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On the excitation energy of deep-hole states in medium-heavy-mass spherical nuclei

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Abstract. Within the particle-hole dispersive optical model it is shown that the spreading effect determines a significant part of the anomalously large excitation energy of deep-hole states in the ^{90}Zr and ^{208}Pb parent nuclei.

1 Introduction

An anomalously large excitation energy of deep hole states in the ^{90}Zr and ^{208}Pb parent nuclei has been experimentally found by Vorobyov et al. [1]. In most Hartree-Fock calculations exploiting different versions of Skyrme-type forces, the energy of deep-hole states in the ^{208}Pb parent nucleus is markedly underestimated (Fig. 1). The same conclusion follows from calculations exploiting a realistic partially self-consistent phenomenological mean field provided that the parameters of this mean field adjusted to describe the observable single-quasiparticle spectra near the Fermi energy [3].

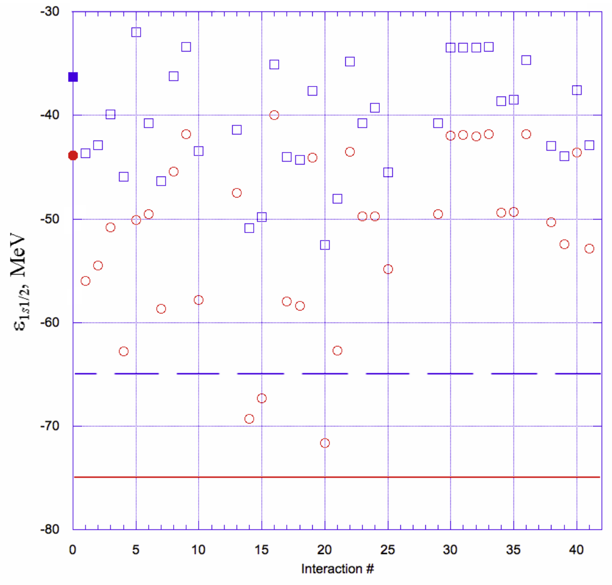

Figure 1. (Color online) The energies of $1s_{1/2}$ hole states in the ^{208}Pb parent nucleus obtained by Hartree-Fock calculations exploiting different versions of Skyrme-type forces (the circles and squares are corresponds to neutron and proton states, respectively) [2]; the filled symbols are related to the partially self-consistent mean field (PSCMF) of Ref. [3]; the dashed and solid lines corresponds to the experimental data of Ref. [1] for proton and neutron states, respectively. The meaning of horizontal axis numbers is described in Table 1.

In the present work we attempt to show that the spreading effect due to coupling of deep-hole states to many-quasiparticle configurations contributes significantly to the deep-hole state excitation energy. To reach this aim, we use the single-quasiparticle dispersive optical model (SQ-DOM) formulated in a rather formal way long ago [4]. Microscopically-based transition to the SQDOM was performed recently [3].

Table 1. Variants of Skyrme forces provided by S. Shlomo [2] and used in calculations presented in Fig. 1.

#	Interaction	#	Interaction	#	Interaction
0	PSCMF	14	SkI3	28	SkI6
1	KDE0	15	SkI5	29	SKM*
2	KDE0v1	16	SkP	30	SkT1
3	SGII	17	SLy5	31	SkT2
4	SkI4	18	SLy6	32	SkT3
5	SK0	19	SV-bas	33	SkT3*
6	SKM*	20	SV-m56-0	34	SkT8
7	SkMP	21	SV-m64-0	35	SkT9
8	SK0‘	22	SV-min	36	Skxs20
9	SkT1*	23	LNS	37	SLy7
10	SLy4	24	MSL0	38	SQMC650
11	UNEDF0	25	NRAPR	39	SQMC700
12	UNEDF1	26	SAMi	40	SV-sym32
13	Sk255	27	SIII	41	Z_sigma

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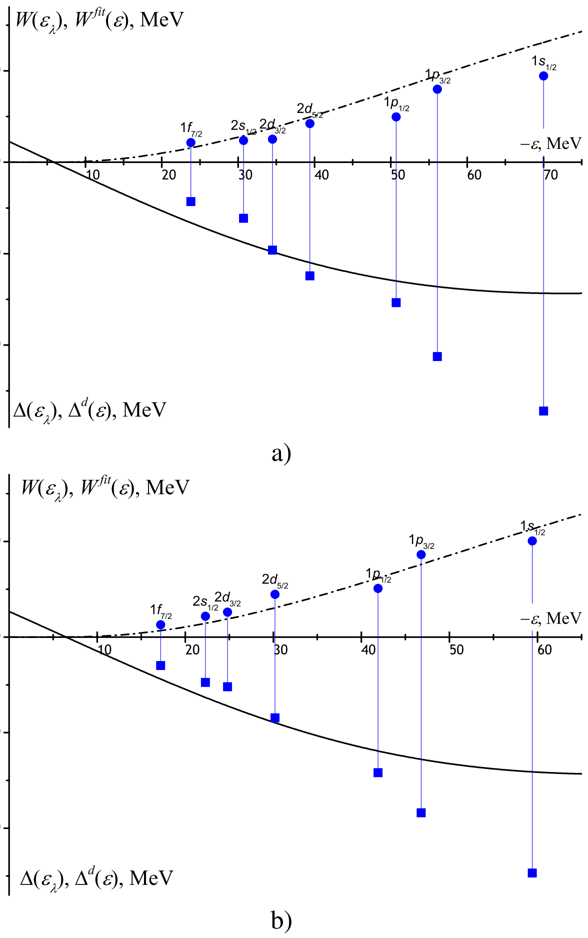

Figure 2. (Color online) The quantities $\Delta(\varepsilon_\lambda)$ (squares) and $W(\varepsilon_\lambda)$ (circles) deduced from the experimental data of Ref. [1] with the use of Eqs. (1) and (2), respectively for the neutron (a) and proton (b) one-hole states in the ^{90}Zr parent nucleus. The adopted function $W^{fit}(\varepsilon)$ of Eq. (5) and the calculated function of Eq. (2) are shown by the dot-dashed and solid lines, respectively.

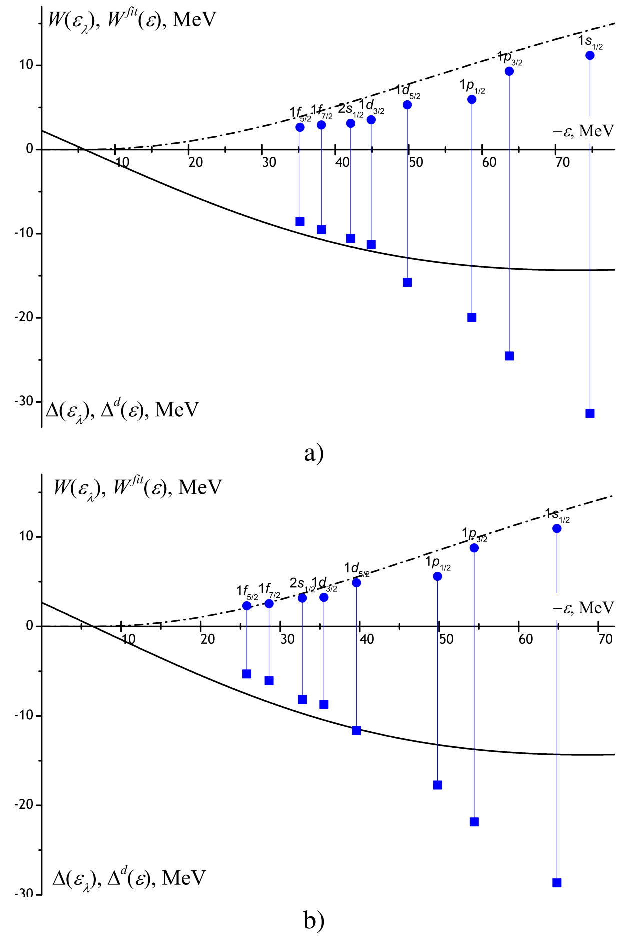

Figure 3. (Color online) The same as in Fig. 2, but for the neutron (a) and proton (b) one-hole states in the ^{208}Pb parent nucleus.

2 Basic relations

In the analysis we use, as the starting point, the phenomenological partially self-consistent mean field (described in details in Ref. [3]), which determines the single-particle (s-p) Hamiltonian $H_0(x)$. Then the optical-model Hamiltonian is (the isobaric index, on which all considered quantities are diagonal, is omitted)

$$H(x) = H_0(x) + [\mp iW(\varepsilon) + \Delta(\varepsilon)]f(x). \qquad (1)$$

Here, the signs "–" and "+" are related to single-particle (s-p, $\varepsilon > \mu$) and single-hole (s-h, $\varepsilon < \mu$) excitations, respectively; μ is the mean (for particle and holes) chemical potential; $f(x)$ is the Woods-Saxon function used also in the definition of the mean field.

In the further use of Eq. (1) it is supposed the following: (i) the energy dependence of W is similar for particles and holes, i.e. $W(\varepsilon) = W(|E|)$, where $E = \varepsilon - \mu$, and $|E|$ is the single-quasiparticle excitation energy; (ii) the real quantity Δ can be presented as the sum $\Delta^d + \Delta^p$, where the first ("dispersive") term is due to the spreading effect while the second ("potential") term simulates the mean-field energy dependence. Using the above supposition for $W(|E|)$, one gets the dispersive relationship which determines the dispersive part of Δ via W [3, 4]:

$$\Delta^d(E) = \frac{2E}{\pi} P.V. \int_0^\infty \frac{W(E')}{E^2 - E'^2} dE' \qquad (2)$$

To find the empirical function $W(|E|)$, we use, firstly, the experimental energies s-h states, ε_λ. Within the model, these energies can be calculated together with the s-h wave functions according to the equation

$$\{H_0(x) + \Delta(\varepsilon_\lambda)f(x) - \varepsilon_\lambda\}\phi_\lambda(x) = 0. \qquad (3)$$

The wave functions, $\phi_\lambda(x)$, are supposed to be normalized to unity. Thus, we can find a set of the empirical quantities $\Delta(\varepsilon_\lambda)$. As shown in Ref. [3], the function $W(\varepsilon)$ determines the spreading (in fact, total) width of s-h states according to the relationship

$$\Gamma_\lambda = 2W(\varepsilon_\lambda) \int f(x)|\phi_\lambda(x)|^2 dx. \qquad (4)$$

Using Eq.(4) together with the experimental values of s-h total widths, we can find a set of quantities $W(\varepsilon_\lambda)$.

Such a set can be adopted by an empirical function $W^{fit}(|E|)$ which is proportional to E^2 for small $|E|$, as it takes place in infinite Fermi-systems. In accordance with Eq. (2), the adopted function $W^{fit}(|E|)$ determines the dispersive part of the optical-model potential, $\Delta^d(\varepsilon)$. Being compared with the values $\Delta(\varepsilon)$, this quantity determines contribution of the spreading effect to the s-h excitation energies.

3 Calculation results

The sets of quantities $\Delta(\varepsilon_\lambda)$ and $W(\varepsilon_\lambda)$ found by the above-described way are shown in Figs. 2, 3 for neutron and proton subsystems of ^{90}Zr and ^{208}Pb. The adopted functions $W^{fit}(|E|)$ are parameterized as follows:

$$W^{fit}(|E|) = W_0 \tanh^2(E/B) \tag{5}$$

with the adjusted parameters $W_0^p = 25$, $W_0^n = 20$ and $B^p = 60$, $B^n = 70$ (in MeV). The functions $W^{fit}(|E|)$ are also shown in Figs. 2, 3. Finally, the dispersive part of the optical-model potential, $\Delta^d(\varepsilon)$, is evaluated by means of Eq. (2). For $\varepsilon < \mu$ these functions are shown in Figs. 2, 3 and compared with the sets of quantities $\Delta(\varepsilon_\lambda)$. From these comparison it follows that the spreading effect gives significant contribution to the excitation energy of deep-hole states.

In conclusion, we demonstrate abilities of the single-quasiparticle dispersive optical model to describe the spreading effect contribution to the excitation energy of deep-hole states in medium-heavy-mass spherical nuclei.

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