Quantum Geometry: Advanced generalized multiconfiguration model of decay of the multipole giant resonances

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Abstract Within quantum-geometrical treating spectra of the finite Fermi-systems it is presented an advanced generalized multiconfiguration model to describe a decay of high-excited states (the multipole giant resonances). The approach is based on the more accurate mutual using the advanced shell model and microscopic model of pre-equilibrium decay with statistical account for complex configurations 2p2h, 3p3h etc.

Keywords Quantum geometry · Multiconfiguration model · giant resonances · Quantization of quasi-stationary states

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1 Introduction

In the modern quantum geometry and quantum theory of the many-fermion systems there is a number of very complex problems, connected with a development of the consistent methods of calculating eigen values of energy for the Hamiltonians of the many-body systems with account of correlation and other corrections (see, for example, [1]–[4]). As it is well known, the multipole giant resonances (MGR) are the highly excited states of nuclei, which are interpreted as the collective coherent vibrations with participation of large number of nucleons. Experimentally, MGR are manifested as the wide maximums in the dependence of cross-section of the nuclear reactions on the incident particle energy r in -th spectrum of incident particles. A classification of MGR as the states of collective type is usually fulfilled on the quantum numbers of vibrational excitations:

entire angle momentum (J) and parity π (J^{π}). The MGR are observed in the spectra of majority of nuclei and situated, as a rule, in the continuous spectrum of excitations in a nucleus (with width of order of several MeV). Two theoretical approaches to description of MGR are usually used. In the phenomenological theories it is supposed that the strong collectivization of states allows applying the hydrodynamical models to the description of vibrations of the nuclear form and volume. The microscopic theory is based on the shell nuclear model. In the simple interpretation an excitation of the MGR is result of transition of the nucleons from one closed shell to another one, i.e. the MGR is a result of coherent summation of many particle-hole (p-h) transitions with necessary momentum and parity. MGR are situated under the excitation energies, which exceed the thresholds of emission of the particles from a nucleus. The interaction of a nucleus with external field with forming the MGR occurs during several stages. There is a production of the p-h excitation which corresponds to 1p-1h states over the Fermi surface (1st stage). Then the excited pair interacts with nuclear nucleons with the creating another 1p-1h excited state or two p-h pairs (2p-2h state; 2nd stage). Then the 3p-3h and more complicated states are created till the statistical equilibrium takes a place. The full width of MGR is provided by the direct decay to continuum ($\Gamma^{\uparrow}$) and decay of the 1p-1h configurations on more complicated multi-particle ($\Gamma^{\downarrow}$) ones. The mixing with complex configurations leads to the loss of the coherence and creating states of the compound nucleus. Naturally an account of complex configurations has significant meaning for correct explanation of the MGR widths, structure, decay properties. Here we present an advanced generalized multiconfiguration model to describe a decay of high-excited states, which is based on the mutual using the shell models and microscopic Zhivopistsev-Slivnov model of pre-equilibrium decay with statistical account for complex configurations 2p2h, 3p3h etc. It generalizes earlier developed models [7]–[10]. The advanced approach has been applied to analysis of reaction (μ-n) on the nucleus ^{40}Ca.

2 Advanced generalized multi-configuration model

The MGR may be treated on the basis of the advanced multi-particle shell model. Process of appearance a collective state of MGR and an emission process of nucleons are described (see details in refs. [3]–[6]) by standard diagram, which contains an effective Hamiltonian of interaction V_{μ}, resulted in capture of muon by nucleus with transformation of proton to neutron and emission by antineutrino. Isobaric analogs of isospin and spin-isospin resonances of finite nucleus are excited.

The corresponding diagrams for photonuclear reactions look to be analogous and contain the full vertex part $\tilde{\Gamma}^n_{22}$ (full amplitude of interaction, which transfers the interacting p-h pair to the finite npnh state). The full vertex Γ $\tilde{\Gamma}^n_{22}$ is defined by the system of equations within quantum Green function modified approach [6]–[7]). Further, all possible configurations are divided on two groups: i) group of complicated configurations 'n_1', which must be considered within shell model with account for residual interaction; ii) statistical group 'n_2' of complex configurations with large state density p$(n, E) \gg$ and strong overlapping the states $G_n \gg D_{n-1} > D_n$ (D_n is an averaged distance between states with $2n$ exciton; G_n is an averaged width).

To take into account a collectivity of separated complex configurations for input state a diagonalization of residual interaction on the increased basis (ph, ph+phonon, ph+2 phonon) is used. All complex configurations are considered within the pre-equilibrium decay model [5] with additional account of 'n_1' group configurations. The input wave functions of the MGR for nuclei with closed or almost closed shells can be found from diagonalization of residual interaction on the effective optimized 1p1h basis [2]. Statistical multistep negative muon capture through scalar intermediate states of compound nucleus is important. Intensities of nucleon spectra are defined by standard way (see refs. [5]–[7]).

The intensity of nucleonic spectra is defined as follows:

$$\frac{dI}{d\varepsilon_f}(E_\mu, l, \varepsilon_f, J\pi) = \sum_{\substack{n=1,\\ \Delta n=1}} \frac{\Gamma_n^{\uparrow}(l, \varepsilon_f, J\pi)}{\Gamma_n(J\pi)} \cdot \left[\prod_{k=1}^{n-1} \frac{\Gamma_k^{\downarrow}(J\pi)}{\Gamma_k(J\pi)}\right] \cdot \Lambda_\mu(E_\mu, J\pi), \qquad (1)$$

where

$$\Gamma_n^{\uparrow}(l, \varepsilon_f, J\pi) = 2\pi \langle |\langle \varphi_{N_n}(J\pi)| I_{N_n, N_B+1}[\varphi^{(+)}(l, \varepsilon_f)\varphi_{N_B}(U_B, I_B)]_{J\pi}\rangle|^2\rangle \times$$
$$\times \rho(l, \varepsilon_f)\rho^{(b)}(N_B, U_B, I_B),$$
$$\Gamma_k^{\uparrow}(J\pi) = \sum_{l,f} \int d\varepsilon_f \Gamma_k^{\uparrow}(l, \varepsilon_f, J\pi),$$
$$\Gamma_k(J\pi) = \Gamma_k^{\uparrow}(J\pi) + \Gamma_k^{\downarrow}(J\pi),$$
$$\Gamma_k^{\downarrow}(J\pi) = 2\pi \langle |\rangle \varphi_{N_k}(J\pi)| I_{N_k, N_k+1} |\varphi_{N_{k+1}}(J\pi)\rangle|^2\rangle \rho^{(b)}(N_{k+1}, J\pi, E_\mu),$$
$$E_\mu = \varepsilon_f + U_B + B_N.$$

Here l is the orbital moment of the emission nucleon, ε_f is its energy; B_N is the bond energy of nucleon in the compound nucleus; $\Lambda_\mu(E_\mu, J\pi)$ is probability of

μ-capture with excitation of the state $\varphi_{in}(E_\mu, J\pi)$ with energy E_mu, spin J and parity π.

As in refs. ([5]–[8]), one could neglect the interference between contributions of separated 'dangerous' configurations. The above indicated features of the statistical group of configurations are not fulfilled for the 'dangerous' configurations. However, the value $\Gamma_n^{\downarrow}(n_1)$ for some dangerous configuration is weakly dependent upon the energy. Indeed, configuration n_1 is the superposition of the large number of configurations, i.e.

$$\Gamma_n^{\downarrow}(n_1) = \sum_{n+1} \frac{|\langle|I_{n_1,n+1}|n+1\rangle|^2}{(E_\mu - E_{n+1})^2 + \Gamma_{n+1}^2/4}$$

Generally, the expressions for the n-step contribution to the emission spectrum are modified as follows:

$$\frac{dI}{d\varepsilon_f}(E_\mu, l, \varepsilon_f, J\pi) = \frac{\Gamma_{n_2}^{\uparrow}(l, \varepsilon_f, J\pi)}{\Gamma_{n_2}(J\pi)} \frac{\Gamma_{n-1,n_2}(J\pi)}{\Gamma_{n-1}(J\pi)} +$$
$$+ \sum_{\{n_1\}} \frac{\Gamma_{n_1}^{\uparrow}(l, \varepsilon_f, J\pi)}{\Gamma_{n_1}(J\pi)} \frac{\Gamma_{n-1,n_1}^{\downarrow}(J\pi)}{\Gamma_{n-1}(J\pi)} \left[\prod_{k=1}^{n-2} \frac{\Gamma_k^{\downarrow}(J\pi)}{\Gamma_k(J\pi)}\right] \tilde{\Lambda}_\mu(E_\mu, J\pi), \tag{2}$$
$$\Gamma_{n-1}^{\downarrow} = \sum_{\{n_1\}} \Gamma_{n-1,n_1}^{\downarrow} + \Gamma_{n-1,n_2}^{\downarrow},$$

where

$$\Gamma_{n-1,n_1}^{\downarrow} = \frac{|\langle\varphi_{N_{n-1}}(J\pi) I_{N_{n-1},N_n} \varphi^{(n_1)N_n}(J\pi)\rangle^2 \Gamma_{n_1}}{(E_\mu - E_{n_1})^2 + \Gamma_{n_1}^2/4}$$

Supposing the input state is isolated, in formalism of the input ph-states one can write:

$$\tilde{\Lambda} = \frac{\Gamma_1(J\pi)\Lambda_\mu(\varphi(E_i, J\pi))}{(E_\mu - E_i)^2 + \Gamma_{n_1}^2/4}$$

where

$$\Gamma_1(\varphi_{in}) = \Gamma_1^{\uparrow} + \Gamma_{1,n_2}^{\downarrow} + \sum_{\{n_1\}} \Gamma_{1,n_1}^{\downarrow}$$

3 Results and conclusion

The wave functions of the input state $\{\varphi_{in}\}$ in the reaction ^{40}Ca $(\mu^- n)$ have been calculated within the shell model [7]–[9]. As one could wait for that a collectivity of initial input state leads to significant decreasing $\Gamma_i^{\downarrow}$. The separation into groups n_1 and n_2 is naturally accounted for the 2p2h configuration space and the contribution of configurations 'ph+phonon' and weakly correlated 2p2h states is revealed. A probability of transition to 'dangerous' configurations 2p2h is provided by value of matrix element:

$$|\langle\varphi_{in}(\mathrm{ph}, J\pi, E)|I_{\mathrm{ph,2p2h}}|\varphi(\mathrm{2p2h}, J\pi, E)\rangle|^2$$

and additionally by density $\rho(\mathrm{2p2h}, J\pi, E)$ for statistical group n_2. The contribution of weakly correlated 2p2h configurations is defined by expression [4]:

$$\Gamma^{\downarrow}_{\mathrm{2p2h}} = 2\pi\langle|\langle|I_{\mathrm{ph2p2h}}|\rangle|^2\rangle\rho_{\mathrm{2p2h}}.$$

The residual interaction has been choosen in the form of Soper forces:

$$V = g_0(1-\alpha+\alpha\sigma_1\sigma_2)\delta(r_1-r_2),$$

where $g_0/(4\pi r_0^3) = -3$ MeV, $\alpha = 0.135$. The phonons have been considered in the collective model and calculation parameters in the collective model and generalized RPA are chosen according to [7]. Our theoretical estimates have been compared with experimental data and other calculation results ([4]–[7]). In the range of 5–13 MeV the experiment gives the intensity ~10% from the equilibrium one. As it has been shown earlier (see, for example, [4]–[6]), the 1^-, 2^- states do not the significant contribution. However, they exhaust ~80% of the intensity of μ^--capture. The analysis shows that an advanced mutual account for $0^{\pm}$, 1^+, 2^+, 3^+ and more high multipoles (plus more less correct microscopic calculation of $\Gamma^{\downarrow}_{in}(J\pi, E)$, the input and 2p2h states, separation of the 2p2h space n configurations n_1 and n_2 etc.) allows to fill the range of high and middle part of spectrum. From this point of view, the presented approach is more correct in comparison with the earlier multiconfiguration models [4]–[6]).

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