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A. Fubini, A. Marino, G. Matone, D. Prospero, M. Roccella and
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1. - INTRODUCTION. -

The aim of this note is to present the proposal of an experiment to study the deexcitation properties of the electric dipole (GDR) and quadrupole (GQR) nuclear giant resonances.

This experiment was planned to carry-out systematical cross section measurements for nuclear elastic and inelastic scattering of monochromatic and plane-polarized gamma rays. The photon beam will be obtained by Compton scattering of Laser light from the high-energy electrons circulating in Adone (see Ladon project⁽¹⁾).

In order to get a general picture of the information one can extract from photon-nucleus scattering experiments, it is convenient to divide the nuclei according to the following three different classes:

- 1) Spherical (vibrational) nuclei,
- 2) Deformed nuclei,
- 3) Hard sphere nuclei.

Nuclear scattering and absorption of photons in the GDR region are usually described in terms of a "polarizability tensor $\epsilon_{\alpha\beta}$ ", defined as D_{α}/E_{β} , where \vec{E} and \vec{D} are respectively the photon electric field and the induced dipole moment. We can have a scalar polarizability ($\epsilon_{\alpha\beta} = \epsilon_{\alpha}\delta_{\alpha\beta}$) only when the nucleus is optically isotropic in its ground state and the GDR is associated only with a pure dipole harmonic oscillation. Detailed theoretical previsions of the tensor character of the optical nuclear polarizability, can now be obtained in the framework of the dynamic collective model (DCM)⁽²⁻⁵⁾. In this picture the GDR depends both on the symmetry of the nucleus in its ground state and on the coupling of the dipole

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vibrations to the quadrupole surface oscillations and rotations of the nucleus.

As it has been shown by several authors over the past few years⁽⁶⁾, the spherical (vibrational) nuclei have a GDR structure which agrees remarkably well with the provisions of the DCM. In this case the tensor part of the nuclear polarizability is essentially determined by the coupling between the dipole and the low-energy quadrupole vibration modes. This naturally implies the existence of inelastic scattering processes which populate those low lying vibrational states that can be reached by E1 transitions. The experimental observation of these inelastic components is by itself sufficient to prove the existence of the above mentioned coupling that is one of the basic concepts of the DCM.

The optical anisotropy properties of the strongly deformed nuclei are very well known⁽⁷⁾: the presence of a symmetry axis splits the GDR into two components. The coupling with the surface oscillations splits the upper resonance further into two, and each of the three resonances acquires an associated satellite resonance. The spectrum of the scattered photons will contain those inelastic components which populate the levels of the ground state rotational band that can be reached by E1 transitions (Raman effect).

The hard sphere nuclei, for instance Pb^{208} , have a pure scalar polarizability and therefore should not exhibit any inelastic scattering⁽⁸⁾.

To conclude this short discussion let us point-out that a fine analysis of the inelastic components of the photon scattering cross section is essential to obtain a quantitative test of the DCM⁽⁷⁾. Moreover, as it will be shown in the following section, the photon polarization is extremely important allowing an easier separation of the different components of the scattering cross sections. By plane-polarized photons it is in some cases possible to separate the contributions connected to different angular momentum transfers, even in poor energy resolution experiments.

Another interesting possibility we want to emphasize here, is the study of giant resonances other than the usual E1⁽⁹⁾. Several evaluations of the energy positions of the resonances E2, E3, are now available: for example an isoscalar E2 resonance has been suggested at the energy⁽¹⁰⁾

$$E \simeq 58 A^{-1/3} \text{ MeV} \quad (\text{E2, } T = 0)$$

and, furthermore, an isovector E2 resonance at the energy⁽¹¹⁾

$$E \simeq 120 A^{-1/3} \text{ MeV} \quad (\text{E2, } T = 1)$$

Experimental evidence for these resonances has been obtained by electron inelastic scattering^(9, 12) but it has been impossible to separate the isoscalar E2 contribution from that due to another isoscalar E0 resonance, predicted approximately at the same energy⁽¹⁰⁾. The experimental yield generally saturates 50% of the E2(T=0) sum rule, but in several cases there are anomalies: for Ca⁴⁴ this fraction is, in fact, 150% and becomes 240% if one assumes the resonance to be E0. Of course, an overlapping between these two resonances could be an obvious explanation.

2. - GENERAL EXPRESSION FOR $d\sigma/d\Omega$.

Let us introduce some preliminar definitions. By coherent scattering will be meant that scattering in which the nuclear system returns exactly to its initial energy and angular momentum state; all nuclear scattering processes by which final excited states are reached, are obviously incoherent. When the nucleus takes up angular momentum but the scattered γ -rays lie so close in energy to the incident ones as to be indistinguishable experimentally, we have a quasi-elastic incoherent scattering.

The general expression for the nuclear scattering cross section ($d\sigma/d\Omega$) in the dipole approximation has been given by several authors^(8, 13). Averaging over the final photon polarization and for completely polarized incoming photons we find:

$$(1) \quad \frac{d\sigma}{d\Omega} = \sum_{\nu} \frac{2}{2\nu+1} A_{\nu}^2 g_{\nu}(\theta, \varphi),$$

where:

A_{ν} are the scattering amplitudes for processes in which $\nu=0, 1, 2$ units of angular momentum are transferred to the nucleus.

They are respectively called scalar, vector and tensor amplitudes;

$g_{\nu}(\theta, \varphi)$ are angular distribution factors, depending on the scattering angle θ and on the angle φ of the incoming photon polarization vector \vec{E} with respect to the scattering plane.

One has:

$$(2) \quad \begin{aligned} g_0 &= \frac{1}{3}(\cos^2 \theta \cos^2 \varphi + \sin^2 \varphi), & g_1 &= 1 - \frac{1}{2}(\cos^2 \theta \cos^2 \varphi + \sin^2 \varphi), \\ g_2 &= 1 + \frac{1}{6}(\cos^2 \theta \cos^2 \varphi + \sin^2 \varphi). \end{aligned}$$

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The $\nu=0$ contribution arises mainly from the coherent elastic scattering, whereas the $\nu=1,2$ terms contribute to the incoherent scattering.

It is straightforward to show that in the even-even nuclei only inelastic components with $\nu=2$ are present. A schematic diagram of typical scattering processes involving even-even nuclei is shown in Fig.1.

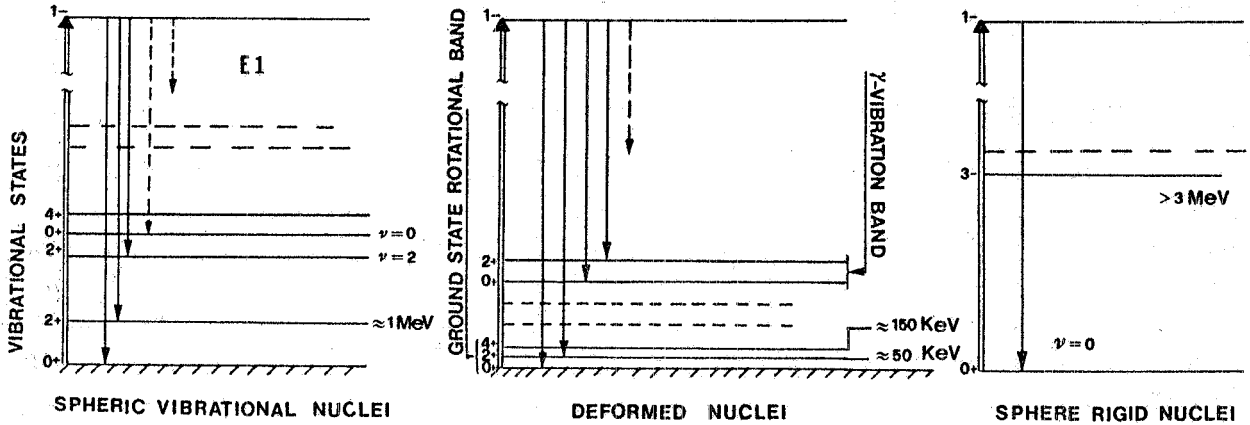


FIG. 1 - Typical scheme for scattering processes. -

In odd-A nuclei, due to the coupling between the even-even core and the extra-nucleon, the level structure becomes more complex. The addition of a nucleon, in the weak coupling limit, splits any of the low-lying vibrational states in a multiplet of levels, producing a distribution of the E1 strength among them. The inelastic components with $\nu=1$ are here strongly suppressed as well: a detailed discussion of this point may be found in ref. (8).

Neglecting A_1 , eq. (1) becomes:

$$(3) \quad \frac{d\sigma}{d\Omega} = |A_0|^2 g_0(\theta, \varphi) + \frac{1}{5} |A_2|^2 g_2(\theta, \varphi).$$

Eq. (3) can be specialized, according to whether the polarization vector \vec{E}_i is parallel or normal to the scattering plane ($\varphi = 0, \pi/2$); we obtain

$$(4) \quad \frac{d\sigma_{\parallel}}{d\Omega} = \frac{1}{3} |A_0|^2 \cos^2 \theta + \frac{1}{5} |A_2|^2 (1 + \frac{1}{6} \cos^2 \theta),$$

$$\frac{d\sigma_{\perp}}{d\Omega} = \frac{1}{3} |A_0|^2 + \frac{7}{30} |A_2|^2.$$

For $\theta = \pi/2$, $(\frac{d\sigma_{\parallel}}{d\Omega})$ does not depend on $|A_0|^2$, so that

$$(5) \quad |A_0(E1)|^2 = 3 \left\{ \frac{d\sigma^\perp}{d\Omega} - \frac{7}{6} \frac{d\sigma^\parallel}{d\Omega} \right\}_{\theta = \pi/2}$$

$$|A_2(E1)|^2 = 5 \left(\frac{d\sigma^\parallel}{d\Omega} \right)_{\theta = \pi/2}$$

In a recent experiment Hayward, Barber and Sazama⁽¹⁴⁾, measured $d\sigma^\parallel/d\Omega$ in several nuclei and found that $|A_2(E1)|^2/|A_0(E1)|^2 \lesssim 0.4$.

The situation is more complex when the E1 and E2 scatterings compete in the same energy regions. In this case, by generalizing equation (1), one has⁽¹⁵⁾:

$$(6) \quad \frac{d\sigma}{d\Omega} = \sum_{\nu} \sum_{L, L'} (2\nu + 1)^{-1} A_{\nu}^x(EL) A_{\nu}(EL') g_{\nu}(LL'; \theta, \varphi).$$

Explicit formulas for the coefficients $g_{\nu}(LL'; \theta, \varphi)$ with $L, L' = 1, 2$ and $\nu = 1, 2$ can be found in ref. (16), pag. 17. In our notations one has $g_{\nu}(11; \theta, \varphi) \equiv g_{\nu}(\theta, \varphi)$.

At $\theta = \pi/2$ all the interference terms vanish and retaining only the incoherent terms with $\nu = 2$ one has:

$$(7) \quad \left(\frac{d\sigma^\parallel}{d\Omega} \right)_{\pi/2} = \frac{1}{5} |A_0(E2)|^2 + \frac{1}{5} \left\{ |A_2(E1)|^2 + \frac{1}{2} |A_2(E2)|^2 \right\};$$

$$\left(\frac{d\sigma^\perp}{d\Omega} \right)_{\pi/2} = \frac{1}{3} |A_0(E1)|^2 + \frac{1}{5} \left\{ \frac{7}{6} |A_2(E1)|^2 + \frac{3}{7} |A_2(E2)|^2 \right\}.$$

A rough information on the difference $|A_0(E1)|^2 - 3/5 |A_0(E2)|^2$ can be obtained by directly subtracting the two terms of eq. (7); the terms in brackets are in fact equal within 15%. Moreover, a complete separation between the scalar E1 and E2 components is immediately obtainable only in the case of hard sphere nuclei. In fact in this case one has:

$$(8) \quad R = \frac{5}{3} \left\{ \frac{d\sigma_{el}^\parallel}{d\Omega} / \frac{d\sigma_{el}^\perp}{d\Omega} \right\}_{\theta = \pi/2} = \frac{|A_0(E2)|^2}{|A_0(E1)|^2}.$$

To further illustrate this point, let us point-out that, when $\theta \neq \pi/2$, the interference terms are always present. Since they depend on $\text{Re} [A_{\nu}^x(E1) A_{\nu}(E2)]$, six amplitudes should be determined in the most general case: $|A_{\nu}(E1)|^2$, $|A_{\nu}(E2)|^2$ and $\text{Re} [A_{\nu}^x(E1) A_{\nu}(E2)]$ with $\nu = 0$ and 2. Therefore, a complete solution of our problem can be, in principle, simply obtained

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by performing six independent cross section measurements at suitably selected angles.

In particular, information on the quantities $\text{Re} [A_{\nu}^{\times}(E1) A_{\nu}(E2)]$ could be obtained by isolating, in suitable experiments, the single interference terms; for instance by comparing the yields at $\theta = \pi/4$ and $\theta = 3\pi/4$, one has:

$$(9) \quad \left(\frac{d\sigma^{\perp}}{d\Omega}\right)_{3\pi/4} - \left(\frac{d\sigma^{\perp}}{d\Omega}\right)_{\pi/4} = \frac{6}{5\sqrt{42}} \text{Re} [A_2^{\times}(E1) A_2(E2)],$$
$$\left(\frac{d\sigma^{\parallel}}{d\Omega}\right)_{3\pi/4} - \left(\frac{d\sigma^{\parallel}}{d\Omega}\right)_{\pi/4} \approx \frac{4}{\sqrt{30}} \text{Re} [A_0^{\times}(E1) A_0(E2)].$$

A suitable choice of angles could be $\theta = \pi/4, \pi/2, 3\pi/4$ and $\varphi = 0, \pi/2$. Unfortunately this program cannot be easily developed in the most general case, due both to the presence of competing non-resonant coherent processes (Thomson, Delbrück scatterings) and to the fact that the coherent amplitudes tend to add up to give an almost isotropic contribution.

However, the direct measurement of the interference terms can be attempted in light nuclei where Delbrück scattering doesn't play an essential role: the nuclear contribution can be isolated, for instance, by studying its resonant energy behaviour.

Finally, we have to stress the fact that a good energy resolution, obtainable with Ge(Li) spectrometers for instance, could be very crucial, both for the separation between the $L=1$ and $L=2$ components (see eq. 7) and for the detailed analysis of the distribution of the E1 strength among the low-lying energy levels. This certainly has to be considered as a quantitative check of the validity of the DCM(7).

3. - PROPOSED EXPERIMENTS. -

In spite of the complexity in the separation of the different amplitudes $A_{\nu}(E1)$, several experiments are reasonably feasible with a simple experimental apparatus: furthermore from the theoretical point of view they appear to be among the most interesting ones.

In the following the proposed experiments will be mentioned in order of increasing experimental difficulty.

We will limit ourselves to the use of natural isotopic targets, leaving the possibility of employing separated isotopes to the second stage of

our experimental program.

A) Measurement of $|A_0(E1)|^2$ and $|A_2(E1)|^2$ near the giant dipole resonance peak ($E \simeq 80 A^{-1/3} \text{ MeV}$) for deformed nuclei. -

The E2 (E3, M1) contributions will be completely negligible in this case so that, according to equation 5), the two measurements at $\theta = \pi/2$ and $\varphi = 0, \pi/2$ would be sufficient. On the other hand, further measurements at $\theta = 3\pi/4$ and $\varphi = 0, \pi/2$ would provide a reasonable direct check on the assumption that both the E2, $\nu = 0$ and the inelastic E1, $\nu = 1$ contributions are really absent. We chose to add an angle in the backward hemisphere to reduce the interference term with the coherent Delbrück amplitude. Furthermore, the beam polarization will allow us to use detectors of medium energy resolution, e.g. NaI(4" x 6") crystals. On the contrary, to study the distribution of the E1 strength among different excited states, we need (for example at $\theta = \pi/2, \varphi = \pi/2$) a higher resolution detector like a sizeable Ge(Li) counter of $\sim 100 \text{ cc}$. A sketch of the experimental apparatus is shown in Fig. 2.

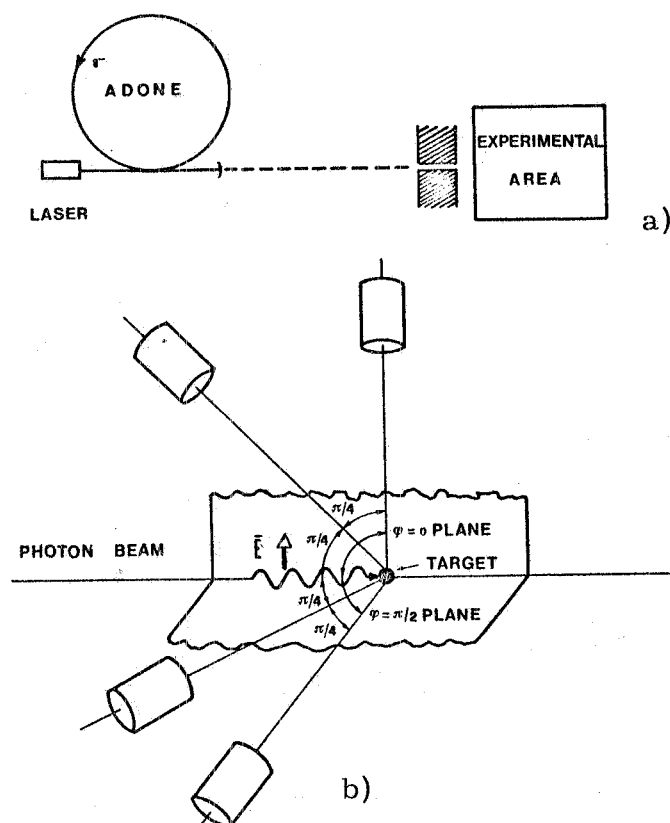


FIG. 2 - Schematic picture of the experimental apparatus. a) Adone and beam line; b) Na-I counters arrangement.

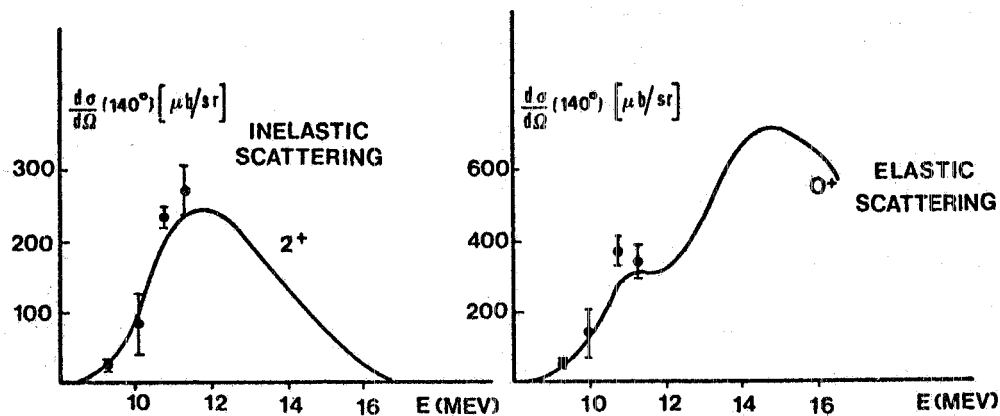


FIG. 3 - Scattering cross sections for U^{238} . The experimental points are taken from ref. (16). The theoretical curves are the DCM predictions.

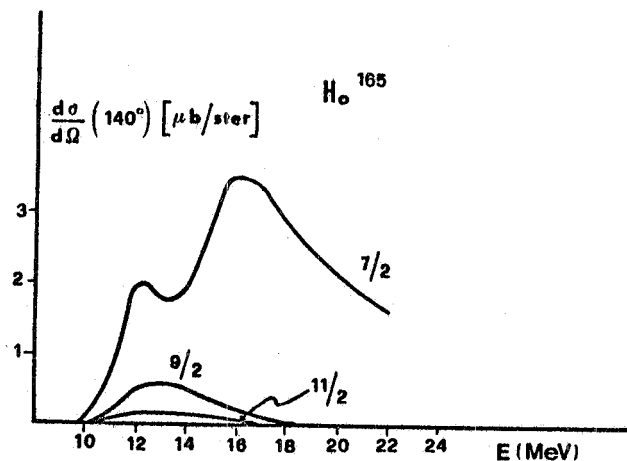


FIG. 4- Differential scattering cross section for different members of the ground state rotational band, obtained for Ho^{165} with the DCM.

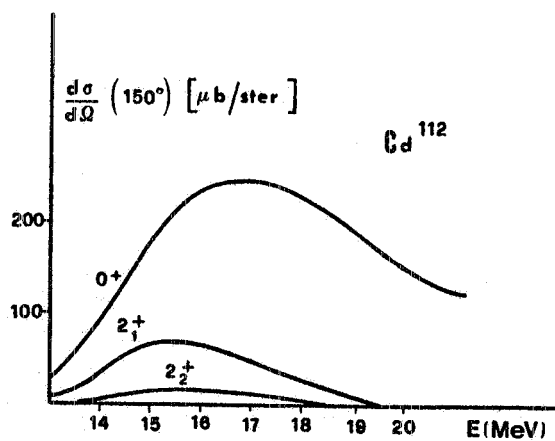


FIG. 5 - Differential scattering cross section for Cd^{112} obtained with the DCM assuming a harmonic oscillator spectrum for the surface quadrupole vibrations.

For every nucleus we would run with NaI crystals at ten different energies, in step of ~ 1 MeV, whereas the measurements with the Ge(Li) detectors could be limited to a few suitably selected energies.

At the present time very few data, obtained with unpolarized photons, are available: inelastic scattering data from the first 2^+ levels of Tb^{159} , Ta^{181} , Th^{232} and U^{238} and in the energy range between 7.9 and 11.4 MeV are reported in refs. (16, 17). A part of these results is summarized in Fig. 3.

We plan here to study the Raman effect in the even-even Th^{232} and U^{238} nuclei and afterwards in the odd-mass nuclei Pr^{141} , Tb^{152} , Ho^{165} , Tm^{169} , Lu^{175} , Ta^{181} . In Fig. 4 the theoretical differential cross sections for Ho^{165} are reported.

Of course, the structure of the first excited levels for Lu^{175} and Ta^{181} are very similar, and therefore any difference between their incoherent amplitudes can only be ascribed to a different polarizability.

Finally, Pr^{141} lies in the transition region between the spherical vibrators and the strongly deformed rotators, so it would be particularly interesting as well.

B) Measurements of $|A_0(E1)|^2$ and $|A_2(E1)|^2$ near the GDR peak for spherical (vibrational) nuclei. -

As far as the experimental apparatus is concerned, the considerations relevant in section A) are still valid here. In addition, the measurements with Ge(Li) detector will be probably unnecessary in many cases, due to higher separation energy of the excited states. We plan to study the even-even natural isotopic mixtures of Ni and Cd as well as the even-odd nuclei Y^{89} , Rh^{103} , La^{139} and Au^{197} . Quasi-elastic scattering experiments in this field are reported in refs. (6) and (8), but information on the distribution of the E1, $\nu = 2$ strength among different excited states is completely absent. Theoretical predictions for Cd^{112} are shown in Fig. 5.

C) Measurements of $|A_0(E2)|^2$ and $|A_0(E1)|^2$ for hard sphere nuclei. -

In this case only three NaI crystals are really needed so that, for instance, we may forego the counter at $\theta = 3\pi/4$ and $\varphi = \pi/2$; also the measurements with the Ge(Li) detector are here redundant.

The proposed nuclei are in this case Ca^{40} and Pb^{208} , where the energy of the first excited state is of the order of 3 MeV. Of course, let us remember that in the second case targets of radiogenic lead must be used. Moreover Bi^{209} does not seem to show any inelastic scattering, so it will give information very similar to those given by Pb^{208} .

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We think that for each of these nuclei, an energy scan between the two quadrupole resonances at $T=0$ and $T=1$ (10-20 MeV for Pb^{208} and 18-36 for Ca^{40}) in steps of (1-2) MeV would be sufficient in the first stage; later on, a further fine scan will be performed in the region of the maxima of the quadrupole resonances.

The E1 coherent scattering has been studied very recently by Jackson et al. (17). In addition, for these nuclei we have at the present time very scarce information on the quadrupole resonance, both experimentally and theoretically. Evidence for an E2 resonance in Pb^{208} at 10.8 MeV has been found only recently (18).

4. - COUNTING RATE. -

The counting rate for a single detector is given by:

$$(10) \quad C_{\gamma} = \left(\frac{d\sigma}{d\Omega} \right) (\Delta \Omega_{\gamma} \varepsilon f_t f_a) \Phi_{\gamma} (sT\rho) A^{-1} \mathcal{N}$$

where:

$\Delta \Omega_{\gamma}$ = accepted solid angle;

ε = detector efficiency (the assumed value will correspond to the total absorption peak);

f_t, f_a = target and filter transmission coefficients;

Φ_{γ} = gamma flux, in photons/cm² x sec;

s, T, ρ = target section, thickness and density;

A = Mass number;

\mathcal{N} = Avogadro number.

In the following calculation the incident photon energy will be assumed to be a typical value of 15 MeV. The amplitudes with $\nu \neq 0$ and $L \neq 0$ as well as the Delbruck and Thomson contributions will be neglected. Moreover, for $|A_0(E1)|^2$ the value given by the Saclay group (14)

$$(11) \quad |A_0(E1)|^2 \sim 0.35 (A/100)^3 \text{ mb/ster} \quad (A \gtrsim 100)$$

will be assumed.

To remove low-energy photons (and eventually neutrons) produced in the target will be probably useful to suitably filter the scattered radiation; in a recent work this purpose has been realized by an Al absorber of thickness ~ 23 cm (14). Then, by choosing target thicknesses with absorption coefficients not greater than 40%, we may rely on a total $f_t \times f_a \sim 0.5$.

An NaI crystal of 4" x 6", placed at 60 cm from the target, covers a solid angle $\Delta \Omega_\gamma \sim 9 \times 10^{-2}$ ster. and its efficiency can be estimated to be of the order of 25%. Its poor energy resolution makes it unnecessary to work with a beam energy resolution better than $\Delta E_\gamma / E_\gamma \sim 5\%$ for which configuration the expected gamma intensity is $s \Phi_\gamma \sim 5 \times 10^6$ photons/sec⁽¹⁾. Finally, assuming $T \rho = 10$ g/cm², one immediately obtains the estimate

$$(12) \quad C_\gamma \approx 10^3 \left(\frac{A}{100}\right)^2 (\cos^2 \theta \cos^2 \varphi + \sin^2 \varphi) \text{ counts/hour.}$$

Now, by averaging all the energy range explored, in the experiments of type A) and B), we will get a value not too far from 50% of this estimate: in the third column of Table I, these averaged counting rates are reported.

For the measurement of $(d\sigma^{\parallel}/d\Omega)_{\pi/2}$ near the GDR peak, the crucial parameter is $|A_2(E1)|^2$: assuming for the spherical (vibrational) nuclei the ratio $|A_2(E1)|^2/|A_0(E1)|^2 \simeq 0.22$ and a value twice as much for the rotational deformed ones⁽¹⁴⁾, at $E = 15$ MeV one finds:

TABLE I - Estimate of obtainable counting rates at $\theta = \pi/2$ and for typical nuclei. In the last column is reported the effective running time (in hours) for each nucleus. In brackets are the numbers of hours needed for the measurement of the E1 strength distribution among the low excitation levels (runs with Ge(Li)). For further details see the text.

Nucleus	Experience	$\langle C_\gamma^{\perp} \rangle$ counts/hour	$\langle C_\gamma^{\parallel} \rangle$ counts/hour	Hours needed
Ca ⁴⁰	C)	$\simeq 80$	$\simeq 20$ k	100/k
Cd ¹¹¹	B)	600	80	50
Ho ¹⁶⁵	A)	1400	340	12(180)
Au ¹⁹⁷	B)	1900	250	16(150)
Pb ²⁰⁸	C)	2200	$\simeq 20$ k	100/k
Th ²³²	A)	2700	700	6(100)

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$$(13) \quad (C_{\gamma}^{\parallel})_{\pi/2} \approx \frac{3}{5} \frac{|A_2(E1)|^2}{|A_0(E1)|^2} (C_{\gamma}^{\perp})_{\pi/2} \approx \begin{cases} 130(A/100)^2 \text{ counts/h-Spherical} \\ \text{(vibrational) nuclei} \\ 260(A/100)^2 \text{ counts/h-Deformed} \\ \text{nuclei} \end{cases}$$

Typical averaged counting rates are reported in column fourth of Table I.

From these figures it turns out that, in order to measure $|A_0(E1)|^2$ and $|A_2(E1)|^2$ at ten different energies with a statistical error of 5% the required time is 6÷12 hours for an experiment of type A) and 20÷50 for an experiment of type B). However, to separate the contributions to $|A_2(E1)|^2$ coming from different low excitation levels, the requested time is much longer. Assuming a beam energy resolution of 1%, and an efficiency for the Ge(Li) detector typically of 5%, the resulting counting rate falls down by a factor ≈ 250 with respect to the previous ones: therefore to get 5 points for Th^{232} and 200 inelastic photons per point at $\varphi = \pi/2$, $\theta = \pi/2$, approximately 100 hours are needed.

Finally, for experiments of type C), the important parameter at $\varphi = 0$ is $|A_0(E2)|^2$, which at the present time is scarcely known. If the observed E2 resonances at $\approx 60 A^{-1/3}$ MeV (T=0) and $\approx 120 A^{-1/3}$ MeV (T=1), do really saturate their respective sum rules, we should expect on the peaks

$$(14) \quad |A_0(E2, T)|^2 \approx 10^{-2} (A/100) (1+3T) \left[\Gamma_{\gamma}(E2, T) / \Gamma \right] \text{ mb/ster.}$$

where $[\Gamma_{\gamma}(E2, T) / \Gamma]$ are the radiative branching ratios corresponding to the two resonances. We expect $\Gamma_{\gamma} / \Gamma \approx 10^{-2} \div 10^{-3}$ so we can put $\Gamma_{\gamma} / \Gamma = 10^{-2} k$ where k probably varies in the range 1÷10. By the previous assumptions we obtain:

$$(15) \quad (C_{\gamma}^{\parallel})_{\pi/2} = \frac{3}{5} \frac{|A_0(E2)|^2}{|A_0(E1)|^2} (C_{\gamma}^{\perp})_{\pi/2} \approx 17 (1+3T) k \text{ counts/h.}$$

Also in this case the required time for a typical experiment with 200 photons per energy is reported in Table I. It turns-out to be reasonable in the limits in which $k \sim 1$.

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