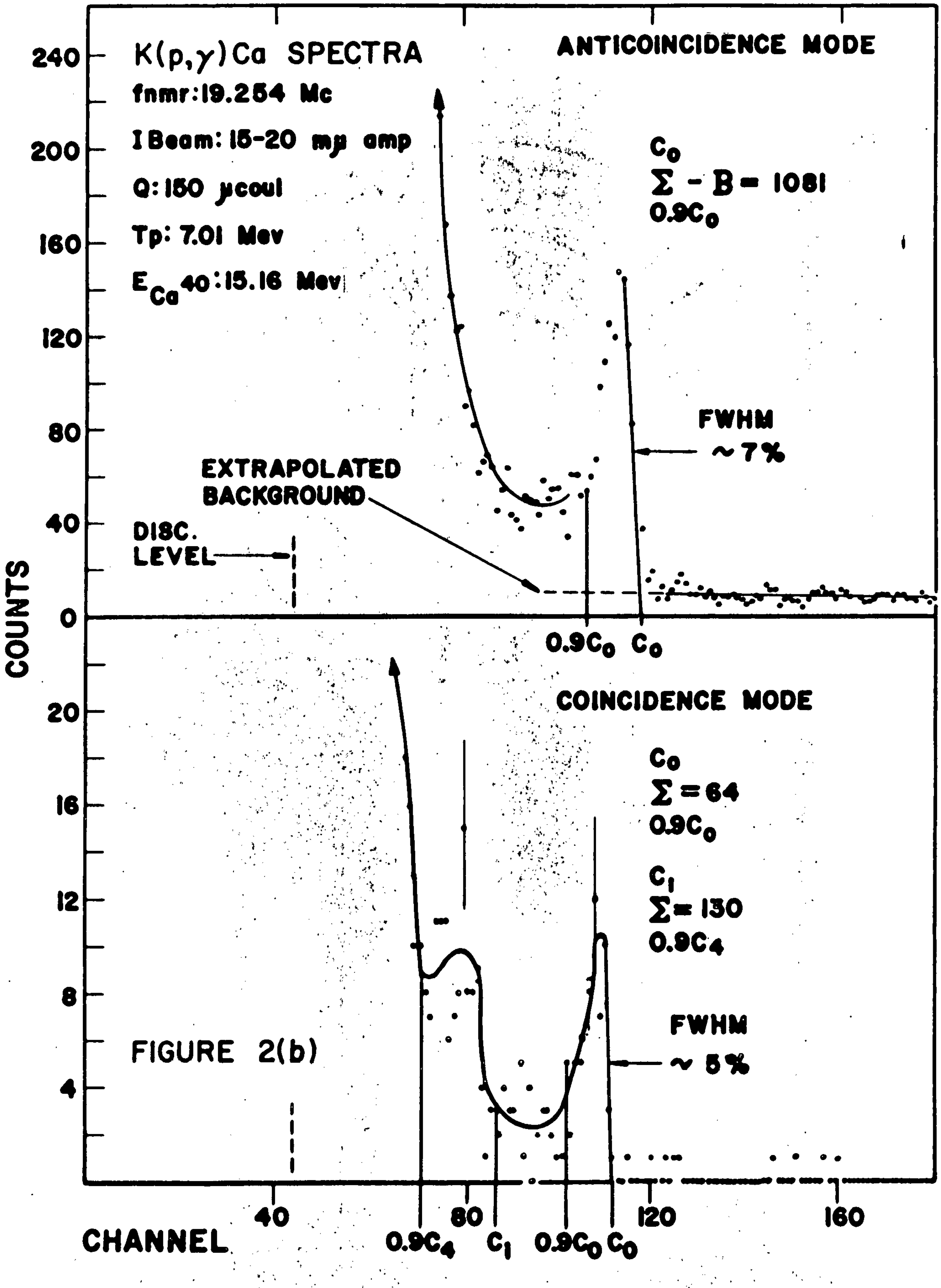

K(p,γ)Ca SPECTRA
ANTICOINCIDENCE MODE
K41(p,γ)Ca42
K39(p,γ)Ca40
fnmr: 26.162
IBeam: 11 mμ amp
Q: 150 μcoul
Tp: 12.91 Mev
ECa40: 20.92 Mev
C0
Σ−B = 2875
0.9C0
FWHM
~8%
COUNTS
0.9C0
C0
COINCIDENCE MODE
C0
Σ = 148
0.9C0
C1
Σ = 145
0.9C4
FWHM
~5%
CHANNEL
0.9C4
C1
0.9C0
C0

FIGURE 2(a)



K(p,γ)Ca SPECTRA
fnmr: 19.254 Mc
I Beam: 15-20 mμ amp
Q: 150 μcoul
Tp: 7.01 Mev
E Ca40: 15.16 Mev
ANTICOINCIDENCE MODE
C0
Σ - B = 1081
0.9C0
FWHM
~7%
EXTRAPOLATED BACKGROUND
DISC. LEVEL
COUNTS
0.9C0 C0
COINCIDENCE MODE
C0
Σ = 64
0.9C0
C1
Σ = 130
0.9C4
FWHM
~5%
CHANNEL
0.9C4 C1 0.9C0 C0

FIGURE 2(b)

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 when the coincidence mode was used. 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 $K^{39}(p,\gamma_1 + p,\gamma_2 + p,\gamma_3 + p,\gamma_4)Ca^{40*}$ 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 Figure 2(a), labeled $K^{39}(p,\gamma)Ca^{40}$ and $K^{41}(p,\gamma)Ca^{42}$, show the expected positions for peaks in this pulse height spectrum 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 energy 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 Figure 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 open circles, between 6 and 11 MeV, were taken at the beginning

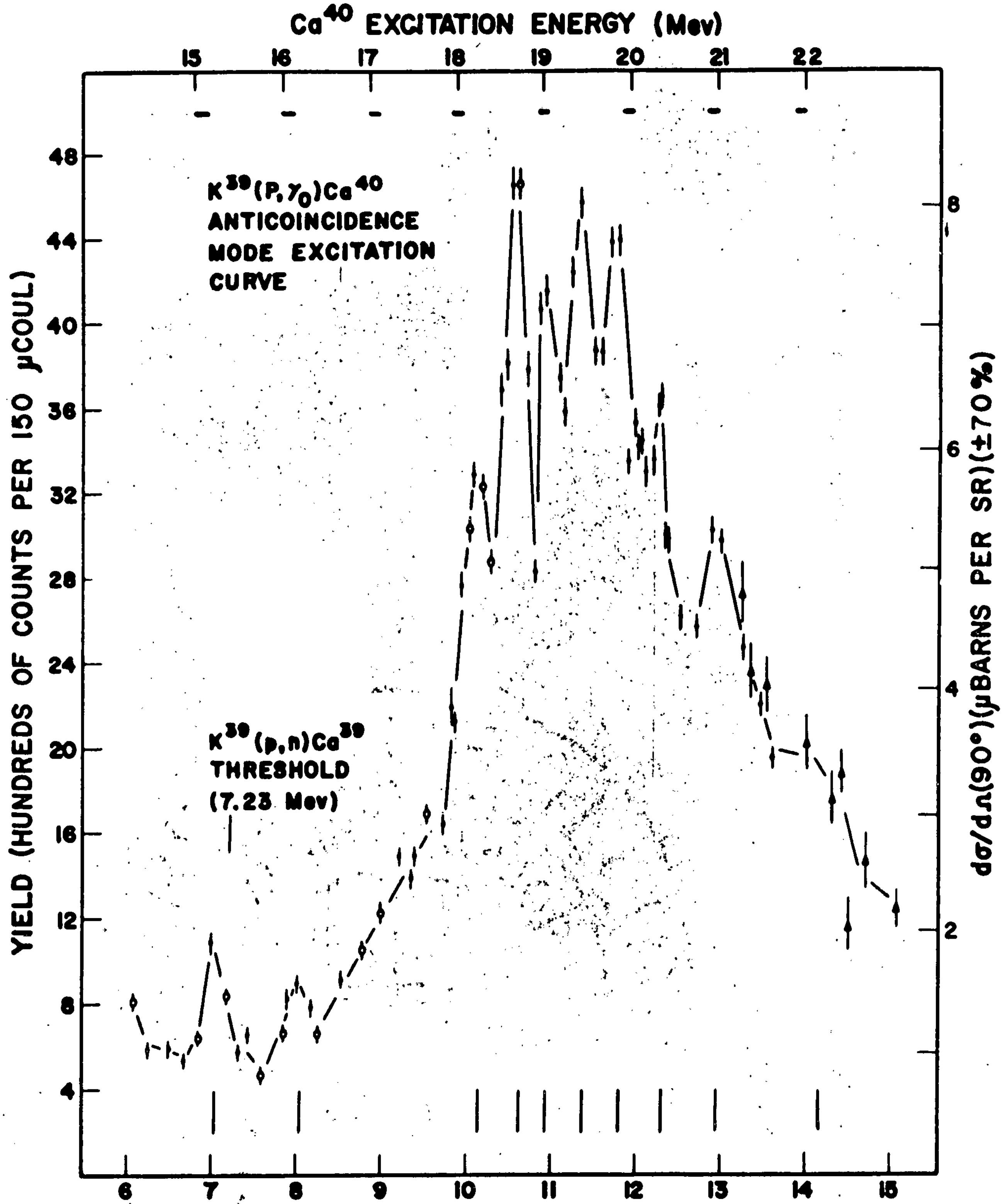


FIGURE 3 LABORATORY PROTON ENERGY (Mev)

of the experiment; near the end of the experiment the cyclotron was returned to lower energies to fill in the gaps. Since both the open and closed points 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 belived to be as accurate as the rest of the data. The indicated errors are statistical and include the errors resulting from the subtraction of the cosmic-ray background. The horizontal bars at the top of Figure 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 Figure 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.

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. (Tanner, 1961) and by Baliga (Baliga, 1963), whose results are also lised in Table I. For

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 parenthesis. Energies are given in MeV.

This Work	Tanner et al.[a]	Baliga[b]
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)

[a](Tanner, 1961)
[b](Baliga, 1963)

comparison with Figure 3, the K^{39} $(p,\gamma)Ca^{40}$ data of Tanner et al. are shown in Figure 5 and the $K^{39}(p,\gamma_0)Ca^{40}$ excitation curve of Baliga is shown in Figure 6. Baliga indicates a maximum cross section of about 2.5 μbarns/sr, which is within the lower limit of the error assigned to the cross section at the maximum shown in Figure 3, that is, 8 - 5.6 = 2.4 μbarns/sr.

The excitation function for the $K^{39}(p,\gamma_0)Ca^{40}$ reaction obtained with the coincidence mode is shown in Figure 4(a). The structure found here is completely consistent with the structure shown in Figure 3, although the statistical accuracy is somewhat inferior. This consistency between the data recorded with the anticoncidence 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 Figure 4(b). The ordinates for the curves in Figure 4(a) and Figure 4(b) are correct relative to each other. However, the yield points shown in Figure 4(b) may include a background contribution as large as 40%. Therefore, we can conclude only that the cross section for the $K^{39}(p,\gamma_1 + p,\gamma_2 + p,\gamma_3 + p,\gamma_4)Ca^{40*}$ reaction increases with

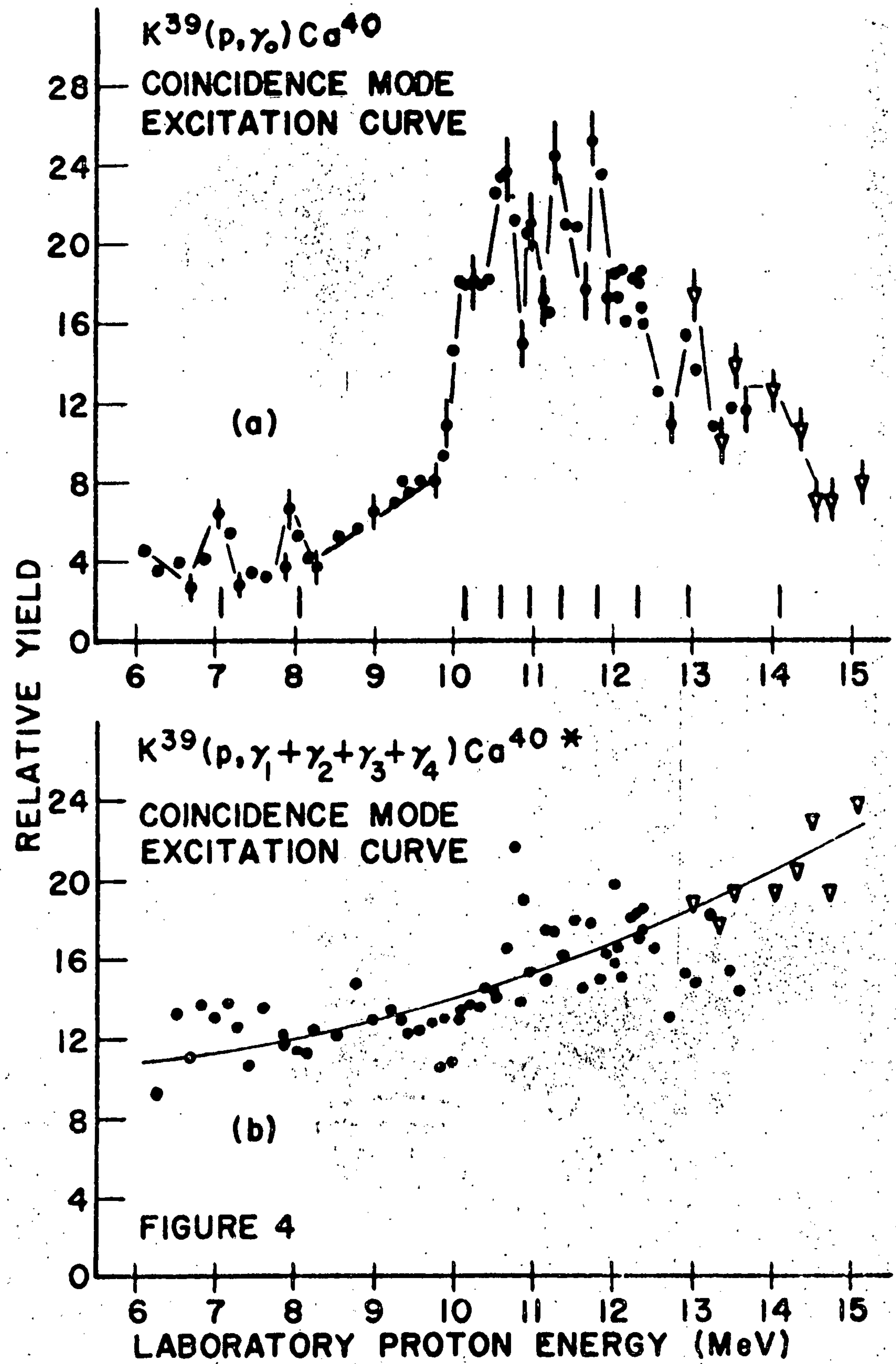

K39(p,γ0)Ca40
COINCIDENCE MODE
EXCITATION CURVE
(a)
K39(p,γ1+γ2+γ3+γ4)Ca40 *
COINCIDENCE MODE
EXCITATION CURVE
(b)
RELATIVE YIELD
LABORATORY PROTON ENERGY (MeV)

FIGURE 4

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excitation energy by about a factor of two over the region of excitation energies 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 Figure 3 by applying the principle of detailed balance, is shown as the upper curve in Figure 7. The ordinate to the left of Figure 7 applies only to this cross section. The $Ca^{40}(\gamma,p_0)K^{39}$ excitation function displays, of course, the same fine structure peaks as those for the inverse reaction.

It is now becoming apparent that considerable fine structure also exists in the photo-neutron excitation function for Ca^{40} (Hayward, 1963). An example of such structure is seen in the $Ca^{40}(\gamma,n)Ca^{39}$ cross section measured by Spicer and Baglin (Spicer, 1963). Their cross section is shown as the lower curve in Figure 7, 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 displaced by about 0.2 MeV, this difference is within the combined uncertainties in the absolute

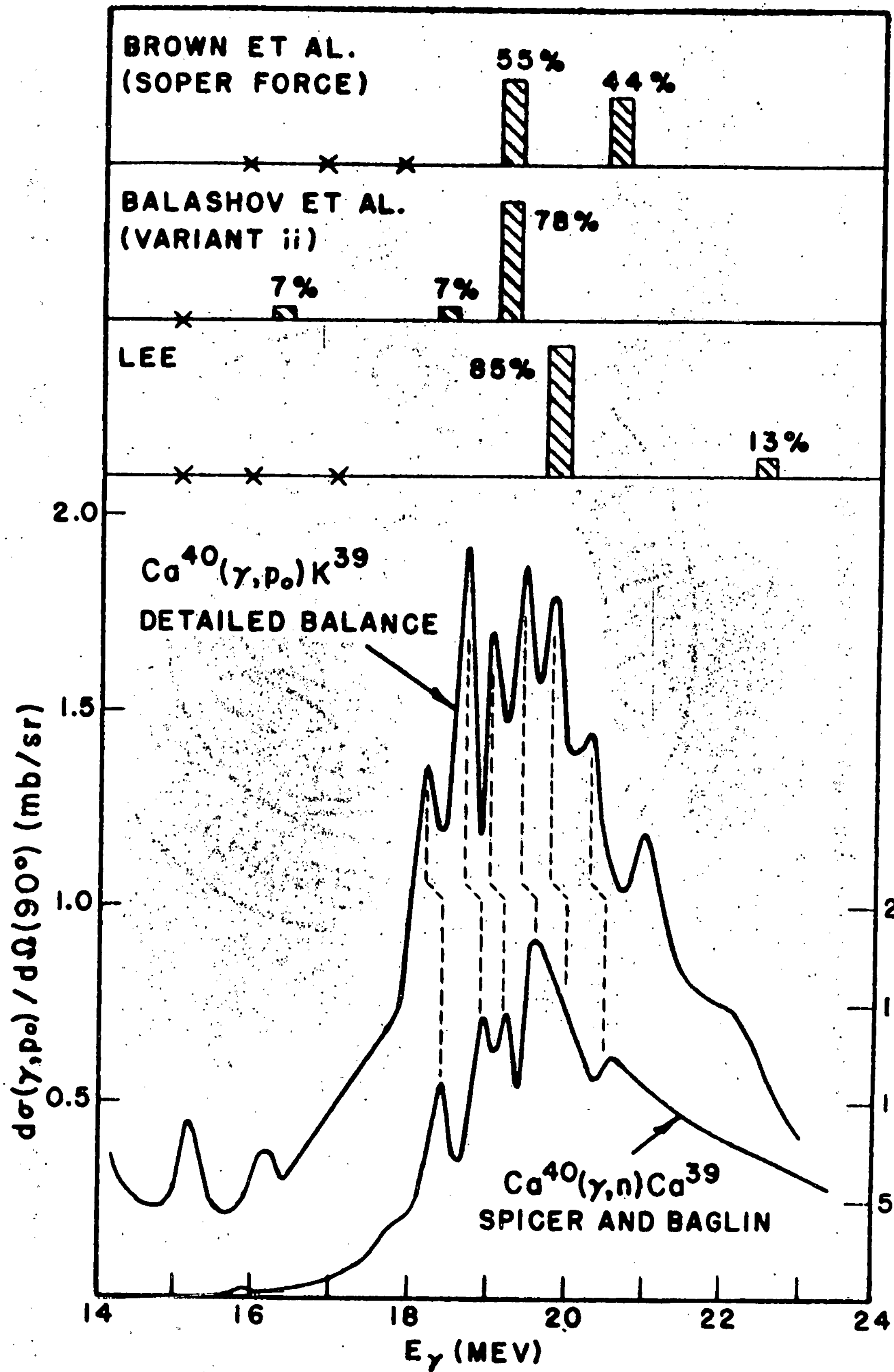

FIGURE 7. COMPARISON OF THE (γ,p_o) AND THE (γ,n) CROSS SECTIONS WITH THEORY

energy calibration for both our measurement and the measurement of Spicer and Baglin. Noteworthy is this comparison, however, is the fact that photo-neutron 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 ($Ca^{40}(\gamma,n)$ 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, photo-neutron 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 (Wilkinson, 1956; Levinger, 1960), 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 (B. Cohen, 1963). 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 (Brown, 1959). 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. (Brown, 1961), by Balashov et al. (Balashov, 1961), and by Lee (Lee, 1963) are indicated by the shaded bars at the top of Figure 7. The X'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 (Gillet, 1962) has also calculated the dipole states of Ca^{40} and his results are similar to the results of the above mentioned authors.

Figure 7 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 Figure 7. Ferrell (Ferrell, 1962b) has reported calculations of the width of the 22 MeV peak in the photo-neutron cross section for O^{16}, which is somewhat analogous to Ca^{40} in that both of these nuclei are doubly magic. Again, the width reported by Ferrell is in good agreement with the width of the 22 MeV peak measured by Bolen and Whitehead (Bolen, 1962). However, none of these calculations offers an explanation for the fine structure shown in Figure 7. More work, both experimental and theoretical, is clearly needed to shed some light onto this aspect of the giant dipole resonance in Ca^{40}. Measurements 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 photo-proton emission to the ground state would allow a precise comparison between the results of experiment and the results of theory.

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TABLE D1. Data tabulation for the yield of the γ_o peak obtained with the full anticoincidence mode.

Run	Q (μCoul)	f_{pp} (Mc/sec)	Y (Counts)	Probable Error	T_p (MeV)	$E_{Ca^{40}}$ (MeV)	(p,γ_o) $d\sigma/d\Omega$ (μb/sr)
1	150	17.920	822	32	6.08	14.26	1.45
2	150	19.033	642	30	6.85	15.01	1.13
3	150	19.496	840	33	7.19	15.34	1.48
4	150	20.036	471	30	7.60	15.74	0.83
5	150	20.377	665	32	7.86	15.99	1.17
6	150	20.893	666	31	8.26	16.38	1.17
7	150	21.826	1238	41	9.00	17.11	2.18
8	125	21.555	1056	42	8.79	16.90	1.86
9	150	22.477	1690	44	9.55	17.64	2.98
10	150	23.064	3032	58	10.06	18.14	5.34
11	150	23.759	4652	71	10.66	18.72	8.20
12	150	24.430	4240	67	11.27	19.32	7.46
13	150	24.929	4359	69	11.74	19.78	7.69
14	150	24.713	3862	66	11.53	19.57	6.81
15	150	24.012	4073	67	10.89	18.95	7.16
16	150	24.268	3738	64	11.12	19.17	6.58
17	150	23.572	3812	64	10.50	18.57	6.70
18	150	23.236	3231	60	10.21	18.28	5.68
19	44	22.813	2190	93	9.84	17.92	3.86
20	150	22.855	2125	50	9.87	17.95	3.74
21	150	22.952	2769	56	9.96	18.04	4.87
22	150	23.498	3695	63	10.43	18.50	6.50
23	150	23.666	4658	71	10.58	18.65	8.20
24	150	24.102	4157	67	10.97	19.03	7.32
25	150	24.320	3577	63	11.17	19.22	6.30
26	150	24.555	4570	70	11.39	19.44	8.05
27	150	23.955	2825	56	10.83	18.89	4.97
28	150	23.854	3793	64	10.75	18.81	6.67
29	150	23.354	2868	58	10.30	18.37	5.05
30	150	22.690	1642	45	9.73	17.82	2.90
31	150	25.134	3349	61	11.93	19.96	5.90
32	150	25.035	4388	69	11.84	19.87	7.70
33	150	24.811	3866	65	11.63	19.67	6.81
34	150	25.542	3654	63	12.31	20.33	6.42
35	150	25.220	3537	62	12.01	20.04	6.22
36	150	25.364	3308	61	12.13	20.16	5.82
37	150	25.292	3453	62	12.08	20.11	6.07
38	112	25.464	3347	73	12.23	20.25	5.90
39	150	25.776	2611	55	12.53	20.55	4.60
40	150	25.630	2974	58	12.39	20.41	5.24
41	150	25.607	3000	59	12.37	20.39	5.29
42	150	25.970	2565	53	12.72	20.73	4.52

TABLE D1 Cont.

Run	Q (μCoul)	f_{pp} (Mc/sec)	Y (Counts)	Probable Error	T_p (MeV)	$E_{ca}{}^{40}$ (MeV)	(p,γ_0) $d\sigma/d\Omega$ (μb/sr)
43	150	26.162	3024	58	12.91	20.92	5.32
44	150	26.278	2971	57	13.03	21.03	5.23
45	150	26.518	2475	53	13.27	21.27	4.35
46	150	26.731	2198	52	13.48	21.47	3.87
47	150	26.870	1951	50	13.62	21.61	3.44
48	150	25.521	3606	63	12.29	20.31	6.35
49	150	25.250	3409	61	12.04	20.07	6.00
50	150	23.129	3291	60	10.10	18.18	5.80
51	150	18.183	596	28	6.26	14.43	1.05
52	150	18.544	597	27	6.51	14.68	1.05
53	150	18.813	539	27	6.69	14.85	0.95
54	150	19.254	1094	37	7.01	15.16	1.93
55	150	19.685	576	27	7.33	15.48	1.01
56	150	19.826	659	29	7.44	15.58	1.16
57	150	20.575	902	35	8.01	16.14	1.59
58	150	20.782	786	32	8.18	16.31	1.38
59	150	21.248	915	34	8.54	16.66	1.61
60	150	22.267	1385	42	9.36	17.46	2.44
61	150	22.102	1489	42	9.23	17.33	2.62
62	150	22.318	1491	42	9.41	17.50	2.63
63	105	20.425	834	39	7.90	16.03	1.47

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