Pis'ma v ZhETF, vol. 104, iss. 9, pp. 635 – 636

Phonon-particle Coupling Effects in Single-particle Energies of Semi-magic Nuclei

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Submitted 31 August 2016
Resubmitted 26 September 2016

DOI: 10.7868/S0370274X16210037

Last decade, there was a revival of the interest within different self-consistent nuclear approaches to study the particle-phonon coupling (PC) effects in the single-particle energies (SPEs) of magic nuclei (see [1] and Refs. therein). In this work we extend the field of this problem to semi-magic nuclei.

A semi-magic nucleus consists of two sub-systems with different properties. One of them, magic, is normal, whereas the non-magic counterpart is superfluid. We will consider the SPEs of the normal sub-system only. Therefore, the main part of the formalism for magic nuclei [1] remains valid. Some new difficulty arises in non-magic nuclei due to appearance of low-lying 2^+ states which is a characteristic feature of such nuclei. As a result, small denominators appear regularly in the expressions for the PC corrections to SPEs which makes unapplicable a plane perturbation theory which is used in magic nuclei.

To find the SPEs with account for the PC effects, we solve the following equation:

$$\left(\varepsilon - H_0 - \delta\Sigma^{\rm PC}(\varepsilon)\right)\phi = 0, \qquad (1)$$

where H_0 is the quasiparticle Hamiltonian with the spectrum $\varepsilon_\lambda^{(0)}$ and $\delta\Sigma^{\rm PC}$ is the PC correction to the quasiparticle mass operator Σ. The $\delta\Sigma^{\rm PC}$ correction, just as in magic nuclei, is found within so-called g_L^2-approximation, where g_L is the vertex of creating the L-phonon. The tadpole term is taken into account approximately, following to [1].

In magic nuclei, the perturbation theory in $\delta\Sigma^{\rm PC}$ with respect to H_0 was used to solve this equation. In this work, we solve Eq. (1) directly, without any additional approximations. The vertex g_L obeys now the QRPA-like TFFS equation [2, 3]

$$\hat{g}_L(\omega) = \hat{\mathcal{F}}\hat{A}(\omega)\hat{g}_L(\omega), \qquad (2)$$

where all the terms are 3×3 matrices containing a normal and anomalous components. For solving the above equations we use the self-consistent basis generated by the version DF3-a [4] of the Fayans EDF [5]. In this work we consider four even lead isotopes, ^{200,202,204,206}Pb, and two phonons, 2_1^+ and 3_1^-.

As the PC corrections are important only for the SPEs nearby the Fermi surface, we limit ourselves with a model space S_0 including two shells close to it, i.e., one hole and one particle shells. In this case, there is only one state for each (l, j) value. Therefore, we need only diagonal elements $\delta\Sigma_{\lambda\lambda}^{\rm PC}$, and Eq. (1) reduces as follows:

$$\varepsilon - \varepsilon_\lambda^{(0)} - \delta\Sigma_{\lambda\lambda}^{\rm PC}(\varepsilon) = 0. \qquad (3)$$

For the model space under consideration and two L-phonons, Eq. (3) has about ten solutions ε_λ^i for each λ. The corresponding single-particle (SP) strength distribution factors (S-factors) are

$$S_\lambda^i = \left(1 - \left(\frac{\partial}{\partial\varepsilon}\delta\Sigma^{\rm PC}(\varepsilon)\right)_{\varepsilon=\varepsilon_\lambda^i}\right)^{-1}. \qquad (4)$$

Two typical examples of S-factors in ^{204}Pb are displayed in Fig. 1. In the upper case, there is a state $|\lambda, i_0\rangle$ with dominating $S_\lambda^{i_0}$ value (a "good" SP state). In such cases, we use the following prescription for the PC corrected SP characteristics:

$$\varepsilon_\lambda = \varepsilon_\lambda^{i_0};\ Z_\lambda^{\rm PC} = S_\lambda^{i_0}. \qquad (5)$$

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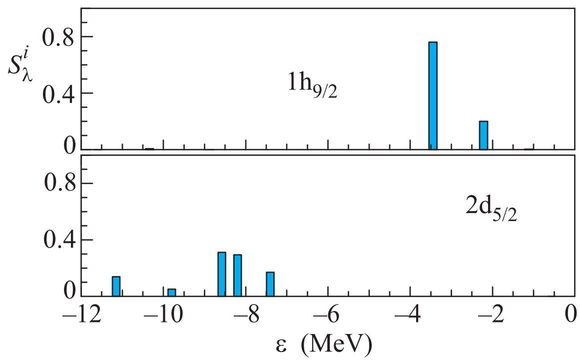

Fig. 1. (Color online) Some S-factors in ^{204}Pb

The down panel represents a case of a strong spread, and we suggest the following generalization of Eq. (5):

$$\varepsilon_\lambda = \frac{1}{Z^{PC}_\lambda}\sum_i \varepsilon^i_\lambda S^i_\lambda,\ Z^{PC}_\lambda = \sum_i S^i_\lambda. \qquad (6)$$

In both the above sums, only the states $|\lambda, i\rangle$ with appreciable values of S^i_λ are included. In practice, we include in these sums the states with $S^i_\lambda > 0.1$. The value of ε_λ is just the centroid of the single particle energy distribution.

The results for SPEs and Z-factors are presented in Table 1. We see that the tadpole correction to the SPEs is of primary importance. It confirms a tendency found previously in magic nuclei [1].

To resume, a method is developed to find the PC corrections to SPEs for semi-magic nuclei beyond the perturbation theory in the PC correction to the mass operator $\delta\Sigma^{PC}(\varepsilon)$ with respect to Σ_0. Instead, the Dyson equation with the mass operator $\Sigma(\varepsilon) = \Sigma_0 + \delta\Sigma^{PC}(\varepsilon)$ is solved directly, without any use of the perturbation theory. The method is checked for a chain of even Pb isotopes. This makes it possible to extend to semi-magic nuclei the field of consistent consideration of the PC corrections to the double odd-even mass differences and some another problems.

We acknowledge for support the Russian Science Foundation, Grants # 16-12-10155 and 16-12-10161. The work was also partly supported by the Russian Foundation for Basic Research Grants # 14-02-00107-a, 14-22-03040-ofi_m, and 16-02-00228-a. Calculations were partially carried out on the Computer Center of Kurchatov Institute.

Full text of the paper is published in JETP Letters journal. DOI: 10.1134/S0021364016210049

Table 1. PC corrected proton SP characteristics ε_λ and Z_λ of even Pb isotopes. The total correction to the SPE $\delta\varepsilon^{PC}_\lambda = \varepsilon_\lambda - \varepsilon^{(0)}_\lambda$ is presented. The corresponding tadpole correction $\delta\varepsilon^{tad}_\lambda$ is given separately

Nucleus	λ	$\varepsilon^{(0)}_\lambda$	$\delta\varepsilon^{tad}_\lambda$	$\delta\varepsilon^{PC}_\lambda$	ε_λ	Z_λ
^{200}Pb	$1i_{13/2}$	−0.26	0.39	0.13	−0.13	0.96
	$2f_{7/2}$	−1.05	0.24	−0.30	−1.35	0.83
	$1h_{9/2}$	−2.33	0.33	0.12	−2.21	0.93
	$3s_{1/2}$	−5.81	0.20	0.01	−5.80	0.89
	$2d_{3/2}$	−6.67	0.21	0.17	−6.50	0.89
	$1h_{11/2}$	−7.06	0.37	0.25	−6.81	0.93
	$2d_{5/2}$	−7.88	0.21	0.28	−7.60	0.88
	$1g_{7/2}$	−9.97	0.29	0.08	−9.89	0.91
^{202}Pb	$1i_{13/2}$	−0.74	0.41	0.13	−0.61	0.95
	$2f_{7/2}$	−1.52	0.25	−0.29	−1.81	0.83
	$1h_{9/2}$	−2.86	0.34	0.13	−2.73	0.93
	$3s_{1/2}$	−6.26	0.21	0.01	−6.25	0.89
	$2d_{3/2}$	−7.09	0.22	0.17	−6.92	0.89
	$1h_{11/2}$	−7.52	0.38	0.25	−7.27	0.93
	$2d_{5/2}$	−8.34	0.22	0.30	−8.04	0.87
	$1g_{7/2}$	−10.46	0.30	0.08	−10.38	0.91
^{204}Pb	$1i_{13/2}$	−1.21	0.32	0.14	−1.07	0.97
	$2f_{7/2}$	−2.01	0.20	−0.23	−2.24	0.87
	$1h_{9/2}$	−3.36	0.27	0.17	−3.19	0.96
	$3s_{1/2}$	−6.72	0.17	0.23	−6.49	0.84
	$2d_{3/2}$	−7.51	0.17	0.05	−7.46	0.94
	$1h_{11/2}$	−7.98	0.30	0.25	−7.73	0.95
	$2d_{5/2}$	−8.80	0.18	0.17	−8.63	0.92
	$1g_{7/2}$	−10.93	0.24	0.13	−10.80	0.95
^{206}Pb	$1i_{13/2}$	−1.67	0.30	0.07	−1.60	0.89
	$2f_{7/2}$	−2.51	0.19	−0.30	−2.81	0.82
	$1h_{9/2}$	−3.82	0.25	0.19	−3.63	0.97
	$3s_{1/2}$	−7.18	0.16	0.08	−7.10	0.89
	$2d_{3/2}$	−7.91	0.16	0.11	−7.80	0.86
	$1h_{11/2}$	−8.42	0.27	0.37	−8.05	0.88
	$2d_{5/2}$	−9.28	0.16	0.12	−9.16	0.95
	$1g_{7/2}$	−11.36	0.22	0.24	−11.12	0.90

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