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DIRECT AND STATISTICAL GAMMA DECAY OF THE GIANT QUADRUPOLE RESONANCE OF ^{208}Pb

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A B S T R A C T

The gamma decay of the giant quadrupole resonance of ^{208}Pb is discussed. The relative contribution of the decay via the compound nucleus is calculated from the statistical theory. It is found that the compound decay is as important as the direct decay. The summed contribution of the direct and compound decay modes, however, is a factor of 2 smaller than the observed gamma-branching ratio GQR → G.S.

In recent years several groups have looked into the question of the decay of nuclear giant resonances (GR) both experimentaly[1] and theoretically[2]. In particular the competition between the "direct" decay of the GR and the "statistical" compound decay, which arises from the mixing of the GR, has been extensively discussed[1]. Usually these two decay modes are treated independently.

Quite recently Dias et al.[3] developed a theory of the GR decay which allows for a consistent introduction of the mixing parameter that determines the degree of the GR fragmentation into the compound background. Before applying this theory to a real situation, it is important to have at hand means of estimating the relative importance of the two decay modes. Beene et al[4], have presented such a simple estimate for the giant quadrupole resonance of ^{208}Pb. However they employed several crude approximations for the different quantities needed to calculate the statistical decay probability, P_C which may render their conclusion questionable.

In the present paper, we present the results of a calculation of P_C for ^{208}Pb which uses exact relations, for the above mentioned quantities from recent research in reaction theory. We also compare our findings with those of Beene et al[4].

We write, as do Beene et al.[4], for the gamma branching ratio P, the following expression, composed of a direct and a statistical (compound) component.

$$P = P_d + P_c = \frac{\Gamma^{\gamma}_{GR}}{\Gamma^{\uparrow}} + \left\langle \frac{\Gamma^{\gamma}_{c}}{\Gamma_c} \right\rangle \qquad (1)$$

We concentrate our attention on the secound term. The average γ width of the compound nucleus $\langle\Gamma^{\gamma}_{c}\rangle$ is estimated as in Ref. 4) to be $\frac{10^{-4}\ \text{MeV}}{\rho_c(2^+, 11\text{MeV})}$, where $\rho_c(2^+)$ is the density of compound 2^+ states at $E^*=11$MeV. As far as the average total compound width, $\langle\Gamma_c\rangle$, is concerned, one may readily evaluate it from the expression

$$2\pi \langle\Gamma_c\rangle \rho_c = \sum_{\alpha} T_{\alpha} \qquad (2)$$

where T_{α} indicates the compound transmission coefficients in channel α.

Eq. (2) has been quite solidly established as a consequence of the statistical theory of nuclear reactions[5]. One possible source of information for $\langle\Gamma_c\rangle$ is the cross-section correlation function (Ericson fluctuation analysis). However, for heavy compound nuclei such as ^{208}Pb, the average life time is expected to be quite along. In fact, empirical findings[6] suggest that the correlation width $\langle\Gamma_c\rangle$, which is inversely proportional to the life time is given by

$$\langle\Gamma_c\rangle = 14 \exp\left[-4.69 \sqrt{\frac{A_c}{E_c^*}}\right] \text{MeV} \quad , \tag{3}$$

where an average over angular momentum and parity has been made. The above equation was extracted from an extensive analysis of compound nuclear reactions involving light and intermediate mass nuclei.

In any case, for ^{208}Pb at an excitation energy of 11 MeV, one obtains $\langle\Gamma_c\rangle = 0.01$ eV, an extremely small width. This implies that Ericson type analysis for such nuclei is not feasible. One may, in principle resort to other methods such as crystal blocking[7] or atomic nuclear x-ray interference[8], which furnish values of $\langle\Gamma_c\rangle$ in the eV regime. Lacking such clearly important experimental information at the present time we rely here on Eq. 2), using for the calculation of $\Sigma' T$, existing Hauser-Feshbach codes.

Writing $\Sigma' T$ in full detail, we have, for total angular momentum $J=2^+$,

$$\sum_{\alpha}{}' T_{\alpha}^{(2^+)} \equiv \sum_{c} \sum_{\ell_c, S_c, \pi_c} T_{c, S_c, \ell_c}^{(2^+)} (E_c) \tag{4}$$

where ℓ_c, S_c and π_c represent respectively the orbital angular momentum, spin and parity in channel c. Since the excitation energy of the quadrupole GR in ^{208}Pb is 11MeV, and the ground state Q-value for neutron emission, (which is the dominant decay channel at this energy) is 7.4 MeV, we conclude that states in ^{207}Pb up to E*=3.6 MeV are being populated. Up to this excitation energy there are exactly 19 states[9].

We present the result of our calculation in table I, where we indicate the spins and parities of the states in ^{207}Pb in the first column, their excitation energies in the second column and the corresponding neutron energies in the third. The summed contribution of different ℓ_c values for a given transition is presented in the fourth column. Here we use the usual parity and angular momentum conservation rules to obtain the different compositions of these partial sums. Finally the numerical values of column 4 are presented in the last column. These numbers were obtained using the optical model code SCAT2[10] with the optical potential parameters taken from Ferrer[11]. The spins of the states in ^{207}Pb at E*=3.185 and 3.202 MeV are not available experimentally. We have assigned a spin of 1/2 to each of these states which would give the largest values of the corresponding $T_\ell^{(2^+)}$, s.

With this assumption, we obtain for $\sum_{\alpha=neutron}' T_\alpha^{(2^+)} = 12.9$ which accordingly gives,

$$\langle \Gamma_c \rangle \rho_c (2^+, 11\,\mathrm{MeV}) = 2.05 \qquad (5)$$

which is to be contrasted with the value of 0.67 obtained by Beene et al.[4] We might mention here that there is an apparent discrepancy in Beene et al. between the number 0.67, given in their table 1 and their equation 4).

Instead of using the empirical density of states deduced by Horen et al[12] for $n+^{206}Pb$ resonances at $E_n = 600 - 900$ keV, and extrapolated to $E^* = 11$ MeV for ^{208}Pb by Beene et al[4], which gave them $\rho_c = 1000\ \mathrm{MeV}^{-1}$, we have opted here for a simple calculation of ρ_c counting all 2^+ states in the interval 10.5 - 11.5 MeV formed by all possible 1p - 1h, 2p - 2h, 3p - 3h and 4p - 4h configurations. For this purpose we have used the single particle energies of Ref.[13], and a pairing energy of 1 MeV. This leads to the conclusion that the 2^+ states in the energy range 10.5 to 11.5 MeV are overwhelmingly 2p-2h excitations. In fact, only 4 1p-1h states having $J^\pi=2^+$ can be formed in the adjacent neutron and proton major shells (because of triangulation and parity restrictions) while the first 3p-3h state with $J^\pi=2^+$ lies above 11.5 MeV. The calculated distribution of the 2^+ 2p-2h states in ^{206}Pb as a function

of excitation energy is shown in Figure 1. From the Figure, we obtain $\rho_{2^+}(^{208}Pb) = 240\ \mathrm{MeV}^{-1}$ which when used in Eq.5) yields $\langle \Gamma_c \rangle = 8.5$ keV, which is about an order of magnitude larger than the value obtained by Beene et al[4]. Further, Γ_c^γ comes out here to be 0.4 eV. Thus

$$P_c = \frac{0.4}{8.5} \times 10^{-3} = 4.7 \times 10^{-5} \qquad (6)$$

We should mention here that the ratio $\frac{\Gamma_c^\gamma}{\Gamma_c} = \frac{4}{\sum_\alpha' T_\alpha} \frac{\Gamma_\gamma^{GR}}{\Gamma^\downarrow}$ is independent of the density ρ_c. Using now the value of P_d given in Ref.[4] we have

$$P = 0.7 \times 10^{-4} + 0.47 \times 10^{-4} \qquad (7)$$

Thus our obviously more precise estimate leads to a similar conclusion as that of Ref. 4) namely that the compound γ-decay of the GQR of ^{208}Pb is quite important.

However, we still find a discrepancy between the observed gamma-branching ratio GQR $\rightarrow$ gs $\approx 3\times10^{-4}$ [14] and our calculation which gives 1.5×10^{-4}.

One possible source of error in these estimates is the use of $\langle \Gamma^\gamma \rangle$ in describing the GQR $\rightarrow$ gs transition. As quadrupole transitions are proportional to ω^5 where ω is the γ energy, we would expect the partial width for the gs transition to have a value larger than the average one.

In order to test the sensitivity of our results with regard to the parameters of the optical model potential employed in the calculation of the neutron transmission coefficients, we have repeated our calculation using the global neutron optical potential of Rapaport et.al.[15]. This gave us $\sum_{\alpha = \text{neutrons}} T_\alpha = 8.67$, $\langle\Gamma_c\rangle = 5.7$ kev, and $P_c = 0.7 \times 10^{-4}$, quite close to the values obtained earlier.

In conclusion, we have estimated the compound nucleus contribution to the gamma decay of the giant quadrupole resonance of ^{208}Pb and found it to be roughly as important as the direct decay contribution. This clearly points to the need to use a more complete theory to describe the GQR decay such as the one developed in Ref. 3).

In contrast to the conclusions reached in Ref. 4), however, our calculation, is still a factor of about 2 short of the experimental result. Further work is needed to elucidate the nature of this discrepancy.

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Table Captions

Table 1: The calculated neutron transmission coefficient for the first 19 states in ^{207}Pb. See text for details.

Figure Captions

Figure 1: Distribution of 2p-2h 2^+ states in ^{208}Pb. See text for details.

SPIN	Excitation Energy (MeV)	E_n (MeV)	$\sum_{\ell s} T_\ell(E_n)$	Numerical values
$1/2^-$	0	3.60	$T_1 + T_3$	1.62
$5/2^-$	0.569	3.03	$2T_1 + 2T_3 + T_5$	3.05
$3/2^-$	0.897	2.70	$2T_1 + 2T_3$	2.72
$13/2^+$	1.633	1.96	$T_4 + 2T_6 + 2T_8$	0.07
$7/2^-$	2.340	1.26	$T_1 + 2T_3 + 2T_5$	0.76
$5/2^+$	2.624	0.98	$T_0 + 2T_2 + 2T_4$	1.71
$7/2^+$	2.662	0.94	$2T_2 + 2T_4 + T_6$	0.88
$7/2^+$	2.703	0.90	$2T_2 + 2T_4 + T_6$	0.84
$9/2^+$	2.728	0.87	$T_2 + 2T_4 + 2T_6$	0.41
$1/2^{+*}$	3.185	0.42	$2T_2$	0.32
$1/2^{+*}$	3.202	0.40	$2T_2$	0.28
$11/2^+$	3.223	0.37	$2T_4 + 2T_6 + T_8$	0
$1/2^+$	3.300	0.30	$2T_2$	0.16
$9/2^+$	3.384	0.22	$T_2 + 2T_4 + 2T_6$	0.04
$9/2^-$	3.413	0.19	$2T_3 + 2T_5 + T_7$	0
$9/2^+$	3.429	0.17	$T_2 + 2T_4 + 2T_6$	0.02
$9/2^+$	3.476	0.13	$T_2 + 2T_4 + 2T_6$	0.01
$11/2^+$	3.509	0.09	$2T_4 + 2T_6 + T_8$	0
$9/2^+$	3.583	0.01	$T_2 + 2T_4 + 2T_6$	0
			Total	12.9

Table 1

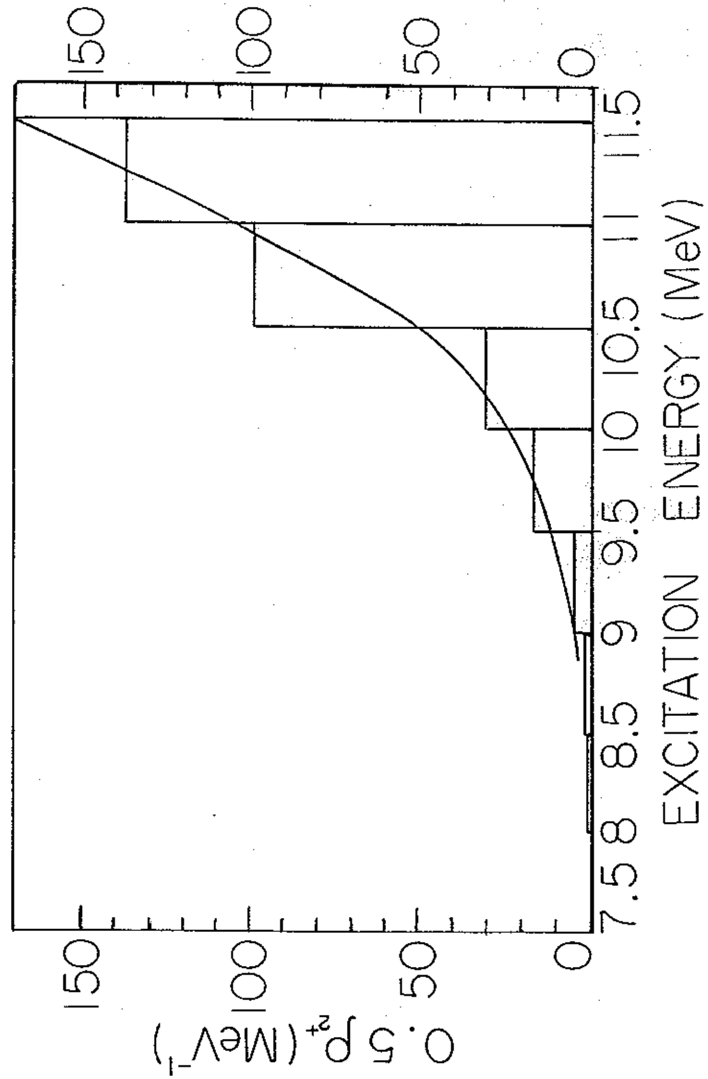

Figure 1