Absolute (γ, p_0) and (γ, p_1) cross sections and angular distributions for the closed-neutron shell nucleus ^{89}Y

E. Van Camp, R. Van de Vyver, H. Ferdinande, E. Kerkhove, R. Carchon,* and J. Devos†
Laboratorium voor Kernfysica, Rijksuniversiteit Gent, B-9000 Ghent, Belgium
(Received 7 July 1980)

Absolute (γ,p_0) and (γ,p_1) differential cross sections for ^{89}Y were measured at seven angles in the energy interval between 13 and 24.6 MeV, from which the angular distribution coefficients were deduced by fitting a sum of Legendre polynomials. In these cross sections we observe a number of isolated resonances which can be identified as the isobaric analogs of known $1/2^+$ and $3/2^+$ excited states in the ^{89}Sr parent nucleus. The appearance of a maximum around 21 MeV excitation energy in both total cross sections may indicate the existence of the $T_>$ coherent dipole state. From the angular distribution coefficients in the (γ,p_0) channel, an upper and lower limit for the $E2$ photon absorption were estimated as being equal to 22% and 6%, respectively, of the total $E2$ energy-weighted sum rule.

NUCLEAR REACTIONS ^{89}Y(γ,p_0), (γ,p_1), $E=13.0$–24.6 MeV, $\theta=37$–$143°$; measured $\sigma(E;\theta)$ absolutely. Deduced $\sigma(E;p_0)$, $\sigma(E;p_1)$; $E1$, $E2$ strengths, isobaric analog states, isospin splitting. Natural target.

I. INTRODUCTION

The features of the giant dipole resonance (GDR) in ^{89}Y have been reasonably well investigated experimentally,[1] although direct measurements in the photoproton channel are scarce. Since this nucleus has a closed $N=50$ neutron shell structure and one proton in the 2 $p_{1/2}$ subshell,[2] the characteristics of the GDR and of the isobaric analog states could be calculated theoretically within the framework of the particle-hole model.[3,4] Because the isospin of the ground state of ^{89}Y equals $\frac{11}{2}$, both $T_<=\frac{11}{2}$ and $T_>=\frac{13}{2}$ dipole states can be excited by photon absorption. Since the low-lying $T_>$ states in ^{89}Y are the analogs of the low-lying excited states in the ^{89}Sr parent nucleus, they are well separated in energy but they are found in the continuum due to the high Coulomb displacement energy which has been experimentally determined[5] to be 10.63 MeV. The ground state of ^{89}Sr contains one neutron outside the closed $1g_{9/2}$ shell so that some of the excited states contain an important single neutron component[6] and as a consequence their analogs have one proton components; as such they can act as doorway states in the photon absorption channel. Due to isospin conservation the neutron emission from these states is strongly inhibited while the decay through the proton channel is not; consequently the lifetime of these states is increased so that they can be observed as narrow resonances superimposed on the much broader giant dipole resonance, especially in the (γ, p) channel.

Although the low-lying isobaric analog states (IAS) were studied in detail in (p, p') reactions,[7] some of the higher-lying $\frac{1}{2}^+$ and $\frac{3}{2}^+$ IAS have been observed in (p,γ) and $(e, e'p)$ photonuclear experiments.[5,8,9] Besides these single-particle resonances, an indication of the existence of the theoretically predicted coherent $T_>$ dipole vibrational state was found in the $(e, e'p)$ experiment of Shoda *et al.*,[10] while this isospin splitting was also suggested by the (γ,γ') measurement of Arenhövel and Maison[11]; the observed $T_>$ strength seems to be in agreement with the theoretical estimation of Fallieros and Goulard.[12]

Information about multipole states other than the well-known giant dipole state in ^{89}Y has been derived from inelastic electron scattering data[13] and from hadron scattering.[14,15] Although no multipole resonances other than $E1$ can be observed directly in the cross sections of the reactions induced by real photons (monopole transitions evidently cannot occur) due to the low angular momentum transfer, indications of the quadrupole absorption can be derived from the detailed analysis of the angular distributions of the emitted particles wherein the interference of states with different multipolarity is reflected.

Since direct investigations of the ^{89}Y nucleus by the (γ,p) reaction have very seldom been performed,[16,17] it was the aim of the present study to determine the absolute photoproton cross sections and angular distributions, especially for the ground state and for the first-excited state channel. Some of the structure observed in the cross section will be related to known IAS while an attempt to estimate the quadrupole contribution to the (γ,p_0) channel will be made using the measured angular distributions.

II. EXPERIMENTAL PROCEDURE AND DATA ANALYSIS

A natural ^{89}Y foil with a thickness of 13.3 mg/cm^2 was irradiated with a beam of bremsstrahlung photons produced at the 70 MeV linear electron accelerator of the Ghent State University. The ^{89}Y target was centered in a vacuum reaction chamber in which seven uncooled 3 mm thick Si(Li) detectors were placed circumferentially at different angles between 37° and 143°. After shaping and amplification, the signals from the various detectors were multiplexed into a 512-channel analog-to-digital converter (ADC) and subsequently routed into the memory of a DEC PDP 11/10 computer. The further details of the experimental setup are described extensively in a previous paper.[18]

The individual photoproton spectra measured at various bremsstrahlung end point energies were corrected for energy loss in the ^{89}Y target itself as well as for counting losses due to the dead time of the ADC (which amounted to a maximum of about 5%). In order to minimize this energy loss in the yttrium foil (which is a function of the detection angle) runs were performed at each bremsstrahlung end point energy wherein the target was placed at +30° and −30°, respectively, with respect to the incident photon beam and only those photoproton spectra, registered in the 5 most-favorably positioned detectors, were accepted for further analysis. Consequently the effective energy resolution, mainly determined by this energy loss, equals about 450 keV for 10 MeV protons. The energy-scale calibration of the detectors was performed with a mixed α source (^{239}Pu, ^{241}Am, and ^{244}Cm). As a check of this procedure, we also measured the structure in the ^{16}O$(\gamma,p)^{15}$N cross section; however, our results showed a discrepancy with the energy values of the resonances known from the literature.[1] In order to make our data consistent with the adopted ^{16}O(γ,p) peak energies we had to shift the energy scale of our detectors upwards by 115 keV. This same effect whose origin could not be understood has already been observed by Frederick *et al.*[19]

As shown in Fig. 1 the first and second excited states in the residual nucleus ^{88}Sr are located 1.84 and 2.73 MeV, respectively, above the ground state; as a consequence the (γ,p_0) and (γ,p_1) cross sections could be determined by measuring photoproton spectra at various bremsstrahlung endpoint energies going up in 1 MeV steps, from 13 up to 25 MeV. Since the uppermost 1.8 MeV interval of each proton spectrum only contains ground state photoprotons, it is essential to know exactly the bremsstrahlung spectrum shape in this energy range in order to convert this ground state proton spectrum correctly into a ground state cross section. This bremsstrahlung photon spectrum was determined by studying the ^{12}C$(\gamma,p)^{11}$B reaction and using the experimentally well-known cross section for this process[20] which was derived by the method of detailed balance from the ^{11}B$(p,\gamma)^{12}$C reaction data, i.e., without the use of a bremsstrahlung photon spectrum. The result for an incident electron energy of 23.5 MeV is shown in Fig. 2, where the points represent the experimentally determined number of photons per unit energy, while the dashed curves show the photon spectra, slightly differing in end point energy, calculated with the use of the Schiff integrated-over-angles formula[21] and normalized using our copy of the NBS-P2/4 ionization chamber. From this figure it is clear that the experimental photon spectral shape does not correspond accurately to the Schiff bremsstrahlung spectrum with an end point taken at the kinetic energy of the incident elec-

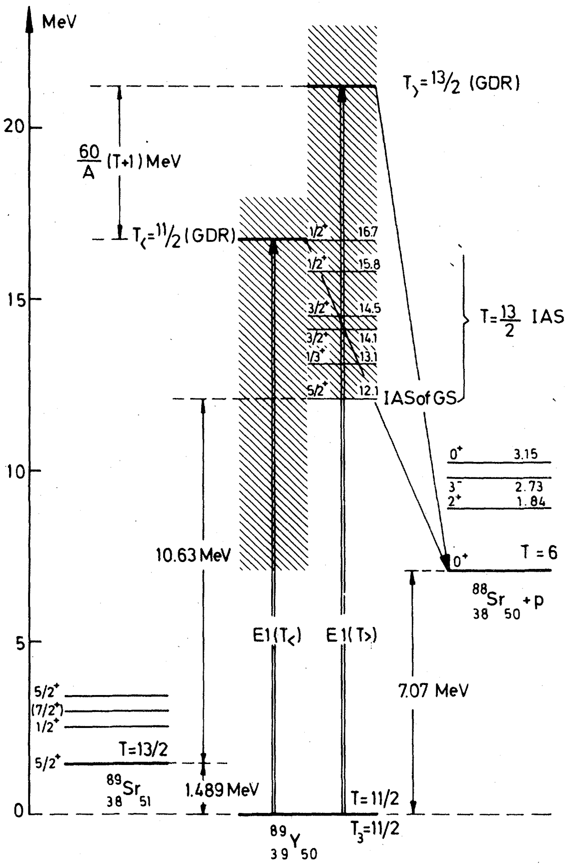

FIG. 1. Level scheme of ^{89}Y on which the $\frac{1}{2}^+$ and $\frac{3}{2}^+$ analog states of the ^{89}Sr parent nucleus are indicated; also the low-lying levels in the residual nucleus ^{88}Sr are shown.

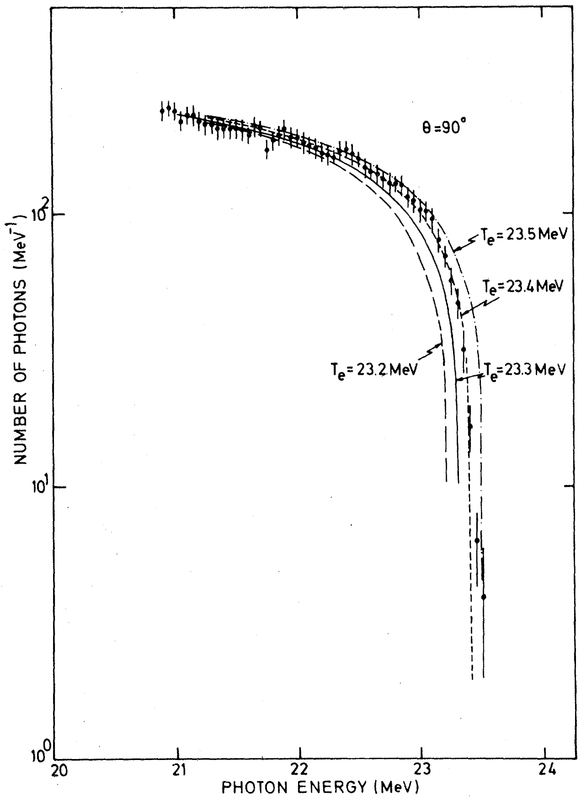

FIG. 2. Absolute number of bremsstrahlung photons per unit energy: the experimental points are derived from a $^{12}C(\gamma,p)^{11}B$ photoproton measurement, at an electron energy of 23.5 MeV, using the cross section for the inverse reaction; the lines show theoretically calculated bremsstrahlung shapes, at various end point energies, using the Schiff formula (Ref. 21).

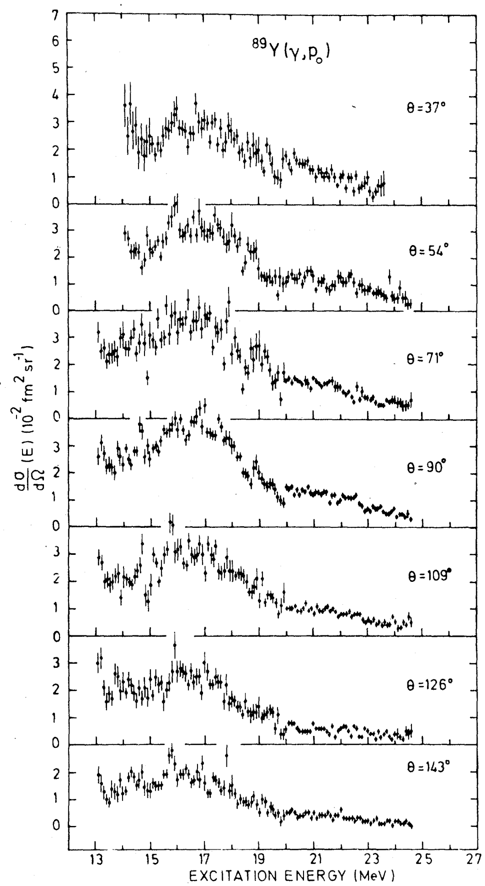

FIG. 3. The absolute differential cross sections for the $^{89}Y(\gamma,p_0)$ reaction.

trons. Evidently, this effect is due to the energy loss of the electrons in the 182 mg/cm^2 thick Au-bremsstrahlung converter target. However, if the kinematic end point is shifted downwards by 100 keV in the theoretical spectrum, then both the magnitude and the shape of the Schiff photon spectrum agree very well with the experimental points derived from the $^{12}C(\gamma,p)$ experiment.

Since, on the other hand, for every experimental $^{89}Y(\gamma,p)$ run performed at a certain end point energy, the true electron energy may deviate slightly (within ±0.3%, determined by the energy-defining slits) from the preset one due to varying linac operating conditions, it became necessary to determine this energy shift of the Schiff photon spectrum experimentally at each incident electron energy. Now, as the end point energy value of our measurements was stepped in 1 MeV increments and as the corresponding pure ground state part of the photoproton spectrum for each run is 1.8 MeV wide, this energy shift can be determined by requiring that the deduced (γ,p_0) cross sections must be the same in the overlapping 0.8 MeV wide energy regions.

Using this procedure the absolute differential (γ,p_0) cross sections, shown in Fig. 3, were obtained for the 7 angles θ in the energy interval ranging from 13 to 25 MeV. After subtraction of the (γ,p_0) spectra from the originally measured (γ,p) spectra, it was also possible to determine the differential (γ,p_1) cross sections, since the energy difference between the first and second excited state in ^{88}Sr is about 0.9 MeV; these cross sections are plotted in Fig. 4. To these differential cross sections a sum of Legendre polynomials was fitted in the usual way:

$$\frac{d\sigma}{d\Omega}(\theta,E)=A_0(E)\left[1+\sum_{l=1}^{k}a_l(E)P_l(\cos\theta)\right],$$

where $a_l(E)=A_l(E)/A_0(E)$. For the (γ,p_0) cross sections this fitting was performed to fourth order in the Legendre polynomials, i.e, $k=4$, while for the (γ,p_1) data $k=2$, due to the much

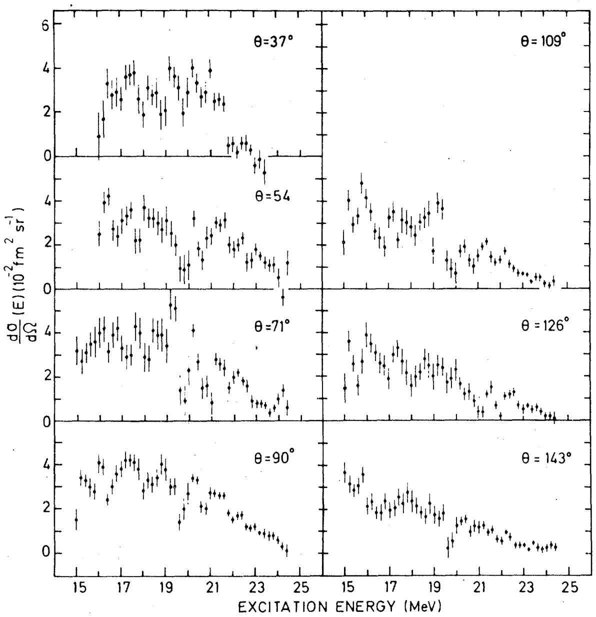

FIG. 4. The absolute differential cross sections for the $^{89}Y(\gamma, p_1)$ reaction.

poorer statistics involved, caused by the subtraction technique.

III. RESULTS AND DISCUSSION

A. The $^{89}Y(\gamma, p_0)$ cross section

The total integrated-over-angles ground state cross section, equal to $4\pi A_0(E)$, is presented in Fig. 5 together with the results of Paul *et al.*,[8] obtained by detailed balance from his (p, γ_0) data; the (γ, p_0) cross section resulting from the $(e, e'p)$ experiment of Shoda *et al.*[9] is shown in the bottom half of the figure. Only the statistical errors on our experimental points are plotted, while the systematic uncertainty is estimated to be of the order of 5%, mainly due to the inaccurate knowledge of the photon spectrum shape. The overall cross section curve peaks at 16.8 MeV, i.e., the energy at which the $T_<$ dipole resonance is found in the (γ, n) experiments[22,23] In the energy region between 15.5 and 17.5 MeV our absolute cross section has the mean value of 0.376 ± 0.003 fm^2 which is slightly larger than the value obtained by Paul *et al.*[8] (0.334 fm^2) or Shoda *et al.*[9] (0.323 ± 0.007 fm^2).

As illustrated in Fig. 5 the (γ, p_0) cross section shows an appreciable amount of detailed structure at energies of 14.0, 15.8, 16.8 and 17.4 MeV, which can be identified as being due to known $\frac{1}{2}^+$ and $\frac{3}{2}^+$ isobaric analog states[6] in ^{89}Y in agreement with previous experimental results.[8,9] Only a fraction of the single-particle dipole

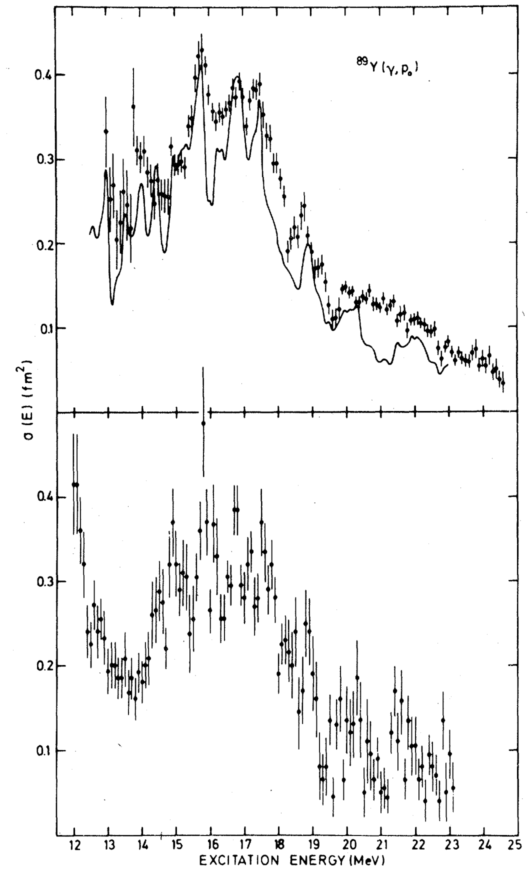

FIG. 5. The points with error bars in the upper half of the figure show our experimentally determined total $^{89}Y(\gamma, p_0)$ cross section, while the full line represents the results deduced from the $^{88}Sr(p, \gamma_0)$ data of Paul *et al.* (Ref. 8); the bottom half of the figure shows the (γ, p_0) cross section resulting from the $(e, e'p)$ experiment of Shoda *et al.* (Ref. 9).

strength is found in these resonances due to their rather small single-particle ground state spectroscopic factors.[6] Such small strength may nevertheless be observed experimentally if it is concentrated in a sufficiently narrow resonance. The fact now that the IAS appear as such narrow peaks is due to the approximate conservation of isospin. In what follows we will briefly explain the underlying arguments. For heavy and medium-heavy nuclei such as ^{89}Y, the decay of the $T_<$ giant dipole resonance mainly proceeds through thermalization followed by the statistical emission of low energy neutrons with low angular momentum. This thermalization starts through coupling of the simple coherent one-particle–one-hole dipole state with the dense 2p-2h states via the two-body residual nuclear interaction. Successive interactions lead to more and more $T_<$ complicated states which have a high density in the energy region of the

GDR. This mechanism goes on until a state is formed that contains a neutron of sufficiently low angular momentum so that it can escape from the nucleus, giving rise to a typical evaporation spectrum. On the other hand, coupling of the well-separated $T_>$ isobaric analog states with the $T_<$ complicated states is only possible via the weak isospin-symmetry breaking electromagnetic interaction and as such, the statistical decay of these IAS by neutron emission is strongly inhibited; consequently, the lifetime of the states is increased leading to the appearance of narrow resonances. The hindrance of neutron emission favors the decay via proton emission through direct coupling of the IAS with the $T_>$ continuum, in one of those proton channels that correspond to the proton-hole ground state and low-lying proton-hole excited states in ^{88}Sr. Nevertheless, although this direct proton decay is favored, indications of the isospin–forbidden statistical decay of the IAS have been observed in the (γ, n) cross section.[23]

Apart from the pronounced structure around 18.8 MeV, Paul *et al.*[8] and Shoda *et al.*[9] observed two additional resonances at about 20 and 22 MeV, respectively; these latter two peaks correspond to only one broad bump in our cross section. For the sake of completeness we should add here that Weller *et al.*[24] in their recent (p, γ) measurements did not observe these two maxima either, while, in general, there exists a good agreement with our results. However, regardless the details of this minor structure, it can be interpreted as originating from the expected $T_>$ coherent dipole state[12] in ^{89}Y, placed around 21.2 MeV.[8,10,11] The decay of this coherent $T_>$ state is different from that of the IAS discussed above as the coupling of this coherent 1p-1h $T_>$ state to more complicated $T_>$ is now possible due to the fact that the density of these latter states may be high in the relevant energy region, while the isolated $T_>$ IAS are only embedded in a region of high $T_<$ state density. Thus the decay of the simple $T_>$ doorway can now proceed by thermalization, without the weak isospin-nonconserving interactions. Consequently, the existence of the coherent $T_>$ state may appear as a broad resonance in the cross section since the decay mechanism is essentially the same as for the $T_<$ dipole state. This means that statistical emission of photoprotons will be possible (statistical neutron decay caused by isospin mixing in the thermalization process is inhibited), although only the more energetic particles can be emitted due to the high Coulomb barrier. From this argument we can understand that little $T_>$ coherent dipole strength will be observed in the direct (γ, p_0) and (γ, p_1) channels and no definite conclusions about the isospin splitting can be drawn. Information about the total $T_>$ strength should be derived from the knowledge of the total (γ, p) cross section and of the $T_>$ part contained in the (γ, n) cross section. Experimental estimates of this strength have already been obtained from the (γ, γ') measurements by Arenhövel *et al.*[11] and from the $(e, e'p)$ data of Shoda *et al.*[10] which seem to be in agreement with the theoretical predictions of Fallieros.[12]

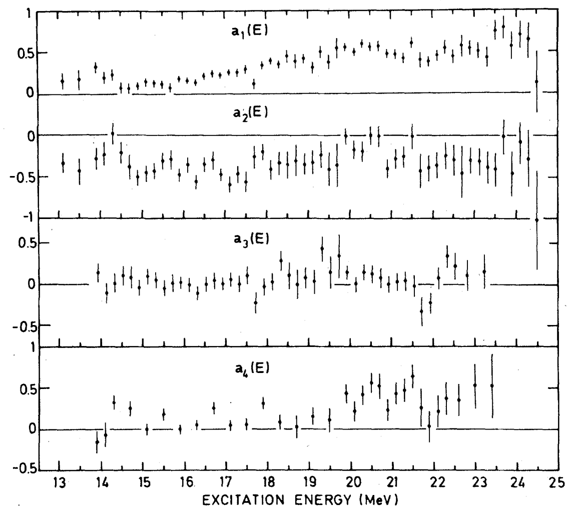

FIG. 6. The angular distribution coefficients $a_l(E)$, $l = 1, \ldots, 4$, as a function of excitation energy for the ^{89}Y(γ, p_0) reaction.

The energy-dependent angular distribution coefficients $a_l(E)$ $(l = 1, \ldots, 4)$ for the ^{89}Y(γ, p_0) reaction are shown in Fig. 6; they are functions of the electromagnetic multipole transition matrix elements and as such they contain the dynamics of the reaction. The asymmetry parameter $a_1(E)$ is clearly positive and increases gradually from about 0.2 at 13 MeV to about 0.7 at 25 MeV; there is a slight indication of the presence of structure. Its nonzero value indicates that interference exists between states of different multipolarity. The other asymmetry coefficient $a_3(E)$ is nearly zero in the entire energy range. The anisotropy parameter $a_2(E)$ always remains negative and has a mean value of about -0.35; again there exists a tendancy to show structure. Finally, the quadrupole interaction parameter $a_4(E)$ seems to be positive, especially above 20 MeV, where it reaches a value of 0.5.

If we limit ourselves to only $E1$ and $E2$ photon absorption (which seems justified as the $M1$ resonance is expected to be located around 9 MeV), the relation between the angular distribution coefficients and the transition matrix elements can explicitly be written as follows[25]

$$1=s^2+2d^2+2p^2+3f^2\,,$$

$$a_1=3.46sp\cos(\phi_s-\phi_p)+6.24df\cos(\phi_d-\phi_f)+0.69dp\cos(\phi_d-\phi_p)\,,$$

$$a_2=-d^2+p^2+1.72f^2-2sd\cos(\phi_s-\phi_d)+pf\cos(\phi_p-\phi_s)\,,$$

$$a_3=-2.77df\cos(\phi_p-\phi_f)-3.46sf\cos(\phi_s-\phi_f)-4.16dp\cos(\phi_d-\phi_p)\,,$$

$$a_4=-1.72f^2-6.86pf\cos(\phi_p-\phi_f)\,.$$

This constitutes a set of five quadratic equations with seven unknowns and wherein the $A_0(E)$ coefficient has been normalized to unity. The symbols s, d, p, f, ϕ_s, ϕ_d, ϕ_p and ϕ_f stand for the four moduli and corresponding phases of the various transition matrix elements which connect the $\frac{1}{2}^-$ ground state in ^{89}Y with the $\frac{1}{2}^+$, $\frac{3}{2}^+$ (s- and d-wave) dipole channels and the $\frac{3}{2}^-$, $\frac{5}{2}^-$ (p- and f-wave) quadrupole channels, respectively. Since this set cannot be solved unambiguously, we have tried to determine the minimum value of the $E2$ contribution to the absorption mechanism by minimizing the $E2$ part of the cross section in the first equation, which is equal to $2p^2+3f^2$, taking into account the fifth equation as a binding condition between p and f. It turns out that this minimum $E2$ cross section is then proportional to the $a_4(E)$ coefficient which, as a matter of fact, only contains $E2$ matrix elements. The following result is obtained:

$$[\sigma_{E2}(\gamma,p_0)]_{\min}=-\lambda a_4(E)\cdot\sigma(\gamma,p_0)$$

with $\lambda=-0.88$ when $a_4>0$, and $\lambda=0.58$ when $a_4<0$. Since a fitting to fourth order in the Legendre polynomial expansion is not always justified, depending on the statistical accuracy of the measured angular distributions, the deduced minimum $E2$ contribution has to be interpreted carefully; i.e., its meaning depends on the significance of the $a_4(E)$ coefficient. Our result is depicted in Fig. 7.; it shows that the $E2$ part relative to the total (γ,p_0) cross section steadily rises from about 6% at 14 MeV to about 40% at 23 MeV.

In order to extract more information from the measured angular distribution coefficients we tentatively assume that the $a_3(E)$ together with the $a_4(E)$ parameter equal zero over the entire energy range. The last assumption may eventually only be justified in the energy region below 20 MeV and it leads to a vanishing f-matrix element. Substituting this result into $a_3(E)$ yields the condition that $\phi_p-\phi_d=(\pi/2)+n\pi$. Consequently we are now left with three equations with four unknowns s, d, p, and

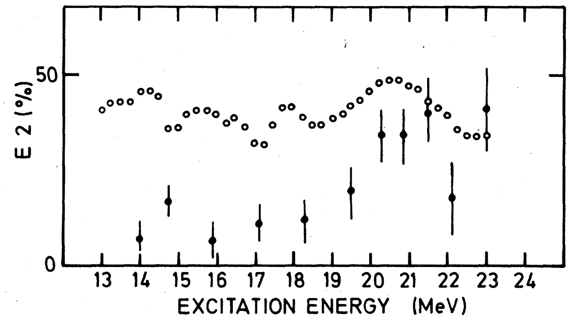

FIG. 7. Upper (open circles) and lower (dotted points) limits of the $E2$ contribution to the ^{89}Y(γ,p_0) photoabsorption.

ϕ_d, which can be solved as a function of the unknown phase ϕ_d. If we now select that phase for which the p-matrix element reaches its maximum value, it is possible to deduce at every energy an upper limit for the $E2$ absorption. This maximum is also shown in Fig. 7 by the open dots (no statistical uncertainties are indicated); it fluctuates between about 30% and 50% of the total (γ,p_0) cross section. From this figure it is also obvious that our estimates of the minimum and maximum $E2$ contributions seem to converge towards the same value of 35–40% at 23 MeV. Integrated between 13 MeV and 23 MeV these upper and lower limits correspond to 22% and 6%, respectively, of the summed $(\Delta T=0+\Delta T=1)$ $E2$ energy weighted sum rule which for ^{89}Y has the value of 1.7×10^{-2} fm^2 MeV^{-1}. It is well known that the $\Delta T=0$ and $\Delta T=1$ giant quadrupole resonances are expected to be located at the energies of 14 and 28 MeV, respectively.[13,14] This means that the quadrupole photon absorption suggested by our measurements must be mainly due to a direct nonresonant process in most of the energy interval under study.

B. The ^{89}Y(γ,p_1) cross section

The total (γ,p_1) cross section, derived using the procedure described before, is shown in Fig. 8, together with its $a_1(E)$ and $a_2(E)$ angular distribution coefficients. The absolute magnitude of the cross section is comparable to that of the (γ,p_0) reaction and originates from a direct emission [compare with the (γ,p_0) process] of protons from the dipole state to the simple first excited 2^+ proton-hole state at 1.836 MeV in ^{88}Sr. Although the statistical accuracy of the data is limited, structure is indicated at 17.4, 18.7–19.3, 20.2, 21.4, and (22.3) MeV. Most of these resonances tend to coincide with peaks identified in the (γ,p_0) cross section. Although the other known IAS cannot be observed in our (γ,p_1) re-

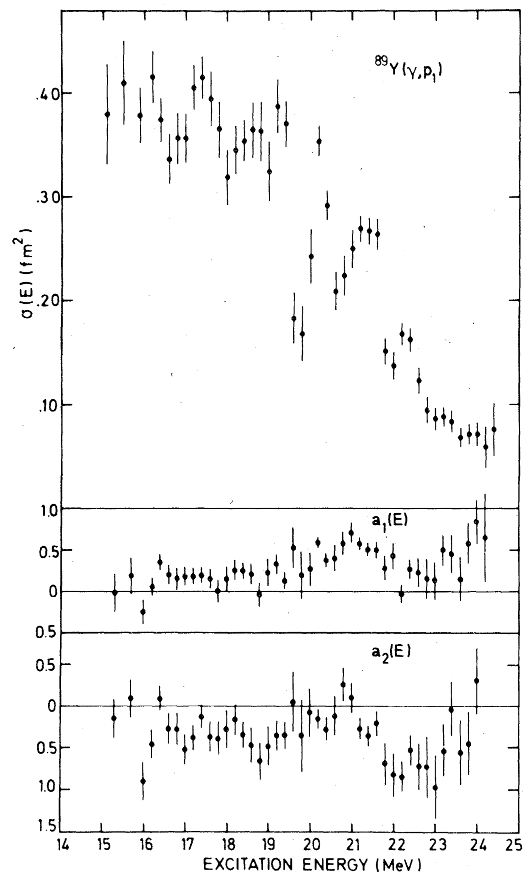

FIG. 8. The upper half of the figure shows the total $^{89}Y(\gamma, p_1)$ cross section, while in the lower half the angular distribution coefficients $a_1(E)$ and $a_2(E)$ are represented.

sults, the $\frac{1}{2}^+$ isobaric analog resonance at 17.4 MeV seems to be present in both cross sections. If this is the case this would mean that the corresponding $\frac{1}{2}^+$ state, located at 5.36 MeV in the ^{89}Sr parent nucleus, at least consists of a mixture of three configurations: a first one wherein a single $3s_{1/2}$ neutron is coupled to the ground state of ^{88}Sr, a second and a third configuration in which a $2d_{5/2}$ and a $2d_{3/2}$ single neutron is coupled to the first 2^+ excited state in ^{88}Sr. This conclusion is in agreement with the particle-core model[26] for the low-lying states in ^{89}Sr and with the results from the study of the proton decay of the low-lying IAS in ^{89}Y induced by elastic and inelastic proton scattering.[27,28] Since from our data it is difficult to deduce the strength of this isobaric resonance in both the ground state and the first excited state (γ, p) channel it is not possible to derive more specific spectroscopic information on the related parent state in ^{89}Sr.

The bump near 21 MeV may again be an indication of the existence of the coherent $T_>$ dipole state located around this same energy. However, it is obvious that the (γ, p_1) cross section is appreciably larger in this energy region than the (γ, p_0) cross section. The $a_1(E)$ angular distribution coefficient (see bottom half of Fig. 8) is definitely positive and again illustrates the interference between states of opposite parity; around 21 MeV a maximum is observed. The anisotropy coefficient $a_2(E)$ is nearly always negative and displays some structure. Even if one makes the assumption that only $E1$ and $E2$ photon absorption takes place, a detailed analysis of these coefficients is impossible as the relations between the angular distribution coefficients and the multipole matrix elements for this proton channel are too complicated to allow unambiguous conclusions.

IV. CONCLUSION

The photoproton cross sections and angular distributions were measured in the energy interval between 13 and 24.6 MeV for both the ground state and first excited state channels using a bremsstrahlung photon beam. The discussion of the (γ, p_0) process leads to the conclusion that the observed cross section mainly originates from direct proton emission from the dipole state; it shows a number of narrow isolated resonances in the lower energy region which can be interpreted as single particle isobaric analogs of the $\frac{1}{2}^+$ and $\frac{3}{2}^+$ excited states in the ^{89}Sr parent nucleus. On the other hand, due to poor statistics, these IAS appear much less pronounced in the (γ, p_1) channel; the cross section for this latter process has the same origin (i.e., from direct proton emission) as in the (γ, p_0) reaction while its magnitude is about the same. In the neighborhood of 21 MeV excitation energy an indication of the existence of the $T_>$ coherent dipole state is found in both the (γ, p_0) and the (γ, p_1) cross sections. However, in order to draw more definite conclusions about this predicted isospin splitting of the giant dipole resonance, the total (γ, p) cross section should be determined. This is the aim of a currently performed further analysis of our measured photoproton spectra. From the determination of the angular distribution coefficients of the ground state photoprotons an estimate was made of the upper and lower limits of the electric quadrupole photon absorption. These amount to 22% and 6%, respectively, of the summed isoscalar and isovector $E2$ energy weighted sum rule. It is hoped that the present results of the $^{89}Y(\gamma, p)$ cross sections and angular distributions will stimulate further theoretical calculations, especially within the framework of the direct-semidirect reaction model, allowing an accurate interpretation of the experimental data.

ACKNOWLEDGMENTS

We wish to thank Professor A.J. Deruytter for his continuing interest during the course of this work. We are especially grateful to the linac crew for the operation of the linear electron accelerator. We also acknowledge the financial support lent by the Interuniversity Institute for Nuclear Sciences (I.I.K.W.) and the National Foundation for Scientific Research (N.F.W.O.), Brussels.

---

*Present address: S.C.K., Mol, Belgium.

†Present address: Picañol, Ypres, Belgium.

[1]E. G. Fuller, H. M. Gerstenberg, H. Vander Molen, and T. C. Dunn, *Photonuclear Reaction Data* (NBS Special Publication No. 380, 1973 and Suppl. I, 1978).

[2]C. D. Kavaloski, J. S. Lilley, D. C. Shreve, and N. Stein, Phys. Rev. 161, 1107 (1967).

[3]T. A. Hughes and S. Fallieros, Phys. Rev. C 3, 1950 (1971).

[4]J. D. Vergados and T. T. S. Kuo, Nucl. Phys. A168, 225 (1971).

[5]S. M. Shafroth and G. J. F. Legge, Nucl. Phys. A107, 181 (1968).

[6]E. R. Cosman, H. A. Enge, and A. Sperduto, Phys. Rev. 165, 1175 (1968).

[7]E. R. Cosman, J. M. Joyce, and S. M. Shafroth, Nucl. Phys. A108, 519 (1968).

[8]P. Paul, in *Proceedings of the International Conference on Photonuclear Reactions and Applications, Asilomar, 1973,* edited by B. L. Berman (Lawrence Livermore Laboratory, University of California, 1973), p. 407.

[9]K. Shoda, M. Sugawara, T. Saito, and H. Miyase, Nucl. Phys. A221, 125 (1974).

[10]K. Shoda, H. Miyase, M. Sugawara, T. Saito, S. Oikawa, A. Suzuki, and J. Uegaki, Nucl. Phys. A239, 397 (1975).

[11]H. Arenhövel and J. M. Maison, Nucl. Phys. A147, 305 (1970).

[12]S. Fallieros and B. Goulard, Nucl. Phys. A147, 593 (1970).

[13]R. Pitthan, F. R. Buskirk, E. B. Dally, J. O. Shannon, and W. H. Smith, Phys. Rev. C 16, 970 (1977).

[14]N. Marty, M. Morlet, A. Willis, Y. Comparat, and R. Frascaria, Nucl. Phys. A238, 93 (1975).

[15]J. Arvieux, J. P. Albanese, M. Buenerd, J. Bolger, E. Boschitz, G. Pröbstle, F. Vogler, K. Gabathuler, P. A. M. Gram, J. Jansen, and R. E. Mischke, Phys. Lett. 90B, 371 (1980).

[16]K. Shoda and H. Taneichi, J. Phys. Soc. Jpn. 26, 217 (1969).

[17]B. I. Goryachev, B. S. Ishkhanov, and V. G. Shevchenko, in *Proceedings of the Second Symposium on the Problems of Nuclear Physics, Novosibirsk, 1970* (Novosibirsk, USSR, 1971), p. 362.

[18]R. Carchon, R. Van de Vyver, H. Ferdinande, J. Devos, and E. Van Camp, Phys. Rev. C 14, 456 (1976).

[19]D. E. Frederick, R. J. J. Stewart, and R. C. Morrison, Phys. Rev. 186, 992 (1969).

[20]R. G. Allas, S. S. Hanna, L. Meyer-Schützmeister, and R. E. Segel, Nucl. Phys. 58, 122 (1964).

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

[22]B. L. Berman, J. J. Caldwell, R. R. Harvey, M. A. Kelly, R. L. Bramblett, and S. C. Fultz, Phys. Rev. 162, 1098 (1967).

[23]A. Leprêtre, H. Beil, R. Bergère, P. Carlos, A. Veyssière, and M. Sugawara, Nucl. Phys. A175, 609 (1971).

[24]H. R. Weller and N. R. Roberson (private communication).

[25]R. W. Carr and J. E. E. Baglin, Nucl. Data Tables A10, 143 (1971).

[26]J. E. Spencer, E. R. Cosman, H. A. Enge, and A. K. Kerman, Phys. Rev. C 3, 1179 (1971).

[27]E. R. Cosman, R. Kalish, D. D. Armstrong, and H. C. Britt, Phys. Rev. C 1, 945 (1970).

[28]K. Ramavataram, R. Larue, T. C. Sharma, C. St-Pierre, and S. Ramavataram, Nucl. Phys. A247, 139 (1975).