Physics Letters B 706 (2012) 477–481

Contents lists available at SciVerse ScienceDirect

Physics Letters B

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Fragmentation of spin-dipole strength in ^{90}Zr and ^{208}Pb

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ARTICLE INFO

Article history:
Received 18 October 2011
Received in revised form 21 November 2011
Accepted 22 November 2011
Available online 25 November 2011
Editor: W. Haxton

Keywords:
Covariant density functional theory
Particle–vibration coupling
Nuclear charge-exchange excitations

ABSTRACT

An extension of time-dependent covariant density functional theory that includes particle–vibration coupling is applied to the charge-exchange channel. Spin-dipole excitation spectra are calculated an compared to available data for ^{90}Zr and ^{208}Pb. A significant fragmentation is found for all three angular-momentum components of the spin-dipole strength as a result of particle–vibration coupling, as well as a shift of a portion of the strength to higher energy. A high-energy tail is formed in the strength distribution that linearly decreases with energy. Using a model-independent sum rule, the corresponding neutron skin thickness is estimated and shown to be consistent with values obtained at the mean-field level.

Spin–isospin excitations present a very active research topic both in nuclear structure and nuclear astrophysics. In particular, a detailed knowledge of the Gamow–Teller resonance, a collective oscillation of excess neutrons that coherently change the direction of their spin and isospin without changing their orbital motion, is essential for understanding weak nuclear reactions involved in the process of nucleosynthesis, i.e. β-decay, electron and neutrino capture. Moreover, it has been shown that spin-dipole charge-exchange excitations, made up of three components with angular momentum and parity $J^\pi = 0^-$, 1^- and 2^-, can significantly contribute to the total reaction rates and even compete with the contribution of Gamow–Teller transitions [1–3].

The spin-dipole strength can also provide information on basic properties of finite nuclei. The thickness of the neutron skin has been shown to constrain the neutron equation of state [4], and is also correlated with the nuclear symmetry energy [5]. While accurate data on the charge distribution in nuclei have been obtained by elastic electron scattering, our knowledge of neutron distribution comes primarily from hadron scattering, and the results are markedly model-dependent. Indirect methods for determining the neutron skin thickness have been proposed, based on energy differences between the Gamow–Teller and isobaric analogue resonances [6], and using the model-independent sum rule for the spin-dipole resonance [7]. Two recent (p,n) and (n,p) measurements of the spin-dipole response of ^{90}Zr and ^{208}Pb [8,9] have also prompted new theoretical studies, in particular investigations based on the random phase approximation [10–13].

Both measurements [8,9] show a high-energy tail in the spin-dipole strength distribution that cannot be described by the simple one-particle — one-hole (1p1h) random phase approximation (RPA). Previous attempts to extend this framework using the 2p2h RPA were based on a non-self-consistent approach that employs a phenomenological Woods–Saxon potential to obtain the ground-state wave functions [14]. In this Letter we introduce a charge-exchange version of the particle–vibration coupling model based on time-dependent covariant density functional theory, and apply it to an analysis of spin-dipole strength distributions in ^{90}Zr and ^{208}Pb.

The basic quantity that describes small-amplitude motion of an even–even nucleus in an external field with frequency ω is its response function $R(\omega)$ [15]. It is obtained as a solution of the Bethe–Salpeter equation:

$$R(\omega) = \tilde{R}^0(\omega) + \tilde{R}^0(\omega) W(\omega) R(\omega), \tag{1}$$

where $\tilde{R}^0(\omega)$ is the propagator of two uncorrelated quasiparticles in the static mean field, and the second term includes the in-medium nucleon–nucleon interaction $W(\omega)$. The two-body interaction $W(\omega)$ contains static terms and a frequency-dependent term:

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0370-2693/$ – see front matter
doi:10.1016/j.physletb.2011.11.050

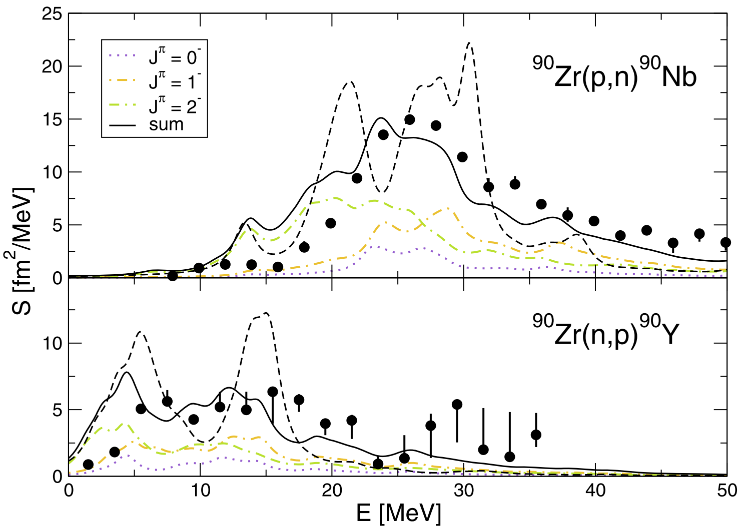

Fig. 1. Spin-dipole strength distributions for the t_- (upper panel) and the t_+ (lower panel) channels in ^{90}Zr. On the horizontal axis the excitation energy is plotted with respect to the ground state of ^{90}Zr. The solid black curve represents the sum of the strength distributions of the 0^-, 1^- and 2^- components, calculated in the RTBA that includes particle–vibration coupling. The dashed black curves denotes the corresponding RRPA strength function. In both cases the imaginary part of the energy is set to $\Delta = 1$ MeV. The experimental results denoted by full circles are from Ref. [8].

$$W(\omega) = V_\rho + V_\pi + V_{\delta\pi}^{LM} + \Phi(\omega) - \Phi(0). \tag{2}$$

V_ρ and V_π represent the finite-range ρ-meson and π-meson exchange interactions, respectively. They are derived from the covariant energy density functional and read:

$$V_\rho(1,2) = g_\rho^2 \vec{\tau}_1 \vec{\tau}_2 (\beta\gamma^\mu)_1 (\beta\gamma_\mu)_2 D_\rho(\mathbf{r}_1, \mathbf{r}_2),$$
$$V_\pi(1,2) = \left(\frac{f_\pi}{m_\pi}\right)^2 \vec{\tau}_1 \vec{\tau}_2 (\boldsymbol{\Sigma}_1 \nabla_1)(\boldsymbol{\Sigma}_2 \nabla_2) D_\pi(\mathbf{r}_1, \mathbf{r}_2), \tag{3}$$

where g_ρ and f_π are the coupling strengths, D_ρ and D_π are the meson propagators and $\boldsymbol{\Sigma}$ is the generalized Pauli matrix [16]. The derivative type of the pion–nucleon coupling necessitates the inclusion of the zero-range Landau–Migdal term $V_{\delta\rho}^{LM}$, which accounts for the contact part of the nucleon–nucleon interaction [16]. $\Phi(\omega)$ describes the coupling of the quasiparticles to vibrations (phonons) generated by coherent nucleonic motion. In the quasiparticle time blocking approximation (QTBA) [17] it can be written in the following operator form:

$$\Phi(\omega) = \sum_{m,\eta} g_m^{(\eta)\dagger} \tilde{R}^{0(\eta)}(\omega - \eta\omega_m) g_m^{(\eta)}, \tag{4}$$

where the index m enumerates vibrational modes with frequencies ω_m and coupling amplitude matrices $g_m^{(\eta)}$, and the index $\eta = \pm 1$ denotes forward and backward components. In Eq. (2) the term $\Phi(0)$ is subtracted to remove the effect of double counting the phonon coupling, because the parameters of the density functional have been adjusted to ground-state data and, therefore, already include essential static phonon contributions. The energy-dependent effective interaction of Eq. (4) leads to fragmentation of nuclear spectra and determines the width of giant resonances [18].

The strength function $S(\omega)$:

$$S(E, \Delta) = -\frac{1}{\pi} \mathrm{Im} \langle P^\dagger R(E + i\Delta) P \rangle, \tag{5}$$

yields the spectral distribution of the nuclear response in a given external field P. The field operators for charge-exchange spin-dipole transitions read:

$$P_\pm^\lambda = \sum_i r(i) \left[\boldsymbol{\sigma}(i) \otimes Y_1(i) \right]_\lambda t_\pm(i), \tag{6}$$

where $t_\pm$ denotes the isospin raising and lowering operators.

The phonon coupling terms augment the RPA spectrum with additional p–h⊗phonon components that generally lead to significant fragmentation of giant resonances [18]. In Fig. 1 we compare the spin-dipole strength distribution in ^{90}Zr calculated using the relativistic random phase approximation (RRPA), and the relativistic time-blocking approximation (RTBA). In both models the NL3 [19] relativistic mean-field effective interaction has consistently been used for the calculation of the mean-field ground-state, the RPA phonons, and the spin-dipole charge-exchange excitations.

The prominent RRPA peaks (dashed curves) disappear when particle–vibration coupling is included in the RTBA (solid curves). In the t_- channel, for instance, only a broad resonance remains with the peak at 23.5 MeV, in very good agreement with available data [8]. The three angular-momentum components do not, however, follow the energy hierarchy $E(2^-) < E(1^-) < E(0^-)$ predicted by recent Skyrme-RPA calculations [10,11]. While the RTBA predicts the 2^- component to be the lowest one with the centroid energy $m_1^{2^-}/m_0^{2^-} = 25.4$ MeV, 0^- is found to be lower than the 1^- component, with centroid energies at 29.4 MeV and 32.6 MeV, respectively. This is probably due to the fact that the exchange terms are neglected in the mean-field calculation. Namely, as shown in a recent study [12], a fully consistent relativistic Hartree–Fock (RHF) + RPA calculation yields $E(2^-) < E(1^-) < E(0^-)$ for the excitation energies of spin-dipole components.

The inclusion of particle–vibration coupling leads to a shift of the strength to higher excitation energies. A high-energy tail is formed in the region above 30 MeV where the strength decreases almost linearly with increasing energy, in close agreement with experimental results. In contrast, the RRPA strength decreases more rapidly above 30 MeV, and becomes 5 to 10 times smaller than the experimental strength above 40 MeV.

In the t_+ channel the two dominant peaks predicted by the RRPA merge into a single broad structure that extends up to approximately 15 MeV excitation energy. The tail at higher energies decreases approximately linearly with increasing energy. One might notice a very good agreement with data, except in the low-energy region below 5 MeV, where both the RRPA and the RTBA predict spin-dipole strength, originating predominantly from the 2^- component, that is considerably larger than the measured distribution.