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Brief Reports

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Dipole nature of statistical gamma ray spectra in (n,γ) reactions

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Experiments concerning gamma-ray emission after thermal-neutron capture by oriented nuclei have been reconsidered in order to show that information on the multipole character of the statistical gamma-ray spectra in (n,γ) reactions can be obtained. It is found that, for the ^{144}Nd and ^{150}Sm compound nuclei, these spectra have mainly dipole character. An upper limit of about 10% quadrupole is deduced.

[NUCLEAR REACTIONS ^{143}Nd(n,γ), ^{149}Sm(n,γ), E_n thermal; dipole nature of statistical γ spectra.]

In (n,γ) reactions many of the observed direct γ transitions (called primary transitions) are shown to be of electric dipole character, or they can be assumed to have such a nature on the basis of parity change between the capturing state and the final states for such transitions. For many years it has been assumed that the "statistical" spectra following (n,γ) reactions, which often consist of very many unobserved transitions, are of an electric dipole nature.[1,2] Some experimental results point into this direction, but not strongly.[3,4]

There are reasons to reconsider the multipole nature of the γ spectra following neutron capture. First of all, deviations from the purely statistical behavior have been observed.[5] Recently, several primary transitions have been identified which have clearly quadrupole nature.[6,7] Quadrupole transitions may be enhanced by giant quadrupole resonances in the compound nucleus. It is not obvious, without further arguing, that the γ-ray spectra following neutron capture are largely of dipole nature, especially for the heavier nuclides. One may ask the question: Which fraction of the very many individually unobserved and very weak transitions might have quadrupole character? This may partly occur as admixtures in dipole transitions, but also as pure quadrupole transitions with spin changes $\Delta I = \pm 2$. In some cases the population of isomeric states has been used to deduce a limit on the quadrupole contribution; Pönitz[4] concluded that a 5% quadrupole contribution may exist, but this conclusion depends rather strongly on assumptions about other parameters.

During the past few years a strong interest evolved in the study of statistical γ-ray spectra following light- and heavy-ion nuclear reactions. These spectra are emitted after several neutrons have been evaporated from the highly excited nuclei; the statistical γ-ray spectra are assumed to precede collective yrast transitions leading to the ground state. Various groups tried to gain information on the electromagnetic nature of the statistical γ-ray spectra. From angular correlation, distribution, and linear polarization experiments,[8-11] as well as from electron conversion data,[12-14] information about the character of the γ radiation was obtained, but in certain aspects the results are conflicting. Some authors[12,13] claim that at the higher end of the statistical spectrum the radiation has a largely dipole nature, while others[8,14] reached the conclusion that a fair amount of quadrupole admixture exists also at the higher energies of the spectrum.

For γ-ray spectra following thermal neutron capture, the initial state, in energy and spin, is much better defined compared to α and heavy-ion reactions. Notwithstanding the difference in character of both types of reactions, it is of interest to consider (n,γ) reactions as a complementary source of information on properties of statistical spectra, and use ideas and models developed for statistical γ spectra following neutron capture in the more complicated nuclear reactions. This philosophy has been followed by Koeling,[15] who developed a detailed model for calculating the average number of γ rays (multiplicity ν) for (n,γ) reactions and applied it thereafter to heavy-ion reactions. The complementarity of (n,γ) reactions to heavy-ion reactions has, in another sense, also been pointed out by Schult.[16] In this light it is of interest to reconsider some nuclear orientation data of statistical γ-ray spectra.

In this paper the multipole nature of statistical γ-ray spectra following thermal neutron capture in ^{143}Nd and ^{149}Sm will be considered using some data from nuclear orientation experiments with these nuclides.[17,18] The experiments concern the directional distribution of γ rays following the capture of unpolarized neutrons by aligned nuclei. In these reactions the observed primary transitions are weak and the decay schemes are very complicated. The lowest levels of the compound nuclei ^{144}Nd and ^{150}Sm are mainly populated by statistical spectra. There are two possibilities for using nuclear orientation for this purpose:

(i) Consider the averaged anisotropy in the emission of the whole γ-ray spectrum.

(ii) Determine the reduction of the orientation parameters of low-lying levels as compared to those of the capturing state.

The effect in the first possibility is expected to be very small, even in the case of a large degree of nuclear orientation, since the anisotropies of stretched and unstretched transitions compensate each other largely. The effect will therefore depend strongly on the ratio of stretched and unstretched transitions. This obscures the influence of the multipole order. In the second possibility mentioned above one has to derive the nuclear alignment parameters $f_2(I_c)$ and $f_2(I_i)$ of the capturing state (with spin I_c) and of one or more of the low-lying states (spins I_i) from the observed anisotropies of primary and secondary transitions of known character (including the initial and final spins). For both mentioned nuclides this could be done. From the derived values of the alignment parameter the reduction factor $G_2=f_2(I_i)/f_2(I_c)$ can be calculated; they are given in Table I for one level (2^+) in ^{144}Nd and for two levels $(2^+$ and $4^+)$ in ^{150}Sm. In the case of the 696-keV level of ^{144}Nd a small correction related to a fairly strong two-step cascade (8% intensity, γ-ray energies of 6.51 and 0.616 MeV) of known character was applied leading to $G_2(3\to 2)=0.42\pm 0.03$, compared to 0.44 ± 0.03 for the uncorrected value. Such a correction was not necessary for the two cases studied in the ^{149}Sm (n,γ) reaction.

The reduction factor $G_2(I_c\to I_i)$ can be calculated theoretically for a purely statistical γ spectrum using a Monte-Carlo type calculation.[19] Also, a somewhat simpler method can be used considering all possible spin sequences between I_c and I_i for a chosen multipolarity and multiplicity. Both methods have been used to derive $G_2(I_c\to I_i)$, and it has been found that the differences are small and thus can be neglected for the present purpose. The spin sequences are weighted for the spin distribution in the pseudocontinuum of the level scheme. This has been done using the following expression for the spin dependence of the level density:

$$\rho(I)=\rho(0)(2I+1)\exp[-(I+\tfrac{1}{2})^2/2\sigma^2] ,$$

in which σ denotes the spin cutoff parameter. The parity distribution over the pseudocontinuum is not important to us, since we are not able to distinguish between electric and magnetic radiation in this work. The derived values of G_2 are rather insensitive to the chosen value of σ. We accepted

TABLE I. Experimental and theoretical values of the nuclear orientation reduction factors $G_2(I_c\to I_i)$ for three levels populated in the ^{143}Nd(n,γ) and ^{149}Sm(n,γ) reactions. A spin cutoff parameter $\sigma = 4$ has been used to deduce the theoretical values.

Compound nucleus	E_x (keV)	$I_c^\pi\to I_i^\pi$	G_2 (exp)	G_2 (theor) $L = 1$					G_2 (theor) $L = 2$		
				$\nu = 2$	3	4	5	6	$\nu = 2$	3	4
^{144}Nd	696	$3^-\to 2^+$	0.42 ± 0.03	0.571	0.583	0.416	0.360		0.191	0.107	0.076
^{150}Sm	773	$4^-\to 4^+$	0.65 ± 0.06	0.805	0.7	0.629	0.549		0.477	0.275	0.196
^{150}Sm	334	$4^-\to 2^+$	0.43 ± 0.04	0.857	0.6	0.612	0.508	0.449	0.162	0.239	0.130
							0.469[a]	0.412[a]			

[a] These values are obtained by correcting for collective transitions ($E2$) for part of the cascades in the last step (see text).

$\sigma=4$ on the basis of experimental information.[20] G_2 depends strongly on the assumed multipolarity and multiplicity. In Table I theoretical values of G_2 are given for pure dipole and pure quadrupole radiation taking $\nu=2$ to $\nu=6$. The number of possible spin sequences is, of course, much larger in the case of quadrupole transitions as compared to dipoles.

In the case of the ^{149}Sm(n,γ) reaction Draper and Springer[21] obtained multiplicity $\nu=6.2\pm0.3$ for the γ spectrum feeding the ground state of ^{150}Sm. Earlier measurements, giving somewhat lower values for ν (given without errors), are likely to be less accurate (see Ref. 4). Using the above-mentioned Monte Carlo method Postma and Potters[19] obtained $\nu=5.8$. A recent calculation by Koeling[15] resulted in $\nu=6.3$. Therefore, a multiplicity $\nu=6.0\pm0.3$ is accepted in this paper for the γ spectrum after thermal neutron capture by ^{149}Sm leading to the ground state ^{150}Sm. Since most of the population of the ground state occurs via the first excited state (2^+ level at 334 keV) of ^{150}Sm, it is reasonable to assume that the spectrum feeding this level has a multiplicity of 5.2 ± 0.4. The multiplicity of the γ decay to the first 4^+ level (at 773 keV) in ^{150}Sm can be set at 4 to 5. This variation in multiplicities feeding the various levels is in accordance with the model calculations by Koeling. No value has been given for the multiplicity for the ^{143}Nd(n,γ) reaction; but by comparing the γ spectrum of this reaction with other reactions, similar multiplicity values can be expected. It seems, therefore, justified to accept $\nu\simeq4$ for the γ decay to the first excited (2^+) state of ^{144}Nd at 696 keV.

With the assumption of pure quadrupoles all calculated $G_2(I_c\rightarrow I_i)$ values quoted in Table I are much lower than the experimental values, which is not surprising. Good agreement exists between calculated and experimental values for dipole transitions and reasonable multiplicity values. For the 696-keV level in ^{144}Nd and the 773-keV level in ^{150}Sm agreement is excellent for the expected multiplicities $\nu=4$ in the case of ^{144}Nd and $\nu=4$ to 5 for ^{150}Sm. The γ spectrum feeding the 334-keV level of ^{150}Sm has an estimated multiplicity $\nu=5.2\pm0.4$. Its calculated reduction factor for the nuclear alignment parameter is in fair agreement with the experimental value for the slightly larger multiplicity $\nu=5.5$ to 6. However, one should realize that the lower part of the level scheme of ^{150}Sm is highly collective and that several relatively strong secondary transitions leading to the 2^+ level at 334 keV have an $E2$ character. Correcting for this collective nature in the last step according to known transition intensities leads to somewhat lower G_2 values as indicated at the bottom of Table I. The corrections are minor, but they bring the experimental and theoretical values of G_2 closer to each other. Considering known transitions to the 2^+ level at 334 keV, the quadrupole nature of the last step is accepted for 68% of all possible cascades; that is, 58% via 4^+, 8% via 2^+, and 2% via 0^+ states.

The above given comparison shows that, indeed, the statistical γ-ray spectra in the considered (n,γ) reactions are largely of dipole character. A more quantitative conclusion can be achieved by comparing the experimental G_2 values with reduction factors for mixed dipole-quadrupole spectra obtained as a linear combination of those for pure dipole and for pure quadrupole transitions. In Fig. 1 theoretical $G_2(I_c\rightarrow I_i)$ values are plotted for $\nu=4$ in the case of the 696-keV level of ^{144}Nd and for $\nu=4$ and 5 for the 773-keV level of ^{150}Sm. Smaller values of ν are highly unlikely. Figure 1 shows that about a 10% quadrupole admixture in the otherwise dipole spectrum should be considered as an upper limit.

The conclusion will not change if other values of the spin cutoff parameter, say $\sigma=3.5$ or 4.5, are

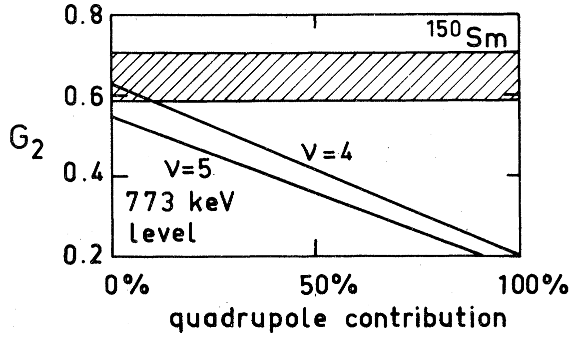

FIG. 1. Experimental values for the reduction factors $G_2(I_c\rightarrow I_i)$ for two transitions in ^{144}Nd and ^{150}Sm compound nuclei, after thermal neutron capture, compared to theoretical values plotted as a function of the dipole-quadrupole ratio in the statistical γ-ray spectrum for the indicated multiplicities, which are expected to be representative.

used. The theoretical values of the reduction parameters $G_2(I_c \rightarrow I_i)$ are very insensitive to σ. It would be of great interest to determine multiplicity values more precisely and for more (n,γ) reactions in order to facilitate the described studies of statistical phenomena.

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