MECHANISM OF INELASTIC PHOTON SCATTERING ON NUCLEI

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The deep hole excitations produced by E2-photon absorption are investigated using the single particle shell model. The main contribution to the damping of such states comes from the radiative decay leading to excited nuclear states. An analysis of the corresponding inelastic photon scattering in the vicinity of 20 MeV shows that the nuclear shell model features are conserved up to very high excitation energies. Some experimental problems are proposed.

THE usual method of investigating the inelastic scattering of photons consists of observing the yield of an isomeric state in the considered nucleus as a function the photon energy. The cross section for the isomer production clearly gives the lower limit for the inelastic scattering cross section. The (γ, γ') reaction has been investigated in this way for the nuclei Y^{89} [1], Rh^{103} [2], Ag^{107} [3], In^{115} [4] and Au^{197} [5]. For all these nuclei, two maxima appear in the energy dependence of $\sigma(\gamma, \gamma')$: the first is located in the vicinity of the threshold of the (γ, n) reaction, and the second (with an integrated cross section of the order of 10 mb-MeV) is located around 20 MeV, i.e., above the peak of the giant resonance (to be precise, in some cases, e.g., in [4], the experiment indicates merely an increase of $\sigma(\gamma, \gamma')$ in the region 20 MeV).

The first maximum is rather trivial: it is due to the excitation of bound nuclear states or of such continuum states where the nucleon emission cannot compete seriously with the radiative transitions.

The nature of the second maximum remains enigmatic. Its presence indicates the existence of an energetically well-separated region located around an excitation energy of 20 MeV, with rather anomalous characteristics in terms of the way one usually thinks of the nucleus. In addition to the very fact that the above-described excitation is localized in such a narrow region, the nucleon emission is sharply suppressed compared to the radiative decay, which is quite unnatural at such a high excitation energy: according to the estimates of Lazareva et al [2] the ratio Γ_γ/Γ_n is $\sim 25-30\%$ for Rh^{103} near 20 MeV. An estimate of Γ_γ/Γ_n performed according to the statistical model [6] yields for states located around the second maximum a discrepancy between theory and experiment by 4—5 orders of magnitude. Furthermore, according to the statistical model the cross section of the reaction (γ, γ') must follow the energy dependence of the photon absorption cross section. Thus, in the statistical model the second maximum of the inelastic scattering cross section corresponds to the giant resonance, i.e., lies lower than the observed maximum, namely at 14—17 MeV.

The statistical model corresponds to the extreme point of view that equilibrium is established between all degrees of freedom of the nucleus. The aim of the present paper is to treat the inelastic scattering of photons from the opposite point of view, i.e., in the independent particle model.

As is well known, the shell model has explained very successfully different aspects of the photonuclear reactions, in particular, the giant resonance. According to the shell model [7], the giant resonance contains those states which can be reached by dipole transitions in which one particle is excited from the last closed shell to the following unfilled shell (see Fig. 1a). It is essential that in the region of the medium and heavy nuclei almost all single particle dipole levels are bound, i.e., they lie below the particle threshold.

We now consider the characteristics of such levels which arise by elevating a nucleon from the next-to-last filled shell to the unfilled shell (Fig. 1b). The energy of such an excitation is, roughly, double the distance between shells, i.e., around 20 MeV in medium nuclei. According to the parity selection rules these transitions imply electric quadrupole absorption. Owing to the smallness of the effective charge of neutrons for quadrupole transitions, we can limit ourselves to the E2 transitions of the protons in evaluating the probability of photon absorption. Just as for the E1 absorption, the present absorption mechanism will lead essentially to bound single particle states. It is,

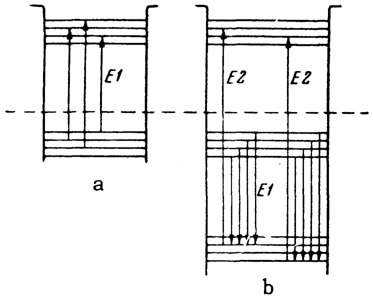

FIG. 1. Scheme of single particle transitions: a – giant resonance transitions, b – transitions responsible for the maximum of inelastic photon scattering in the vicinity of 20 MeV.

however, well known that in the former case the residual dipole-dipole interaction between the nucleons raises the energy of the giant resonance (approximately by a factor 1.5 as compared to the single particle value), which leads to the appearance of open channels. In the present case the residual quadrupole-quadrupole interaction has to play an analogous role.[8] This role seems at the present time not to be fully understood. However, for our purposes it suffices to remark that the effect of the quadrupole-quadrupole interaction on the E2 absorption is smaller and of opposite sign to the effect of the dipole-dipole interaction on the E1 absorption. This allows one in the following considerations to remain within the single-particle model and to consider the relevant levels to be bound, as before.

In this way, the single particle model leads automatically to the existence in the vicinity of 20 MeV of a group of excited states characterized by an anomalously high stability against particle emission and which are reached by E2 photon absorption. It remains to consider the question of radiative decay of such states.

The radiation width Γ_γ of the inverse E2 transition of the proton back to the initial state ("particle-hole" annihilation) is very small. The peculiar "single hole" E1 transition (Fig. 2) has a much higher probability. Physically it corresponds to a process in which a proton from the last filled shell makes a transition into the free space in the lower shell under emission of a high energy dipole photon (Fig. 1b). Thus the peculiarity of the situation is the circumstance that the probability of the

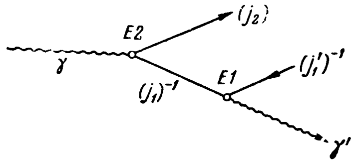

FIG. 2

inelastic photon scattering (E1 transitions) is much higher than that of elastic scattering (E2 transitions). Each E1 transition initiates a photon cascade which in the end leads either to the ground state or to an isomeric state, depending on the particular E1 transition. Using the single particle model it is easy to follow the development of each cascade and by computing the different radiation widths to obtain the ratio of the cross section for isomer production to the total inelastic scattering cross section.

As an example we consider the inelastic photon scattering on the nucleus $_{49}In^{115}$ (see [9] for the level scheme). The characteristics of the partial E2 transitions responsible for the inelastic scattering in the region of 20 MeV are given in the table. The calculation was performed strictly in the single particle model, i.e., all nucleon-nucleon correlations were completely neglected. However, the Pauli principle and the angular momentum coupling rules where fully taken into account. For the protons harmonic oscillator wave functions with a parameter $r_0 = \sqrt{\hbar/m\omega} = 2 \times 10^{-13}$ cm were used. The "hole" transition matrix elements were related to single particle matrix elements by means of well known shell model relations.[10] For definiteness the distance from the orbitals ($1d_{5/2}$, $2s_{1/2}$, $1d_{3/2}$) to the orbital $1f_{7/2}$ was taken to be 10 MeV, and to the orbitals ($2p_{3/2}$, $1f_{5/2}$, $2p_{1/2}$, $1g_{9/2}$) was set to be 20 MeV.

By summing all transitions we find that out of the total absorption cross section of 23 mb-MeV approximately 19 mb-MeV is associated with inelastic scattering leading to the ground state while the cross section leading to the isomeric state is 4 mb-MeV. Only less than 0.5 mb-MeV is left for the elastic-scattering cross section (we emphasize that all these numbers are of course only tentative, owing to the schematic nature of the treatment). Thus, even though the total absorption cross section due to this mechanism is relatively small, the inelastic photon scattering plays the decisive role because of the anomalously high radiation widths (up to 5 keV). Furthermore, the ratio of the isomer yield to the ground state transitions is about $1/5$, and the integrated cross section for the isomer production is in the region of the second maximum of the same order of magnitude as found by experiment.

The simplest possible single particle model thus describes correctly the main characteristics of the effect, but it corresponds only to the most simplified picture of the nucleus. Clearly a number of factors exist which will change the results obtained in this model. The most important among them is

Partial transitions in the nucleus $_{49}In^{115}$ responsible for the inelastic photon scattering in the vicinity of 20 MeV

1	2	3	4	5	6	7	8
$1d_{5/2} \to 1g_{9/2}$	1.3	230	$(1d_{5/2})^{-1} \to (1f_{7/2})^{-1}$	$(1d_{5/2})^{-1} \to (2p_{3/2})^{-1}$ $(1d_{5/2})^{-1} \to (1f_{5/2})^{-1}$	2.0	67	0.9
$1d_{5/2} \to 2d_{5/2}$	1.6	32	$(1d_{5/2})^{-1} \to (1f_{7/2})^{-1}$ $(1d_{5/2})^{-1} \to (2p_{3/2})^{-1}$ $(1d_{5/2})^{-1} \to (1f_{5/2})^{-1}$	—	2.0	—	—
$1d_{5/2} \to 1g_{7/2}$	1.2	24	$(1d_{5/2})^{-1} \to (1f_{7/2})^{-1}$ $(1d_{5/2})^{-1} \to (1f_{5/2})^{-1}$	$(1d_{5/2})^{-1} \to (2p_{3/2})^{-1}$	2.0	55	0.7
$1d_{5/2} \to 3s_{1/2}$ $1d_{5/2} \to 2d_{3/2}$	0.4 0.4	8 8	$(1d_{5/2})^{-1} \to (1f_{7/2})^{-1}$ $(1d_{5/2})^{-1} \to (2p_{3/2})^{-1}$ $(1d_{5/2})^{-1} \to (1f_{5/2})^{-1}$	—	2.0 2.0	— —	— —
$2s_{1/2} \to 2d_{5/2}$	1.8	36	$(2s_{1/2})^{-1} \to (2p_{3/2})^{-1}$	$(2s_{1/2})^{-1} \to (2p_{1/2})^{-1}$	6.5	33	0.6
$2s_{1/2} \to 2d_{3/2}$	1.1	22	$(2s_{1/2})^{-1} \to (2p_{3/2})^{-1}$ $(2s_{1/2})^{-1} \to (2p_{1/2})^{-1}$	—	6.5	—	—
$1d_{3/2} \to 2d_{5/2}$	0.4	8	$(1d_{3/2})^{-1} \to (2p_{3/2})^{-1}$ $(1d_{3/2})^{-1} \to (1f_{5/2})^{-1}$	$(1d_{3/2})^{-1} \to (2p_{1/2})^{-1}$	6.4	14	0.1
$1d_{3/2} \to 1g_{7/2}$	10.5	210	$(1d_{3/2})^{-1} \to (1f_{5/2})^{-1}$	$(1d_{3/2})^{-1} \to (2p_{3/2})^{-1}$ $(1d_{3/2})^{-1} \to (2p_{1/2})^{-1}$	6.4	16	1.7
$1d_{3/2} \to 3s_{1/2}$ $1d_{3/2} \to 2d_{3/2}$	0.3 0.9	6 18	$(1d_{3/2})^{-1} \to (2p_{3/2})^{-1}$ $(1d_{3/2})^{-1} \to (1f_{5/2})^{-1}$ $(1d_{3/2})^{-1} \to (2p_{1/2})^{-1}$	—	6.4 6.4	— —	— —
$1f_{7/2} \to 1h_{11/2}$	2.8	56	$(1f_{7/2})^{-1} \to (1g_{9/2})^{-1}$	—	0.9	—	—

Columns: 1 – partial E2 transition; 2 – integrated absorption cross section $\int \sigma(E2)dE_\gamma$ (mb-MeV); 3 – radiation width for elastic scattering $\Gamma_\gamma(E2)$ (eV); 4 – E1 transitions initiating a cascade leading to the ground state; 5 – the same, but leading to the isomeric state; 6 – total radiation width for inelastic scattering Γ_γ (E1) (keV); 7 – fraction of inelastic scattering leading to the isomer (in %); 8 – integrated cross section for isomer production (mb-MeV).

the inclusion of the residual two-body interactions. By admixing excitations of the type "hole" in the last shell plus particle in the continuum [e.g., $(1f_{5/2})^{-1}(1h_{9/2})$ in the case In^{115}] they would open nucleon (proton and neutron) channels. Since the open channels in the present case have a large kinetic energy, this admixture will evidently be weak; furthermore the particle widths for the most intensive transitions of the type $l \to l + 2$ are particularly small because of the large barrier. On the other hand the configuration mixing will lead to an increase of the yield of the isomer by increasing the general absorption cross section due to admixture of new transitions and by redistributing the intensities amongst the transitions leading to the ground and isomeric states. At the present time it is hardly possible to account for the above considerations in the spirit of an exact theory.

Without paying too much attention to the concrete numerical results which have been obtained above in a very schematic manner, it is therefore useful to extract general qualitative results which could be used in further theoretical and experimental investigations of this very interesting effect.

1. The maximum in the (γ, γ') cross section in the vicinity of 20 MeV is due to a resonance in the photon absorption-emission mechanism.

2. The shell model approach allows us to establish a connection between the inelastic photon scattering and another effect, namely the photonuclear giant quadrupole resonance.[11,12] According to the scheme proposed, the second maximum in the inelastic scattering cross section must lie at the energy of the quadrupole resonance.

3. The spectrum of the inelastically scattered photons (corresponding to the second maximum) must contain an intense hard component with an energy in the order of 10 MeV.

Evidently the possibilities of studying the reaction (γ, γ') by means of isomers at the present time are already to a high degree exhausted. Without belittling the importance of improving the accuracy of the experimental data on nuclei which have already been investigated, we remark that only an analysis of the spectrum of the inelastically scattered photons can give a direct answer to the question of the nature of the inelastic scattering. Up to now only one paper of such a kind exists.

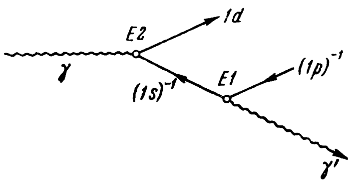

FIG. 3

Penfold and Garwin[13] have observed a maximum in the inelastic scattering on O^{16} in the vicinity of 30 MeV while the energy of the scattered photons on the average exceeded 20 MeV. In the light of the above-described resonance scheme, this fact could be explained by the quadrupole-dipole mechanism of the inelastic scattering depicted in Fig. 3 (from this also follows in a natural way the absence in O^{16} of the maximum of the inelastic scattering corresponding to dipole absorption in the region of the particle threshold). If a similar picture will be confirmed in the investigation of other, in particular medium and heavy nuclei one will be compelled to reexamine the usual thoughts on the structure of nuclei at high excitation energies.

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