Study of the Breathing Mode of ^{208}Pb through Neutron Decay

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The neutron decay of the giant monopole resonance region between 13 and 15 MeV in ^{208}Pb is analyzed in terms of collective and statistical doorway states. The direct escape widths of the giant monopole resonance populating the lowest five valence hole states of ^{207}Pb are determined, and compared with the results obtained from complex collective states. This comparison discriminates sharply between different model Hamiltonians which predict similar energies and collectivities for the resonance.

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Giant resonances are correlated states of particle-hole configurations, which carry a large fraction of the energy-weighted sum rule. They are found at excitation energies above particle threshold, where the density of levels is very high. The correlation existing between the particle and the hole can thus be destroyed by particle emission, or by the coupling to the background of complicated states leading to the compound nucleus. In the case of the excitation of giant resonances in closed-shell nuclei like ^{208}Pb, the particle decay to pure hole states of the odd neighboring nucleus can take place either directly, or after the giant resonance has been damped into the compound nucleus.

In the past few years the decay properties of giant resonances in ^{208}Pb have been studied both experimentally[1-4] and theoretically.[5-11] Neutron decay following the giant-resonance excitation through α inelastic scattering has been measured and compared with statistical-model calculations. As a result of these studies it was concluded in Ref. 3 that about 10%-15% of the neutron decay from the giant monopole resonance (GMR) region was nonstatistical while the analysis of Dias and Wolynec[12] is consistent with purely statistical decay, the upper limit for direct neutron decay being set at 10%. In a recent work,[4] the neutron decay following ^{17}O inelastic scattering was measured with better energy resolution and statistics allowing the neutron branching ratios for the decay to the low-lying excited states of ^{207}Pb to be studied as a function of ^{208}Pb excitation energy in steps of 1 MeV. The comparison of the experimental branching ratios in the excitation energy region 9-15 MeV with the statistical-model predictions was carried out for the first time on an absolute basis. The neutron branching ratios in the isoscalar-quadrupole-resonance region were reproduced fairly well by the calculations, while the ratios from the isoscalar-monopole-resonance region show an excess with respect to the statistical-model predictions leading to a direct branching ratio of $(15 \pm 4)\%$.

In the present paper, an analysis of the neutron decay data[4] in the GMR region, between 13 and 15 MeV, to the valence hole states of ^{207}Pb is presented and the associated escape widths are determined. A formalism is used which involves the contributions of both the direct and the statistical decay channels; unitarity controls the interplay of the two contributions.[13]

The direct escape width associated with individual hole states obtained in this analysis is compared with the results of a microscopic model of the direct decay of giant resonances, based on energy-dependent, complex random-phase-approximation (RPA) states.[14]

The branching ratio for neutron decay of the giant resonance (GR) to a single-hole state i of ^{207}Pb is

$$\frac{\sigma_{\mathrm{GR}\to i}}{\sigma_{\mathrm{g.s.}\to\mathrm{GR}}}=\left[(1-\mu_1)\frac{\tau_i^D}{\sum_i\tau_i^D}+\mu_1\frac{\tau_i^C+\mu_1\tau_i^D}{\sum_j\tau_j^C+\mu_1\sum_i\tau_i^D}\right], \tag{1}$$

where $\sigma_{\mathrm{g.s.}\to\mathrm{GR}}$ is the formation inelastic-scattering cross section. The ratio (1) was obtained from the experimental data of Ref. 4 on the assumption that the decay of the background underlying the giant monopole resonance in the excitation-energy region between 13 and 15 MeV is equal to the decay of the ^{208}Pb excitation-energy region between 15 and 16 MeV. Two significant concentrations of strength are known to occupy the 13–15-MeV region: the giant dipole resonance ($E^*=13.6$ MeV, $\Gamma=4$ MeV) and the giant monopole resonance ($E^*=13.9$ MeV, $\Gamma=2.9$ MeV). The contribution of the dipole resonance to the inelastic ^{17}O cross section above 13 MeV is very small, less than 15% of that due to the monopole resonance, on the assumption that each exhausts its respective energy-weighted sum rule. Thus the 13–15-MeV region contains about equal contributions from localized $L=0$ strength and an underlying continuum. Therefore, if the properties of the background are slowly varying it is expected that the values obtained by this subtraction are dominated by the decay of the nucleus from states with angular momentum $J=0$.

The label j in Eq. (1) runs over all the states, including the pure hole states i of the final system, that can be populated from the compound nucleus. The quantities

$$\tau_j^C=2\pi\Gamma_j^C\rho, \tag{2}$$

and

$$\tau_i^D=2\pi\Gamma_i^\uparrow\rho^D, \tag{3}$$

represent the compound-nucleus neutron decay and the direct decay transmission coefficients, respectively. The quantities Γ and ρ are the neutron decay widths and level densities associated with the direct escape ($D,\uparrow$) and compound emission (C) processes.

The mixing parameter μ_1 measures the coupling of the giant resonance to the compound nucleus. It is related to the spreading width ($\Gamma^\downarrow$) according to

$$\mu_1=\Gamma^\downarrow/\Gamma, \tag{4}$$

where

$$\Gamma=\Gamma^\downarrow+\Gamma^\uparrow. \tag{5}$$

In writing expression (5) it was assumed that Γ coincides with the total width of the resonance. Consequently, the mixing parameter will be written as

$$\mu_1\simeq\frac{\Gamma-\Gamma^\uparrow}{\Gamma}=\frac{\Gamma-\sum_i\Gamma_i^\uparrow}{\Gamma}. \tag{6}$$

Identifying τ^C with the Hauser-Feshbach transmission coefficients, and restricting the sums $\sum_i\tau_i^D$ and $\sum_i\Gamma_i^\uparrow$ in (1) and (6) to the observed lowest five hole states of ^{207}Pb, one obtains a set of coupled equations in the unknown quantities μ_1 and $\Gamma_i^\uparrow$.

The calculations of τ_j^C were carried out with the optical-model potential of Rapaport, Kulkarni, and Finlay[15] and the level density of Gilbert and Cameron.[16] In addition, and in keeping with the discussion carried out following Eq. (1), the calculations were done under the assumption that the compound nucleus in the excitation energy range 13–15 MeV has multipolarity $J=0$.

By our making use of the experimental cross sections[4] and $\rho^D\simeq1$ MeV^{-1}, the numbers quoted in Table I under the label "Expt." were obtained. The total direct escape width was found to be $\Gamma^\uparrow\simeq425\pm100$ keV and $\mu_1=0.86$. The main uncertainty in the calculations is associated with the quantity ρ^D. On the other hand, $\Gamma^\uparrow$ is rather stable with respect to the ratio ρ^D/ρ. In fact, our changing ρ^D from 1 to 10 MeV^{-1} led to $\Gamma^\uparrow\simeq140$ keV.

Within the framework of Ref. 14, and with use of different model Hamiltonians, the decay properties of the giant monopole resonance of ^{208}Pb were calculated and the associated strength functions

$$S(E)=-\frac{1}{\pi}\mathrm{Im}\sum_{a=1}^{N}\langle\tilde{o}|r^2Y_{00}|D_a\rangle^2\left[\frac{1}{E-\omega_a+\Gamma_a^\uparrow/2}+\frac{1}{E+\omega_a-\Gamma_a^\uparrow/2}\right] \tag{7}$$

determined. Here, the quantities ω_a, $\langle\tilde{o}|r^2Y_{00}|D_a\rangle$, and $\Gamma_a^\uparrow$ are the energies, the transmission amplitudes, and the direct escape widths associated with the different poles of the complex RPA solutions.

In the calculations carried out following the phenomenological model of de Haro, Krewald, and Speth,[8] the single-particle basis is determined by diagonalization of a Woods-Saxon potential on a harmonic-oscillator basis of frequency $\hbar\omega_0\sim41/A^{1/3}$ MeV, and replacement of the levels around the Fermi energy with the experimental values. The residual interaction used is of the Landau-Migdal type, with parameters adjusted to reproduce the energy of the GMR. The associated strength function is shown in Fig. 1(a). In the region 13–15 MeV there is a single peak, exhausting 60% of the energy-weighted sum rule (EWSR), and displaying an escape width $\Gamma^\uparrow\simeq250$ keV. Thus we reproduce with the

TABLE I. Partial direct escape widths from the GMR in ^{208}Pb populating the lowest five hole states of ^{207}Pb. In columns one and two the quantum numbers and experimental energies of the states are given. In the third column the results of the analysis of the experimental data making use of Eqs. (1)-(6) are reported. A single number (140±35 keV) is reported for the population of the $p_{1/2}^{-1}$ and $i_{13/2}^{-1}$ hole states, as explained in Ref. 4. In the fourth column, the predictions of the present work making use of the phenomenological Hamiltonian of de Haro, Krewald, and Speth (Ref. 8) [cf. Fig. 1(a)] are displayed.

l_j	E_x (MeV)	$\Gamma_i^{\downarrow}$ (keV), expt.	$\Gamma_i^{\downarrow}$ (keV), theory
$p_{1/2}$	0	140±35	5
$i_{13/2}$	1.630		6
$f_{5/2}$	0.570	70±15	92
$p_{3/2}$	0.890	50±10	8
$f_{7/2}$	2.340	165±40	174

methods of Ref. 14 the findings of de Haro, Krewald, and Speth.[8] The partial width $\Gamma_{\alpha i}^{\uparrow}$ is calculated as the squared modulus of the matrix element of the mean field between the complex states D_α and the hole state i of the residual nucleus coupled to the decaying particle in a continuum state properly orthogonalized to the single-particle resonances.[14,17,18] Because the α states are complex, they fulfill the relation $\sum_i \Gamma_{\alpha i}^{\uparrow} = N\Gamma_{\alpha}^{\uparrow}$, with $N \geq 1$.

The resulting values are collected in Table I under the label "Theory," in comparison with the experimental data. While the width associated with the p states is badly underpredicted, the order of magnitude of the summed contributions is within the experimental error.

A very different situation is encountered if one uses a more consistent model based on a Skyrme-type force, SG II,[7] as seen from Fig. 1(b), where the associated GMR strength function is displayed. Although the main peak carrying about 60% of the EWSR has essentially the same energy and collectivity as that resulting from the phenomenological model, the associated escape width $\Gamma^{\uparrow} \simeq 1.5$ MeV is almost an order of magnitude larger.[19]

It should be noted that in the phenomenological model, the GMR is built out of particle-hole configurations which mostly involve the bound states of the first unoccupied shell in ^{208}Pb, coupled by a relatively weak residual interaction. On the other hand, the GMR calculated with the Skyrme Hamiltonian is distributed over a much larger number of particle-hole excitations also involving the positive-energy single-particle states.

The large width predicted by the Skyrme-type Hamiltonians seems to be restricted to the GMR, as a very narrow strength function was obtained[6] for the isoscalar quadrupole and hexadecapole resonances.

We conclude that the study of direct neutron decay allows for a deep probing of the microscopic structure of giant resonances. In particular, different model Hamiltonians which reproduce the energy and the collectivity

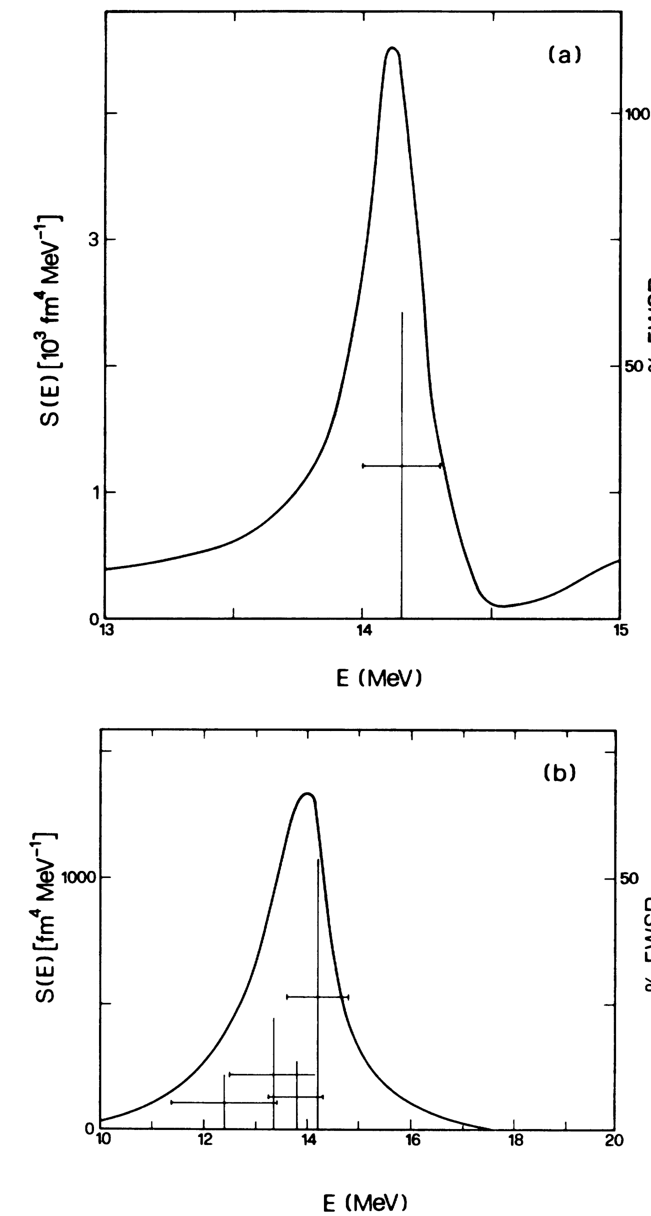

FIG. 1. The strength function associated with the GMR of ^{208}Pb as a function of the excitation energy. The calculations were carried out with use of Eq. (7). The scale on the left corresponds to the continuous curve, while that on the right corresponds to the single peaks. The results reported in (a) correspond to the use of a phenomenological Hamiltonian (Ref. 8) and those of (b) to the Skyrme-type interaction denoted SG II (Ref. 7). As explained in Ref. 14, the function $S(E)$ displays, in the RPA approach, the spreading associated with both the fragmentation and the direct neutron escape mechanisms. In (a) a single peak exhausts ≃60% of the EWSR, while the strength is considerably more broken in (b). Also in this case, there is a main contribution carrying a large fraction of the EWSR. The main difference between the two calculations is to be found in the magnitude of the neutron escape widths $\Gamma^{\uparrow}$ associated with the two main peaks of (a) and (b). In this context note the different energy scales in the two figures.

of the GMR of ^{208}Pb equally well lead to direct escape widths which differ by almost an order of magnitude. This result underscores the different role played by the correlated particle-hole excitations in virtual and in on-the-energy-shell processes.

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