

NEUTRON ESCAPE WIDTHS OF GIANT MONOPOLE RESONANCE
IN ^{208}Pb

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The neutron escape widths of the isoscalar giant monopole resonance in ^{208}Pb are calculated within the framework of a self-consistent model, taking into account the coupling with the continuum and with a number of 2 particles-2 holes states. Due to the latter effect, the discrepancy between experimental and theoretical results is reduced with respect to previous calculations.

Giant resonances are collective states of the nucleus, and can be described as coherent superposition of particle-hole excitations. After many experimental and theoretical investigations (for a review, see e. g. Ref. 1), their mean properties

are well known, and can be explained in terms of well established nuclear model Hamiltonians. However, much remains still to be understood of this collective modes at the microscopic level. This is especially true for the variety of relaxation mechanisms acting in the damping of giant resonances, in particular particle decay. In what follows, we will discuss some of the issues related to this subject.

Due to the residual interaction between nucleons, giant resonances are damped even at zero temperature. Collisions can distribute energy and angular momentum among nucleons, until a statistical equilibrium has been reached, and the system becomes a compound nucleus. Important »doorway states« in this process are 2 particles—2 holes excitations. In particular, particle-hole pairs coupled with a surface vibration are known to play a very important role and to account for most of the damping width $\Gamma^{(2,3)}$. Giant resonances can also decay by light particle emission, since they are above threshold. In heavy nuclei, the Coulomb barrier strongly hinders proton emission and only neutron decay is observed. The coupling of giant resonances with states in which a neutron is in the continuum gives rise to a width we denote by Γ^\dagger .

The measurement of direct neutron decay from giant resonances is a delicate probe of its microscopic structure. Studies of the decay of the isoscalar giant monopole resonance (GMR) in ^{208}Pb have been carried out during recent years. A first attempt was made by Eyrich and co-workers⁴⁾, who analyzed their results with statistical models, based on the hypothesis that before particle emission the compound nucleus state had been reached. Besides these »delayed« neutrons, they found a 15% neutron excess, which could be interpreted as arising from direct decay of the GMR. However, an analysis of the same experiment carried out by Dias and Wolyneć⁵⁾ is in principle consistent with a merely statistical decay, and this conclusion was also reached by Brandenburg et al. from the analysis of an equivalent experiment⁶⁾.

The most recent work on neutron decay of the breathing mode in ^{208}Pb was performed by A. Bracco and co-workers⁷⁾. The GMR was excited by ^{17}O scattering. The neutron separation energy is in this nucleus quite small, so it was possible to discriminate the events with projectile excitation. Both the neutrons and the gamma rays of ^{207}Pb de-excitation were detected. The energy resolution and statistics were adequate to allow for a detailed study of branching ratios for the decay to the low-lying excited states of ^{207}Pb , in steps of 1 MeV in the 9—15 MeV region of excitation energy. The partial widths of the GMR, corresponding to the decay on a configuration with a particular neutron valence hole, have been extracted from the experimental data using the McVoy-Hussein formalism⁸⁾.

The theoretical analysis was carried out in Ref. 9. The configuration space for the description of the GMR in ^{208}Pb is divided in subspace P and $Q^{(10)}$: Q is the space of the configurations with all the particles on a discrete state, either a bound or resonant embedded in the continuum. In P are the configurations in which one particle is in a continuum state. By construction, the two subspaces are orthogonal. The giant resonance, in the usual Tamm-Dancoff (TDA) or Random Phase Approximation (RPA), is built on a particle-hole configuration basis belonging to Q , and the amplitudes are eigenvectors of an Hamiltonian including the mean field H_0 and a residual interaction V_{ph} . We denote this Hamiltonian by QHQ . To take into account the coupling with the continuum, one can diagonalize an effective Hamiltonian

$$\mathcal{H}(E) = QHQ + QHP \frac{1}{E - PHP + i\eta} PHQ, \quad (1)$$

where P, Q are projectors on the subspaces. This is an energy-dependent, complex Hamiltonian, whose eigenvalues are denoted by $\omega_\alpha - i \frac{\Gamma_\alpha^\dagger}{2}$, whereas the eigenvectors are $|D_\alpha\rangle$. We solve the Hamiltonian by approximating H with H_0 in the energy-dependent part, since the matrix elements of $PV_{ph}Q$ and $PV_{ph}P$ are expected to be small. The quantity V_{ph} is a zero-range force and the wave functions of the discrete and continuum states have small overlap. The corresponding strength function is

$$S(E) = -\frac{1}{\pi} \text{Im} \sum_{\alpha=1}^N |\langle 0|r^2 Y_{00}|D_\alpha\rangle|^2 \left(\frac{1}{E - \omega_\alpha + i \frac{\Gamma_\alpha^\dagger}{2}} + \frac{1}{E + \omega_\alpha - i \frac{\Gamma_\alpha^\dagger}{2}} \right), \quad (2)$$

where $r^2 Y_{00}$ is the operator for the isoscalar monopole excitation.

This function was determined using two different Hamiltonians. In the phenomenological model of De Haro et al.¹¹⁾, the single-particle levels were obtained by diagonalizing a Saxon-Woods potential on an harmonic oscillator basis, and substituting the eigenvalues near the Fermi energy with the experimental values. The residual interaction is of Landau-Migdal type, with the parameters adjusted to fit the GMR centroid. Also a self-consistent model has been used, based on a Hartree-Fock calculation of the single-particle levels. A Skyrme force, namely the SGII introduced in Ref. 12, has been employed. The two strength functions associated with these calculations are depicted in Fig. 1.

The partial widths Γ_i^\dagger were calculated for the state $|D_\alpha\rangle$ which carries the largest fraction of the monopole EWSR (Energy-weighted Sum Rule). These partial widths are the squared modulus of the matrix element of the mean field between the complex state $|D_\alpha\rangle$ and the residual nucleus in a single-hole state i . The quantity $\sum_i \Gamma_i^\dagger$ calculated with the phenomenological Hamiltonian agrees with the observation within the experimental errors. It is however much bigger when evaluated with the self-consistent interaction. The two Hamiltonians reproduce equally well the collective properties of the GMR, as the mean energy and the fraction of EWSR, but the different underlying microscopic structure is underscored by the differences in the partial widths. In what follows, we discuss some of the reasons for this discrepancy.

In the region of the GMR the density of more complicated states with zero angular momentum and positive parity is very high. The 2 particles-2 holes states with $J^\pi = 0^+$ have indeed a density of the order of 10^2 – 10^3 states/MeV, and the matrix elements which couple these states with the 1 particle-1 hole of the basis of the GMR are not negligible. To include the 2 particles-2 hole states in the description of giant resonances a formalism has been developed, known as the Second Random Phase Approximation (SRPA)¹³⁾. In it one builds the creation operator of a vibrational mode on a basis including 2 particles-2 holes excitations as

$$Q_\nu^\dagger = \sum_{ph} X_{ph}^\nu a_p^\dagger a_h - Y_{ph}^\nu a_h^\dagger a_p + \sum_{p,p' > p} \sum_{h,h' > h} X_{p'h'}^\nu a_p^\dagger a_{p'}^\dagger a_h a_{h'} - Y_{p'h'}^\nu a_{h'}^\dagger a_h^\dagger a_p a_{p'}. \quad (3)$$

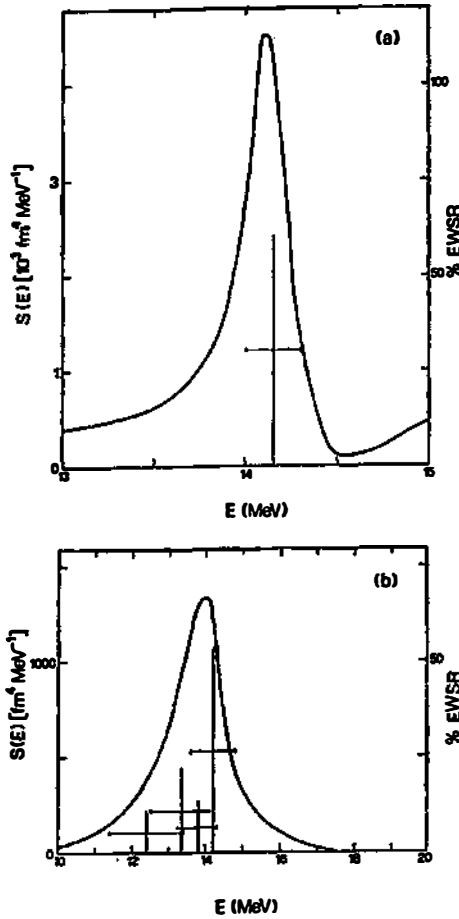


Fig. 1. The strength function of the monopole excitation of ^{208}Pb , cfr. equation (2). On the left, the scale corresponding to the continuous curve, and on the right the percentage of EWSR carried by individual peaks. In (a) the function is calculated by using the phenomenological model by De Haro¹¹⁾, in (b) with a self-consistent Skyrme RPA. Notice the different energy scale, as well as the discrepancy between the escape widths of the peaks.

The formalism is analogous to RPA, but one has to work out a matrix equation in a much bigger space, and calculations has been carried out only for light nuclei. To deal with heavy nuclei, one projects the SRPA equation on 1 particle-1 hole states basis and gets³⁾

$$\begin{pmatrix} A + \Sigma(\omega) & B \\ -B^* & -A^* - \Sigma^*(-\omega) \end{pmatrix} \begin{pmatrix} x^p \\ y^p \end{pmatrix} = \hbar\omega_p \begin{pmatrix} x^p \\ y^p \end{pmatrix}. \quad (4)$$

Taking the 2 particles-2 holes $|N\rangle$ states as non-interacting, we can write

$$\Sigma_{ph, p'h'}(\omega) = \sum_N \frac{\langle ph|V|N\rangle \langle N|V|p'h'\rangle}{\hbar\omega - \hbar\omega_N + i\eta}. \quad (5)$$

In this way, we split Q in a subspace Q_1 of 1 particle-1 hole states and Q_2 of 2 particles-2 holes and solve

$$\mathcal{H}(E) = Q_1 H Q_1 + Q_1 H Q_2 \frac{1}{E - Q_2 H Q_2 + i\eta} Q_2 H Q_1 + Q_1 H P \frac{1}{E - P H P + i\eta} P H Q_1. \quad (6)$$

We have calculated the term Σ only between those 1 particle-1 hole states which give to the three most collective vibrational states a contribution with a squared amplitude X_{ph}^2 greater than 1%. These states are 37, whereas the complete basis is made up by 88 1 particle-1 hole configurations.

We found a strong cancellation between the contributions to Σ coming from the diagrams corresponding to self-energy insertions within a particle or a hole line, and contributions from «bubble» diagrams, as expected on general grounds^{2,3}. To display this cancellation, we defined a mean value of Σ as in Ref. 14:

$$\langle \Sigma \rangle_F \equiv \frac{\sum_{ph,p'h'} F_{ph}^+ \Sigma_{ph,p'h'} F_{p'h'}}{\sum_{ph} F_{ph}^+ F_{ph}}, \quad (7)$$

where F is the operator $r^2 Y_{00}$. We found, for the imaginary part of Σ ,

$$\begin{aligned} \text{Self-energy contribution} &= -1001 \text{ keV} \\ \text{Bubbles contribution} &= 994 \text{ keV}, \end{aligned}$$

which means the cancellation is almost complete.

The partial neutron decay widths for the $|D_{\alpha}\rangle$ state, calculated by solving the Hamiltonian (6), are markedly changed. The results are shown in the last column of Table 1, where one can see that the discrepancy with experimental data has

TABLE 1.

Decay Channel	Experimental values	Phenom. RPA	Skyrme RPA	
			without 2p-2h	with 2p-2h
$p \frac{1}{2}$	140 ± 35	11	250	121
$\frac{1}{2} \frac{1}{2}$				
$f \frac{5}{2}$	70 ± 15	92	1240	681
$p \frac{3}{2}$	50 ± 10	8	433	227
$f \frac{7}{2}$	165 ± 40	174	640	528
$h \frac{9}{2}$	—	45	0	0
$\Sigma I \uparrow_c$	425 ± 100	330	2563	1557

Results for the partial widths of GMR in ²⁰⁸Pb. The values are in keV.

been reduced by about 40%. We note again that the subspace in which the mixing of configurations has been evaluated is rather small. In particular, we have not considered the coupling of 1 particle-1hole states with the low-lying collective states, which are known to be the most important doorway states in the damping of giant resonances, leading to the largest contribution to $\Gamma^{(1,5)}$. To get a simple estimate of their importance, we can notice that the collective states of ^{208}Pb with excitation energy below 5 MeV, like the vibrational states of multipolarity 2^+ or 3^- , have a transition probability to the ground state of the order of 10^2 single particle units. We can thus expect that the coupling of the GMR with 2 particles-2 holes states containing low-lying vibrations is about a factor 3 larger than that associated with the uncorrelated particle-hole pairs, and essentially remove the remaining difference between the predictions of the two model Hamiltonians. Systematic calculation along this line are in progress.

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NEUTRINSKE ŠIRINE GIGANTSKIH MONOPOLNIH REZONANCI U ^{208}Pb

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Izračunate su neutronske širine izoskalarnih gigantskih rezonanci u ^{208}Pb uzimajući u obzir vezanje s kontinuumom i sa stanjima 2 čestice — 2 šupljine.