# THE PHOTODISINTEGRATION OF NUCLEI WITH $Z$ BETWEEN 9 AND 30

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*Summary*

It is pointed out that the Danos-Okamoto effect (splitting of the giant resonance for non-spherical nuclei into two components) should be more readily observable in the region $9 \leqslant Z \leqslant 30$ than in the rare earth region where the initial search for the effect has been made. The ratio of the energies of the two components of the split resonance depends on the deformation of the nucleus from spherical shape. Deformations are even larger in this region of atomic number than for the rare earth nuclei, whose intrinsic electric quadrupole moments are large. The predictions of the theory of Danos (1958) are shown to be verified experimentally in five cases. Five other cases where the effect should be observable are discussed.

## I. INTRODUCTION

The application to non-spherical nuclei of the long-range correlation model of the nuclear photoeffect was made by Danos (1958) and Okamoto (1956, 1958). Their work predicted a splitting of the giant resonance into two components for these nuclei. If $\hbar\omega_a$ and $\hbar\omega_b$ are the energies of the two resonances, they are related to the shape of the nucleus in its ground state by

$$\hbar\omega_b/\hbar\omega_a = 0\cdot911a/b + 0\cdot089, \qquad (1)$$

where $a$ and $b$ are the lengths of the half axes of the nucleus, which is assumed spheroidal. $a$ refers to the axis of rotational symmetry. The electric quadrupole moment of a spheroid having a uniform charge distribution is given by

$$Q_0 = \tfrac{2}{5}Z(a^2 - b^2). \qquad (2)$$

Defining $R^3 = R_0^3 A = ab^2$, where $R$ is the radius of a sphere having the same volume as the spheroid, we can write the eccentricity $\varepsilon$ as $(a^2 - b^2)/R^2$. This gives

$$Q_0 = \tfrac{2}{5}R_0^2\varepsilon \cdot ZA^{2/3}. \qquad (3)$$

The electron scattering of Hofstadter (1956), when interpreted in terms of a uniform charge distribution, leads to $R_0 = 1\cdot2$ fermi. That value is used throughout this paper.

If the eigenvalue splitting $(\hbar\omega_b - \hbar\omega_a)$ is less than $\Gamma$ (the width at half maximum cross section of the giant resonance for spherical nuclei), the cross section consists of one broadened peak, but, if the splitting is greater than $\Gamma$, then two peaks should be resolved if their heights are approximately equal.

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In a nucleus with a positive $Q_0$, the peak of greater integrated cross section occurs at higher energy, while the opposite is true if the nucleus concerned has a negative $Q_0$.

This theory has been verified experimentally for tantalum and terbium by Weiss and Fuller (1958), and independently by Spicer, Thies, *et al.* (1958) for tantalum. Both these experiments indicate the existence of two peaks in the cross section for nuclear absorption of photons, although neither experiment indicated two completely separated peaks.

Since the theory of the Danos-Okamoto effect is based on a strong interaction model of the nucleus, all nuclei where the collective model (Bohr and Mottelson 1953) has been applied successfully should also exhibit the splitting of the giant resonance. The purpose of the present paper is to point out that the range of nuclei $9 \leqslant Z \leqslant 30$ is one in which the Danos-Okamoto effect should be observable.

In this region of atomic number, the Chalk River group (Litherland *et al.* 1956; Bromley, Gove, and Litherland 1957; Litherland *et al.* 1958) have been able to account for a large body of experimental data in terms of one unique spheroidicity parameter $\delta$ for each nucleus considered. This spheroidicity parameter $\delta$ was defined by Nilsson (1955) and is related to the $\varepsilon$ of Danos by

$$\varepsilon = 2\delta(1+\tfrac{2}{3}\delta).$$

This expression was obtained from comparison of the expressions for $Q_0$ given by Nilsson (1955) and Danos (1958).

Therefore, a number of nuclei in the range $9 \leqslant Z \leqslant 30$ are examined for the existence of the Danos-Okamoto effect. Using values of $Q_0$ obtained from measurements in either Coulomb excitation or microwave spectroscopy, the ratio of the two resonance energies for each nucleus is calculated, and, where possible, compared with experiment. Table 1 summarizes this comparison, and discussion follows below.

Table 1

Comparison of predicted and observed resonance energy ratios

| Nucleus | $\varepsilon$ | Reference | $\hbar\omega_b/\hbar\omega_a$ | |
|---|---|---|---|---|
| | | | Predicted | Observed |
| $^{19}$F | 0·69 | Sherr, Li, and Christy (1955) | 1·31 | 1·43 |
| $^{25}$Mg | 0·89 | Litherland *et al.* (1958) | 1·43 | 1·45 |
| $^{29,30}$Si | —0·37 | Bromley, Gove, and Litherland (1957) | 0·84 | 0·73 |
| $^{51}$V | 0·28 | Alder *et al.* (1956) | 1·12 | 1·17 |
| $^{63}$Cu | —0·30 | Bleaney, Bowers, and Pryce (1955) | 0·86 | 0·87 |

The resonances found on the low energy side of the giant resonance for two of the nuclei considered, namely $^{19}$F and $^{25}$Mg, were formerly classed as “ pigmy ” resonances. They are here reinterpreted as components of a split giant resonance.

## II. Examination of Data

The ratio of the two resonance energies as given by Danos (1958) is linearly dependent on the ratio $a/b$. Verification of the existence of this effect was first sought in or near the rare earth region, since it is there that large electric quadrupole moments are found. Since the difference between the two resonance energies is a function of $a/b$ and since the factor $ZA^{\frac{2}{3}}$ appears in the expression for $Q_0$, it was thought worthwhile to seek through other regions of the periodic table for nuclei having large values of $\varepsilon$, and hence of $a/b$. The region $9 \leqslant Z \leqslant 30$ is a region where $\varepsilon$-values are found of the same magnitude or larger than those in the rare earth region.

(*a*) $^{19}F$ (($\gamma$, n) *threshold* $10 \cdot 41 \pm 0 \cdot 01$ *MeV*; ($\gamma$, p) *threshold* $7 \cdot 96 \pm 0 \cdot 01$ *MeV*)

It has been pointed out by Paul (1957) and Rakavy (1957) that the energy level structure of the low-lying levels of $^{19}$F can be accounted for satisfactorily in terms of the collective model. This leads to a deformation parameter $\delta$ of $0 \cdot 3$. This interpretation also gives correctly the ratio of $\gamma$-ray transition probabilities from the $3/2^{+}$-state ($1 \cdot 59$ MeV) to the ground and second excited states, the magnetic moments for the ground and second excited states, and the $E2$ lifetime for the second excited state. The above value of $\delta$ gives an $\varepsilon$ of $0 \cdot 72$.

Coulomb excitation of the 198-keV level of $^{19}$F by $\alpha$-particles leads to a value of $B(E2)$ for the electric quadrupole excitation of this level. $B(E2)$ is the reduced transition probability for the $\gamma$-ray transition, and is defined by Bohr and Mottelson (1953). It is calculable from the yield function for $\gamma$-rays from the Coulomb excitation process, and in this case is found to be $0 \cdot 0034 \times 10^{-48} e^2$ cm$^4$ (Sherr, Li, and Christy 1955).

$B(E2)$ is related to the intrinsic quadrupole moment for the nucleus (Heydenburg and Temmer 1956), in this case by the relation

$$Q_0^2 = \frac{8}{15}\pi(2I_0+3)(I_0+2)B(E2),$$

which holds for $E2$ transitions $I_0$ to $I_0+1$, $I_0$ being the spin of the initial state. The quoted value of $B(E2)$ leads to a value of $0 \cdot 24$ barn for $Q_0$. From this value of $Q_0$, whose absolute accuracy is estimated as about 25 per cent., we find $\varepsilon$ to be $0 \cdot 65$, in good agreement with the value obtained by Paul (1957). The mean value of $\varepsilon$ gives $a/b$ as $1 \cdot 34$. The ratio of the two resonance energies $\hbar\omega_b/\hbar\omega_a$ for the photodisintegration process is thus predicted to be $1 \cdot 31$. If we assume $\hbar\omega_b$ to be 20 MeV, then $\hbar\omega_a$ is predicted to be $15 \cdot 1$ MeV.

A measurement of the $^{19}$F($\gamma$, $n$)$^{18}$F cross section by Horsley, Haslam, and Johns (1952) shows evidence for a peak on the low energy side of the 20 MeV resonance. The position of this lower energy peak is uncertain but is estimated as 14 MeV. We interpret these peaks as the two components of the split giant resonance due to the non-spherical shape of $^{19}$F. Both peaks must then be due to electric dipole transitions.

The ($\gamma$, $p$) cross section is assumed to have approximately the same shape as the ($\gamma$, $n$), allowing for the ($\gamma$, $p$) threshold being $2 \cdot 4$ MeV lower than the

$(\gamma, n)$ threshold. Lasich, Muirhead, and Shute (1955) measured angular distributions of photoprotons from fluorine for $\gamma$-ray energies between 10 and 17 MeV. They concluded that the multipolarity of the radiation absorbed in this energy region is predominantly either electric dipole or magnetic dipole. The $E1$ possibility is required by the interpretation of this paper.

(*b*) $^{25}Mg$ (($\gamma$, n) *threshold, 7·33±0·02 MeV;* ($\gamma$, p) *threshold, 12·07±0·02 MeV*)

The properties of $^{25}$Mg are discussed in terms of the collective model by Gove *et al.* (1956) and by Litherland *et al.* (1958). These latter authors conclude, on the basis of a detailed analysis of the properties of $^{25}$Mg and $^{25}$Al, that the equilibrium distortion of both these nuclei lies between $\eta=4$ and $\eta=6$, with the value 4·5 most favoured. $\eta$ (see Nilsson 1955) is related to $\delta$ by

$$\eta=\frac{\delta}{\varkappa}\left[1-\frac{4}{3}\delta^2-\frac{16}{27}\delta^3\right]^{-\frac{1}{3}}.$$

$\varkappa$ is a measure of the strength of the spin-orbit interaction assumed by Nilsson in the calculation of particle states in a spheroidal potential. He obtained a value of $\varkappa=0\cdot05$ for nuclei of atomic mass greater than 100. For the atomic mass region considered, the value suggested is 0·08 (see Bromley, Gove, and Litherland 1957). This lack of accurate knowledge of $\varkappa$ thus limits our knowledge of $\delta$.

Using $\varkappa=0\cdot08$ and taking $\eta$ as 4·5, we get $\delta=0\cdot36$. The value of $\varepsilon$ corresponding to this value of $\delta$ is 0·89. Following the same procedure as for $^{19}$F, the ratio of the two resonance energies for photon absorption is 1·43. This assumes a positive electric quadrupole moment and is reasonable since surrounding nuclei ($^{23}$Na and $^{27}$Al) are known to have positive quadrupole moments. If we take $\hbar\omega_b$ as 20 MeV, then $\hbar\omega_a$ is given as 14 MeV.

Nathans and Yergin (1955) determined the cross section for the $^{25}$Mg$(\gamma, n)$ reaction using a target of magnesium oxide enriched to 92·33 per cent. in $^{25}$Mg. They found that this cross section exhibited a plateau in the region 13½–15 MeV and showed the expected giant resonance at 20 MeV. However, Katz *et al.* (1954) have found a peak at 13·5 MeV, and Spicer, Allum, *et al.* (1958) at 13·8 MeV in the cross section computed from the yield curve of neutrons from natural magnesium. This peak is believed to be due mainly to neutrons emitted from $^{25}$Mg. The $(\gamma, n)$ thresholds in $^{24}$Mg and $^{26}$Mg are 16·57±0·02 and 11·12±0·03 MeV respectively. $^{24}$Mg cannot make any contribution to the 13·5 MeV peak on energetic grounds. $^{26}$Mg has its $(\gamma, n)$ threshold some 4 MeV above that of $^{25}$Mg and would therefore be expected to contribute much less because of this. The discussion of the present paper requires that the 13·8 MeV peak be due to electric dipole absorption of photons. The 20 MeV peak is also expected to be due to $E1$ transitions, since it comes in the region expected for the giant dipole resonance.

Spicer, Allum, *et al.* (1958) find the width of the 13·8 MeV resonance to be 2 MeV. Since Nathans and Yergin (1955) give the only unambiguous data on the 20 MeV resonance in the $(\gamma, n)$ cross section, their observed width is noted as

5 MeV. Toms and Stephens (1951), measuring the $^{25}$Mg($\gamma$, $p$) cross section, find a resonance at 20·5 MeV, with width of 3·5 MeV. The energy of the ($\gamma$, $p$) threshold is high enough to prevent the 13·8 MeV peak appearing in the cross section of this reaction. Thus these widths are in approximate agreement with those found necessary to fit the measured cross section for photon absorption in tantalum (Spicer, Thies, *et al.* 1958).

If the 13·8 MeV peak found by Spicer, Allum, *et al.* (1958) is ascribed to $^{25}$Mg alone, then it is approximately the same height as the 20 MeV peak. This latter height was obtained by adding the peak cross sections found by Nathans and Yergin ($\gamma$, $n$) and Toms and Stephens ($\gamma$, $p$). Thus the condition required by Danos's theory that $\int \sigma \mathrm{d}E$ for the higher energy peak shall be twice that for the lower energy peak is approximately satisfied.

The interpretation given here is consistent with the available experimental data, although the reason for the non-appearance of the 13·8 MeV peak in the results of Nathans and Yergin is still unknown.

(*c*) $^{29}$*Si* (($\gamma$, n) *threshold, 8·48±0·03 MeV ;* ($\gamma$, p) *threshold, 12·34±0·03 MeV*)
$^{30}$*Si* (($\gamma$, n) *threshold, 10·61±0·03 MeV;* ($\gamma$, p) *threshold, 13·80±0·11 MeV*)

$^{29}$Si has been the subject of a detailed examination to see whether its properties can be correlated with the predictions of the collective model (Bromley, Gove, and Litherland 1957). These authors conclude that the correlation can be made, and assign the parameter $\delta$ a value of $-0·22$ (assuming $\varkappa=0·08$ as for $^{25}$Mg). This value of $\delta$ corresponds to $\varepsilon$ equals $-0·37_4$. This leads to a value for the ratio $\hbar\omega_b/\hbar\omega_a$ of 0·836. Since the minus sign of $\delta$ implies an oblate spheroid, the peak of larger integrated cross section must come at the lower energy. Taking $\hbar\omega_a$ as 20 MeV, $\hbar\omega_b$ is predicted as 16·7 MeV.

Evidence from photodisintegration reactions is given by Katz *et al.* (1954). We assume that what is obtained by Katz for the low abundance $^{29}$Si and $^{30}$Si can be explained in the same way as his results for $^{25,26}$Mg. That is, we assume that the energy of the ($\gamma$, $n$) giant resonance in $^{28}$Si is also the energy of a component of the split giant resonance in $^{29,30}$Si. This has the value of 20·5 MeV. Katz also observed a peak in the cross section of the $^{29,30}$Si($\gamma$, $n$) reaction at 15 MeV. Unfortunately, it was not possible here to separate the effects of the two silicon isotopes being considered.

It is suggested that the 15 and 20·5 MeV peaks are the components of a split giant resonance as in the Danos-Okamoto effect. The agreement is not particularly good in this case.

The foregoing discussion of the experimental results for $^{29,30}$Si has been entirely in terms of the properties of $^{29}$Si. However, inclusion of the effect of $^{30}$Si on the experimental results will not improve the results unless $^{30}$Si is of prolate shape in contrast to the oblate shape specified for $^{28}$Si and $^{29}$Si by Bromley, Gove, and Litherland (1957). These authors indicate that $^{28}$Si and $^{29}$Si have the same value of the spheroidicity parameter $\delta$. Further, a comparison of the spheroidicity parameter for the even-even nuclei $^{28}$Si, $^{30}$Si may be obtained from comparison of the energies of their first excited states (Bohr and Mottelson

1955). This comparison indicates that, if anything, $^{28}$Si is more non-spherical than $^{30}$Si. This observation is not in the direction to give better agreement with the experimental results, if we assume both $^{29}$Si and $^{30}$Si to be oblate spheroids. The assumption that $^{30}$Si is a prolate spheroid would improve the agreement.

(*d*) $^{51}V$ (($\gamma$, n) *threshold, 11·08 MeV;* ($\gamma$, p) *threshold, 7·90 MeV*)

Measurement of the intrinsic quadrupole moment of $^{51}$V by the technique of microwave spectroscopy gave a result $0 \cdot 6 \pm 0 \cdot 4$ barn.

Coulomb excitation of the 0·32 MeV state in $^{51}$V gives a value of $0 \cdot 0056 e^2 \times 10^{-48}$ cm$^4$ for the reduced transition probability $B(E2)$ of the excitation process. The ground state spin is $7/2^-$, and the first two excited states, of energy 0·32 and 0·93 MeV, probably have spins $5/2^-$ and $3/2^-$ respectively (Bunker and Starner 1955). The Coulomb excitation of the 0·32 MeV level is thus a $7/2^- \rightarrow 5/2^-$ transition, and has been verified to be an $E2$–$M1$ mixture. The relation between $B(E2)$ and $Q_0$ for this case is given by Bohr and Mottelson (1953) as

$$B(E2) = \frac{15}{16\pi} Q_0^2 \frac{K^2(I+1-K)(I+1+K)}{I(I+1)(2I+3)(I+2)}$$

for an $I+1 \rightarrow I$ transition. It is assumed that the three levels known form a rotational series having $K=3/2$. No other value of $K$ will give a value of $Q_0$ within the wide limits of error of the spectroscopic moment. Using $K=3/2$, we obtain $Q_0$ as 0·51 barn, with an estimated error of $\pm 30$ per cent.

Okamoto (1956) has successfully accounted for the width of the giant resonance in $^{51}$V. An attempt is made here to estimate the detailed shape of the resonance by summing two Breit-Wigner shape resonances.

The data of Nathans and Halpern (1954) on the $^{51}$V($\gamma$, $n$)$^{50}$V reaction show some evidence for giant resonance splitting. With this in mind, an attempt was made to fit the experimental cross section values obtained by Nathans and Halpern with the sum of a pair of Breit-Wigner resonance curves of equal height. The lower energy peak was assumed to have width 2 MeV and the higher energy peak 4 MeV. The integrated cross sections of the two components thus satisfy one of the conditions of the Danos theory. The two widths were chosen as 2 and 4 MeV respectively because the same type of fit to the measured cross section for photon absorption in tantalum required peaks of these widths (Spicer, Thies, *et al.* 1958) and because these values for the widths evidently hold in the case of $^{25}$Mg. The higher energy peak was fixed at 20 MeV and the position of the lower energy peak was adjusted until the best fit was found. The result of this fit is shown in Figure 1. The agreement with the experiment of Nathans and Halpern (1954) is excellent. The low energy peak is at 17 MeV according to this fit, and this leads, using Danos's theory, to a $Q_0$ of $0 \cdot 67 \pm 0 \cdot 11$ barn. The error quoted was estimated on the assumption that the energy separation has maximum inaccuracy of $\pm 0 \cdot 5$ MeV. This agrees with the value of $Q_0$ obtained from Coulomb excitation within the experimental errors of the two values.

(*e*) $^{63}Cu$ (($\gamma$, n) *threshold, 10·83±0·02 MeV;* ($\gamma$, p) *threshold, 6·12±0·01 MeV*)

The nucleus $^{63}$Cu was considered in the same way as $^{51}$V. The spectroscopic quadrupole moment of $^{63}$Cu has been measured, and is quoted as $-0 \cdot 16$ barn $\pm 20$ per cent. (Bleaney, Bowers, and Pryce 1955). This leads to $Q_0 = -0 \cdot 80 \pm 0 \cdot 16$ barn, and thus to the prediction that $\hbar\omega_b/\hbar\omega_a$ equals 0·86. In this case, the negative $Q_0$ means that the peak of smaller integrated cross section (at $\hbar\omega_a$) comes at the higher energy. A cross section shape for the $^{63}$Cu($\gamma$, $n$) reaction was computed on the same basis as that used to fit the

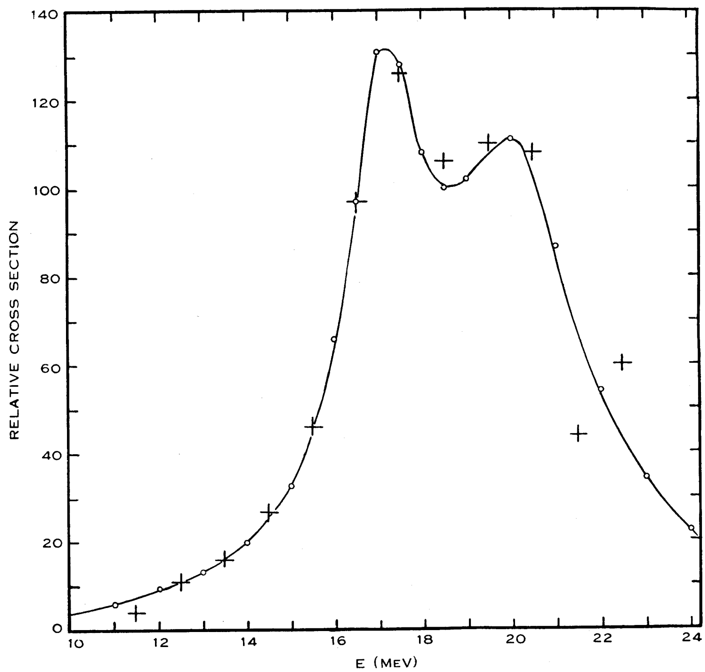


Fig. 1.—Fit of two Breit-Wigner resonance curves to the cross section for the $^{51}$V($\gamma$,$n$)$^{50}$V reaction. The resonance curves assumed had widths 2 and 4 MeV respectively, and were of equal height.
○ Predicted values, + experimental values.

vanadium cross section. The two peaks were assumed to have width 4 and 2 MeV respectively, and, for this fit, $\hbar\omega_a$ was assumed to have the value 19 MeV. This gave $\hbar\omega_b$ equal to 16·4 MeV. This computed cross section was compared in shape with the $^{63}$Cu($\gamma$, $n$) given by Katz and Cameron (1951). This experimental result was chosen because it used the smallest energy steps of any published cross section, namely 0·5 MeV. This fit is shown in Figure 2. Once again the agreement in shape is excellent.

### (*f*) *Other Nuclei*

We now consider five other nuclei in the chosen atomic number range, in which this effect should be clearly observable. They are $^{23}$Na, $^{27}$Al, $^{39}$K, $^{55}$Mn, $^{59}$Co. All save potassium are 100 per cent. isotopes, and $^{39}$K is 93·38 per cent.

abundant in natural potassium. In all these cases the value of $Q_0$ is known as a result of either microwave spectroscopy or Coulomb excitation. The known data concerning these nuclei are exhibited in Table 2.

Using the Danos theory, the ratio of the energies of the two components of the split giant resonance was computed in each case.

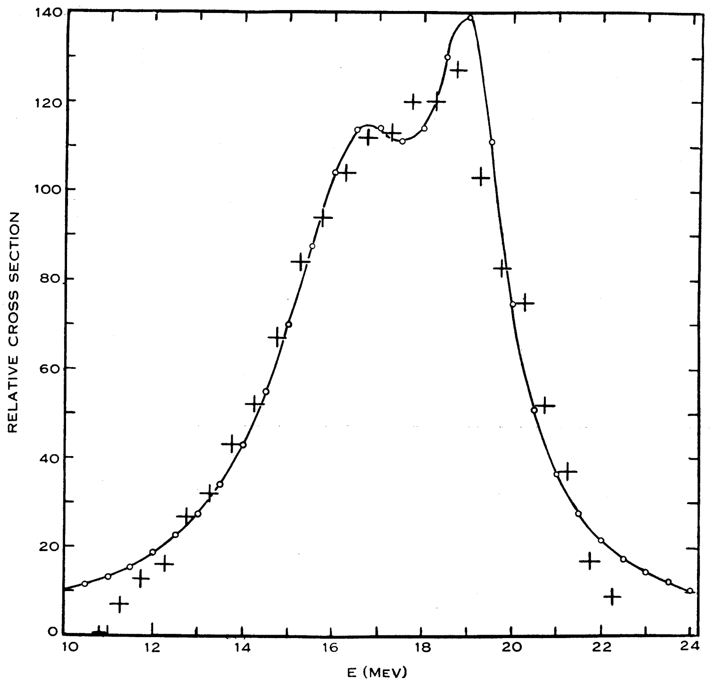


Fig. 2.—Comparison of $^{63}Cu(\gamma,n)^{62}Cu$ cross section with shape predicted using Danos's theory and the measured electric quadrupole moment of copper 63. The Breit-Wigner resonances assumed have widths 4 and 2 MeV respectively.

○ Predicted values, + experimental values.

To give an idea of the magnitude of the resonance splitting which may be expected, an energy value was assumed for the higher energy peak. The systematic study of $(\gamma, n)$ reactions by Montalbetti, Katz, and Goldemberg (1953) was used as a guide in the choice of this value. However, the ratio of energies $\hbar\omega_b/\hbar\omega_a$ is the significant number in this result. The predictions are shown in Table 3.

For $^{23}Na$ the predicted energy of the low energy peak is at the $(\gamma, n)$ threshold. In this case, the Danos-Okamoto effect should not be observable in the $^{23}Na(\gamma, n)$ reaction cross section, as the effect of competition from proton emission will be to keep the $(\gamma, n)$ cross section low near threshold, and should therefore remove evidence of this low energy peak. The low energy peak should, however, be observable in the cross sections for the $^{23}Na(\gamma, p)$ and $^{23}Na(\gamma, \alpha)$ reactions. No measurements have yet been made of these two cross sections. A prediction of the variation of the cross section for photon absorption with energy is shown in Figure 3. The peaks are assumed to have widths 2 and 4 MeV respectively, and to be of equal height.

TABLE 2

ECCENTRICITY AND PHOTONUCLEAR THRESHOLDS FOR ELEMENTS CONSIDERED

| Nucleus | $Q_0$* (barn) | $\varepsilon$ | $(\gamma,n)$ Threshold (MeV) | $(\gamma,p)$ Threshold (MeV) |
|---|---|---|---|---|
| $^{23}$Na | $+0\cdot50\pm0\cdot05$(S)(CE)† | 0·975 | $12\cdot41\pm0\cdot02$‡ | $8\cdot25\pm0\cdot03$‡ |
| $^{27}$Al | $+0\cdot44\pm0\cdot01$(S)† | 0·652 | $13\cdot06\pm0\cdot03$‡ | $8\cdot25\pm0\cdot03$‡ |
| $^{39}$K | $+0\cdot70\pm0\cdot17$(S)† | 0·56 | $13\cdot08\pm0\cdot09$‡ | $6\cdot42\pm0\cdot09$‡ |
| $^{55}$Mn | $+1\cdot54\pm0\cdot8$(S)†<br>$1\cdot26\pm0\cdot4$§ | 0·63 | $10\cdot15\pm0\cdot25$‡ | $8\cdot16\pm0\cdot20$‡ |
| $^{59}$Co | $+1\cdot1\pm0\cdot4$(S)† | 0·47 | $10\cdot49\pm0\cdot01$‖ | $7\cdot41\pm0\cdot01$‖ |

* The method of measurement of $Q_0$ is indicated by the initial in parentheses after the value. (S) means a spectroscopically determined moment, and (CE) means that the moment is obtained from Coulomb excitation measurements.

† Value taken from Blin-Stoyle (1956).

‡ Thresholds computed from mass data given by Wapstra (1955).

§ This Coulomb excitation measurement was by Mark, McClelland, and Goodman (1955).

‖ Thresholds given by Quisenberry, Scolman, and Nier (1956).

In the cases of $^{27}$Al, $^{39}$K, $^{55}$Mn, and $^{59}$Co, the predicted energy of the low energy peak is above the $(\gamma, n)$ threshold, and therefore, in principle, the low energy peak should be observable. It is possible, however, that even in these

TABLE 3

PREDICTIONS OF THE RESONANCE ENERGY RATIO

| Nucleus | $\hbar\omega_b/\hbar\omega_a$ | Assumed $\hbar\omega_b$ (MeV) | Predicted $\hbar\omega_a$ (MeV) |
|---|---|---|---|
| $^{23}$Na | $1\cdot47\pm0\cdot06$ | 18·3 | 12·5 |
| $^{27}$Al | $1\cdot31\pm0\cdot01$ | 19·7 | 15·1 |
| $^{39}$K | $1\cdot26\pm0\cdot07$ | 18·3 | 14·5 |
| $^{55}$Mn | $1\cdot30\pm0\cdot08$ | 20·5 | 15·8 |
| $^{59}$Co | $1\cdot22\pm0\cdot08$ | 18·0 | 14·8 |

cases the effect of competition from proton emission will prevent evidence for the low energy peak from appearing in the $(\gamma, n)$ cross section for these nuclei. Again, the low energy peak should be present in the $(\gamma, p)$ cross section. Halpern and Mann (1951) describe measurements of the $(\gamma, p)$ cross sections in $^{27}$Al and $^{59}$Co. In these two cases, the yield curve was not measured in sufficient detail to show the existence of a low energy peak. A programme of careful measurements of the low energy region of the $(\gamma, n)$ cross sections and of the $(\gamma, p)$ cross sections of the nuclei discussed in this section is under way in this laboratory, in an attempt to verify the predicted existence of the Danos-Okamoto effect in these nuclei.

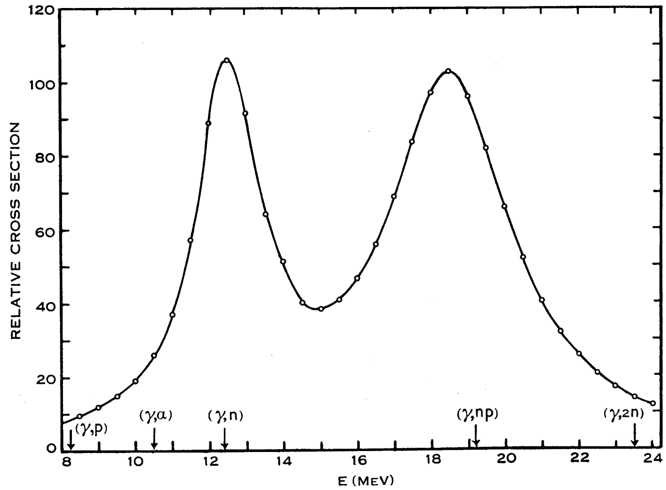


Fig. 3.—Predicted shape of the cross section for photon absorption in $^{23}$Na. The various photonuclear thresholds in $^{23}$Na are indicated by arrows. Parameters of the resonances are :

$$\hbar\omega_a = 12 \cdot 5 \text{ MeV}, \ \Gamma_a = 2 \ ; \ \hbar\omega_b = 18 \cdot 5 \text{ MeV}, \ \Gamma_b = 4.$$

## III. Conclusion

The predictions of the Danos-Okamoto theory on the splitting of the giant resonance into two component peaks are supported by experiments on the nuclei $^{19}$F, $^{25}$Mg, $^{29}$Si, $^{51}$V, and $^{63}$Cu. The positions of the two peaks in the cross section for nuclear photon absorption are estimated for five other nuclei, but experimental data are either not good enough or are completely lacking in these cases. Therefore we cannot say whether or not the Danos-Okamoto effect occurs in these nuclei also. If it does, then the measurement of the cross section for nuclear photon absorption can be expected to give a measure of the deformation from spherical shape of that nucleus, and hence of the intrinsic electric quadrupole moment. In the region considered, the deformations are in many cases larger than those in the rare earth region, although the values of $Q_0$ are not large here.

One of the more striking results of this investigation concerns the widths of the components of the split giant resonance. The fit to the observed cross section for nuclear photon absorption in tantalum (Spicer, Thies, *et al.* 1958) required Breit-Wigner shapes of widths 2 and 4 MeV respectively. In the case of

$^{25}$Mg, where the peaks are well separated, these widths apply also. Further, the shapes of the giant resonance in $^{51}$V and $^{63}$Cu have been successfully fitted using components of this width. Thus it appears that these two widths pertain for the two components of the split giant resonance throughout the periodic table from $A=19$ up. If this is so, then the width of the giant resonance for photon absorption, in the case where the two components are not resolved, may be used to give a measure of the ground state nuclear deformation.

To do this, one would have to assume the correctness of the model used by Danos (1958) in his predictions of this effect. This model is the classical model of Steinwedel and Jensen (1950). One of the assumptions of this model which is not expected to be correct is the assumption of a rigid nuclear surface. However, the success of the Danos (1958) theory indicates that this assumption is at least a good approximation.

## IV. Acknowledgment

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