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TWO-CENTER HARMONIC OSCILLATOR MODEL FOR HIGHLY ASYMMETRIC FISSION

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A very asymmetric two-center harmonic-oscillator shell model with different depths of the potential wells was developed in order to study the dynamical effects on the alpha decay widths. Only the one-dimensional (the z-component) problem was considered in detail, allowing the use of a numerical procedure for finding the solution of the Schrödinger equation. It is shown that such a model enhances the amplitudes of the single particle wave functions in the vicinity of the surface of the mother nucleus relative to the corresponding single-particle wave functions of the static one-center harmonic oscillator model. Thus, the intrinsic alpha decay overlap integrals may increase values of the amplitudes.

1. *Introduction*

The fission theory was successfully applied [1–3] to alpha decay by using a phenomenological shell correction to the deformation potential energy, computed in the framework of macroscopic models [4–6], extended for the nuclear systems with different charge densities [7,8]. This kind of shell correction, inspired by Ref.

4, was utilized instead of the standard Strutinsky prescription [9], because the latter approach can be applied for an asymmetry as large as that of alpha decay of heavy nuclei.

The fission-like theory of alpha decay is also supported by a time dependent Hartree-Fock description of the decay process [10], or by models built up on the large amplitude collective motion concept [11], which propose a decay mechanism of slow shape deformation from any initial shapes configuration of the studied many-particle system through shapes that are energetically unfavoured to a shape corresponding to the two-daughter nuclei in contact. All these descriptions are based on the modifications of the self-consistent field during the decay process, i.e. on the dynamical effects on alpha decay process. Nevertheless, one can get some insight into the dynamics of the process by studying a single particle asymmetric two-center harmonic oscillator model, at least in the asymptotic regions (two separated fragments). On this basis, if the two potential wells have same depth, one can draw the conclusion [12] that alpha particle is formed from nucleons that occupy levels lying deeply below the Fermi energy, which are usually localized in the bulk, not near the nuclear surface. This is physically not acceptable [13,14].

The purpose of this paper is to present an asymmetric two-center shell model with different depths of the potential wells, chosen in such a way that during the decay process, the small fragment could be formed from nucleons that occupy levels closely lying to the Fermi energy. From such a model, we expect an enhancement of the single particle wave functions at the surface of the mother nucleus. In the previous paper [15], we separated two essential factors in the alpha decay amplitude of the reduced width: the cluster overlap and the intrinsic overlap integral (see section IV A and B of Ref. 15). The replacement of the usual one-center oscillator single particle wave function (see Eq. (50) of Ref. 15) by the two-center ones leads to an increase in the magnitude of the intrinsic overlap integral and to an enhancement of the absolute values of the alpha reduced widths, respectively. In spite of many theoretical shell model calculations [16–18], which show an agreement between experimental and theoretical absolute alpha decay rates, we believe, there are many open problems concerning the clusterization and penetration process. For instance, in Refs. 16–18 the channel radius seems to be to large in order to describe the penetration process. The barrier penetrability cannot be described by the Coulomb potential only. Finally, we conclude that our mechanism of increasing the reduced widths may shed some light on the old problem of discrepancy between the theoretically evaluated and experimentally determined absolute values of the alpha reduced widths.

2. *The potential and the nuclear shape parametrization*

As in Refs. 1–3, we consider a simple parametrization of two intersected spheres (Fig. 1a). The radius R_2 of the small fragment is kept constant $R_2 = R_{2f}$ during the deformation process of the parent nucleus A to the two separated fragments A_1, A_2, when $R \geq R_1 + R_2$. The values A, A_1 and A_2 are the nucleon numbers of the parent nucleus, the heavier and the lighter fragment, respectively, $A = A_1 + A_2$, the respective radii are $R_o = r_o A^{1/3}$, $R_1 = r_o A_1^{1/3}$ and $R_2 = r_o A_2^{1/3}$, and the separation distance is $R = R_o - R_2$.

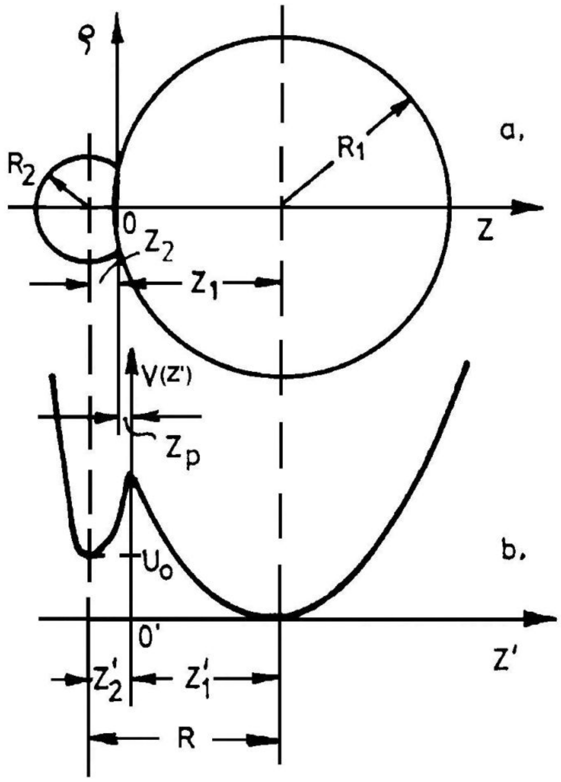

Fig. 1. A simple parametrization of two intersected spheres (see the text).

In cylindrical coordinates, the nuclear surface equation is given by

$$\rho^2 = \begin{cases} R_1^2 - (Z - Z_1)^2, & Z > 0 \\ R_2^2 - (Z - Z_2)^2, & Z \leq 0 \end{cases} , \tag{1}$$

where Z_1 and Z_2 are positions of the two centres.

A harmonic oscillator potential $V = V(Z) + V(\rho)$, for which the equipotential surface is that of two intersected spheres with radii R_1 and R_2, has the origin of the reference frame O' shifted by Z_p with respect to the intersection plane O (Fig. 1b). Therefore, the positions of the two potential minima are: $Z_1' = Z_1 - Z_p$ and $Z_2' = Z_2 - Z_p$. The potential $V(Z')$ is given by

$$V(Z') = \begin{cases} m\omega_1^2 (Z' - Z_1')^2/2, & Z' \geq 0 \\ m\omega_2^2 (Z' - Z_2')^2/2 + U_o, & Z' < 0 \end{cases} , \tag{2}$$

and the equipotential $V = V_o$ surface are two intersected spheres with radii

$$R_1 = \frac{1}{\omega_1}\sqrt{\frac{2V_o}{m}},$$

$$R_2 = \frac{1}{\omega_2}\sqrt{\frac{2(V_o - U_o)}{m}}. \tag{3}$$

Therefore,

$$V_o = m\omega_1^2 R_1^2/2 = m\omega_1^2 R_2^2/2 + U_o, \tag{4}$$

where m is the nucleon mass. The continuity of $V(Z)$ at the matching point $Z' = 0$ leads to

$$m\omega_1^2(Z_p - Z_1)^2/2 = m\omega_1^2(Z_p - Z_2)^2/2 + U_o. \tag{5}$$

The alignment of the Fermi levels for the separated small and large fragments, allow to obtain the third equation

$$\lambda_2\hbar\omega_2 + U_o = \lambda_1\hbar\omega_1, \tag{6}$$

where λ_1 and λ_2 are Fermi energies of the two fragments in units of $\hbar\omega_1$ and $\hbar\omega_2$, respectively, $\lambda_1 = 6.36$ for the proton levels of ^{212}Po and $\lambda_2 = 1.5$ for alpha particle. In this way, from. Eqs. (4)-(6) one obtains

$$\hbar\omega_1 = \left\{\lambda_1 + \left[\lambda_1^2 + (m/\hbar^2)R_1^2\hbar\omega_2(m\hbar^{-1}R_2^2\omega_2 - 2\lambda_2)\right]^{1/2}\right\}(\hbar^2/m)R_1^{-2}, \tag{7}$$

$$U_o = \lambda_1\hbar\omega_1 - \lambda_2\hbar\omega_2, \tag{8}$$

$$Z_p = \left\{\omega_2^2 Z_2 - \omega_1^2 Z_1 \pm \left[(\omega_2^2 Z_2 - \omega_1^2 Z_1)^2 \right.\right.$$

$$\left.\left. + \ (\omega_2^2 - \omega_1^2)(\omega_1^2 Z_1^2 - \omega_2^2 Z_2^2 - 2U_0/m)\right]^{1/2}\right\}/(\omega_2^2 - \omega_1^2). \tag{9}$$

For a given separation distance, R, one gets R_1, R_2 Z_1 and Z_2 from the volume conservation condition. The oscillator frequency $\hbar\omega_2$ for alpha particle proton levels, computed with $r_o = 1.2$ fm, leads to $\hbar\omega_2 = 41A_2^{-1/3}$ MeV. In this equation $\hbar\omega_2 \sim r_o^{-2}$, that means $\hbar\omega_2 = 25.8\ (1.20/1.16)^2 = 27.6$ MeV for the radius constant r_o $= 1.16$ fm. By taking into account that $\hbar^2/m \approx 41.5$ MeV fm^2, the parameters of the nuclear shape, potential and proton levels given in Table 1, have been obtained from Eqs. (7)–(9), when R was increased from $R = R_i = 5.16$ fm to $R = R_t = 8.86$ fm. The quantities of the last six columns in Table 1, will be defined in the next section.

TABLE 1.
The parameters of the nuclear shape, potential and the proton levels for alpha decay of ^{212}Po *(*R_2 *= 1.84* fm, $\hbar\omega_2$ *= 27.6* MeV, R_o *= 7.036* fm, λ_1 *= 6.36 and* λ_2 *= 1.5).*

R (fm)	Z_1 (fm)	Z_2 (fm)	Z_p (fm)	Z'_1 (fm)	Z'_2 (fm)	R_1 (fm)	$\hbar\omega_1$ (MeV)	U_o (MeV)
5.53	6.92	1.39	-0.72	7.64	2.11	7.034	8.95	15.46
6.27	6.79	0.52	1.59	5.20	-1.07	7.025	8.98	15.66
7.01	6.76	-0.25	1.06	5.70	-1.31	7.012	9,02	15.92
7.75	6.81	-0.94	0.60	6.21	-1.54	7.000	9.06	16.16
8.49	6.92	-1.58	0.19	6.73	-1.76	6.992	9.08	16.31

q	α	ξ_1	ξ_2	ξ	v_o
9.54	0.464	3.55	0.98	2.57	3.45
9.47	0.465	2.42	-0.50	2.92	3.49
9.38	0.466	2.66	-0.61	3.27	3.53
9.31	0.467	2.90	-0.72	3.62	3.57
9.26	0.468	3.15	-0.83	3.97	3.59

3. *One-dimensional Schrödinger equation*

The nuclear shape and the corresponding potential $V(\rho, Z)$ have a symmetry axis reducing the three-dimensional problem to a bidimensional one. Unfortunately, we are able to solve numerically only a one-dimensional Schrödinger equation. Consequently, we shall consider the Z-component $V(Z)$ of the potential $V(\rho, Z)$ (see Eq. (2)). We also do not include the l–s coupling. In the asymmetric regions, the known solutions of the Schrödinger equation with a three-dimensional spherical harmonic oscillator could be used.

The Schrödinger equation is

$$\frac{\mathrm{d}^2\psi(Z)}{\mathrm{d}Z^2} + \frac{2m}{\hbar^2}\left[E - V(Z)\right]\psi(Z) = 0, \tag{10}$$

where $V(Z)$ is given by Eq. (2) in which the primes are dropped. It is convenient to replace the variable Z by the dimensionless one $x = \alpha Z$ (and $\xi_i = \alpha Z_i$; $i = 1, 2$; $\xi_1 + \xi_2 = \xi = \alpha R$), where $\alpha^2 = m\omega_1/\hbar$, and to introduce the asymmetry parameter $q = \omega_2^2/\omega_1^2$. In this way, the potential and Schrödinger equation become

$$\frac{2V(x)}{\hbar\omega_1} \equiv v(x) = \left\{ \begin{array}{cc} (x - |\xi_1|)^2, & x \geq \xi_m \\ q(x + |\xi_2|)^2 + v_o, & x < \xi_m \end{array} \right. , \tag{11}$$

$$\frac{\mathrm{d}^2\psi(x)}{\mathrm{d}x^2} + \left[\epsilon - v(x)\right]\psi(x) = 0, \tag{12}$$

in which

$$\epsilon = \frac{2E}{\hbar\omega_1} \equiv 2\nu_{1n} + 1; \qquad v_o = \frac{2U_o}{\hbar\omega_1}. \tag{13}$$

For an asymmetric two-center potential (11), the solution of Eq. (10) is [19,20]

$$\psi_\nu(Z) = \begin{cases} C_{1\nu}\exp[-\alpha_1^2(Z-Z_1)^2/2]\; H_\nu[\alpha_1(Z-Z_1)], & Z \geq 0 \\ C_{2\nu}\exp[-\alpha_2^2(Z+Z_2)^2/2]\; H_\nu[\alpha_2(Z+Z_2)], & Z \leq 0 \end{cases}, \tag{14}$$

where $C_{1\nu}$ and $C_{2\nu}$ are the normalization constants and $H_\nu(Z)$ the Hermite function. Matching the wave functions $\psi_\nu(Z)$ and the derivatives $\mathrm{d}\psi(Z)/\mathrm{d}Z$ at $Z=0$, and using the relation $\mathrm{d}H_\nu(Z)/\mathrm{d}Z = 2\nu H_{\nu-1}(Z)$, we obtain easily

$$C_{1\nu}\exp(-\alpha_1^2 Z_1^2/2) H_\nu(-\alpha_1 Z_1) = C_{2\nu}\exp(-\alpha_2^2 Z_2^2/2) H_\nu(\alpha_2 Z_2) \tag{15}$$

$$C_{1\nu}\exp(-\alpha_1^2 Z_1^2/2)\left[H_\nu(-\alpha_1 Z_1)\alpha_1^2 Z_1 + 2\nu H_{\nu-1}(-\alpha_1 Z_1)\right] =$$

$$= -C_{2\nu}\exp(-\alpha_2^2 Z_2^2/2)\left[H_\nu(\alpha_2 Z_2)\alpha_2^2 Z_2 - 2\nu H_{\nu-1}(\alpha_2 Z_2)\right]. \tag{16}$$

The orthonormality condition of the functions (14), $\langle\psi_\nu|\psi_{\nu'}\rangle = \delta_{\nu\nu'}$ becomes

$$C_{1\nu}C_{1\nu'}J_{\nu\nu' Z_1} + C_{2\nu}C_{2\nu'}J_{\nu\nu' Z_2} = \delta_{\nu\nu'}, \tag{17}$$

where

$$J_{\nu\nu' Z_1} = \int_0^\infty \exp(-\xi_+^2) H_\nu(\xi_+) H_{\nu'}(\xi_+)\mathrm{d}Z,$$

$$J_{\nu\nu' Z_2} = \int_0^\infty \exp(-\xi_-^2) H_\nu(\xi_-) H_{\nu'}(\xi_-)\mathrm{d}Z, \tag{18}$$

$$\xi_+ = \alpha_1(Z - Z_1); \qquad \xi_- = \alpha_2(Z - Z_2).$$

Equations (15)-(17) form a system with three unknown quantities: $C_{1\nu}$, $C_{2\nu}$ and ν. With the help of the relation [20]

$$(\nu - \nu')\exp(-\xi_+^2) H_\nu(\xi_+) H_{\nu'}(\xi_+) =$$

$$= \frac{\mathrm{d}}{\mathrm{d}\xi_+}\left\{\exp(-\xi_+^2)\left[\nu' H_\nu(\xi_+) H_{\nu'-1}(\xi_+) - \nu H_{\nu-1}(\xi_+) H_{\nu'}(\xi_+)\right]\right\} \tag{19}$$

the expressions of the integrals (18) take the form

$$J_{\nu\nu' Z_i} = \frac{\exp(-\alpha_i^2 Z_i^2)}{\nu - \nu'}\left\{\nu H_{\nu-1}(-\alpha_i Z_i) H_{\nu'}(-\alpha_i Z_i)\right.$$

$$\left. - \nu' H_\nu(-\alpha_i Z_i) H_{\nu'-1}(-\alpha_i Z_i)\right\}, \qquad i = 1, 2. \tag{20}$$

The indeterminacy at $\nu = \nu'$ can be removed by l'Hospital's rule. We obtain

$$J_{\nu\nu' Z_i} = \exp(-\alpha_i^2 Z_i^2) \left\{ H_{\nu-1}(-\alpha_i Z_i) H_\nu(-\alpha_i Z_i) + \nu \frac{\partial H_{\nu-1}(-\alpha_i Z_i)}{\partial \nu} H_{\nu-1}(-\alpha_i Z_i) \right.$$

$$\left. -\nu \frac{\partial H_\nu(-\alpha_i Z_i)}{\partial \nu} H_{\nu-1}(-\alpha_i Z_i) \right\}, \tag{21}$$

where the formal derivatives relative to ν of the Hermite functions are given by [20]

$$\frac{\partial H_\nu(Z)}{\partial \nu} = \psi(-\nu) H_\nu(Z) - \frac{1}{4\Gamma(-\nu)} \sum_{m=0}^{\infty} \frac{(-1)^m}{m!} \psi(\frac{m-\nu}{2}) \Gamma(\frac{m-\nu}{2}) (2Z)^m, \tag{22}$$

in which

$$\psi(Z) = \frac{\mathrm{d}}{\mathrm{d}Z} \ln \Gamma(Z). \tag{23}$$

In conclusion, if we know the Hermite functions $H_\nu(Z)$ and the derivatives $\partial H_\nu(Z)/\partial \nu$, we have practically solved the problem of any two-center harmonic oscillator model for highly asymmetric fission.

4. Results

As can be seen from Table 1, the parameters q and v_o have a small range of variation during alpha decay of ^{212}Po. One can choose $q = 10$ and $v_o = 3.4$ as typical values. If $\xi_1 = 3.2$ is kept constant, the different separation distances, ξ, are obtained by varying ξ_2. In this way, the matching point $x = \xi_m$, the solution with positive sign of the second order equation,

$$(\xi_m - |\xi_1|)^2 = q(\xi_m + |\xi_2|)^2 + v_o \tag{24}$$

is usually different from zero.

The quantum numbers ν_{1n} defined in Eq. (13), obtained for $q = 10$, $v_o = 3.4$ and $\xi_1 = 3.2$ for various separation distances between the two centers (various ξ_2), are plotted in Fig. 2. This figure shows that for large separation distances, the well known sequence of the one-dimensional harmonic oscillator energy levels, corresponding to the large fragment (the daughter nucleus) $\nu_{1n}^d = 0, 1, 2, 3, 4, \ldots$, is interrupted by the levels of the alpha particle $\nu_{1n}^\alpha = 2.78, 5.94, \ldots$. The fact that these levels are localized in one or another potential well can be seen from Fig.3 in which the corresponding wave functions at $\xi_2 = 1$ and 3 are plotted. This result for $v_o = 3.4$ is compared with the preceding one [12] which corresponds to $v_o = 0$, $q = 10$ (Fig. 4). Now the alpha particle comes from a level lying at the nuclear surface as it was imposed by Eq. (6).

The fact that this is a correct result can be checked immediately by introducing three different potentials $v(x)$ in the Schrödinger equation (12). For $v(x) = x^2$, one has the following eigenvalues: $\epsilon_n = 1, 3, 5, \ldots, (2n+1), \ldots$ and $\nu_{1n} = (\epsilon_n - 1)/2 = 0, 1, 2, 3, \ldots, n, \ldots$. This is a case of the daughter nucleus, because we have used in Eq. (13) the reference energy $\hbar\omega_1$. For $v(x) = qx^2$, one can make a change of the variable by defining $\xi^2 = qx^2$. Then Eq. (12) becomes

$$\frac{\mathrm{d}^2\psi(\xi)}{\mathrm{d}\xi^2} + \left[\frac{\epsilon}{\sqrt{q}} - \xi^2\right]\psi(\xi) = 0, \tag{25}$$

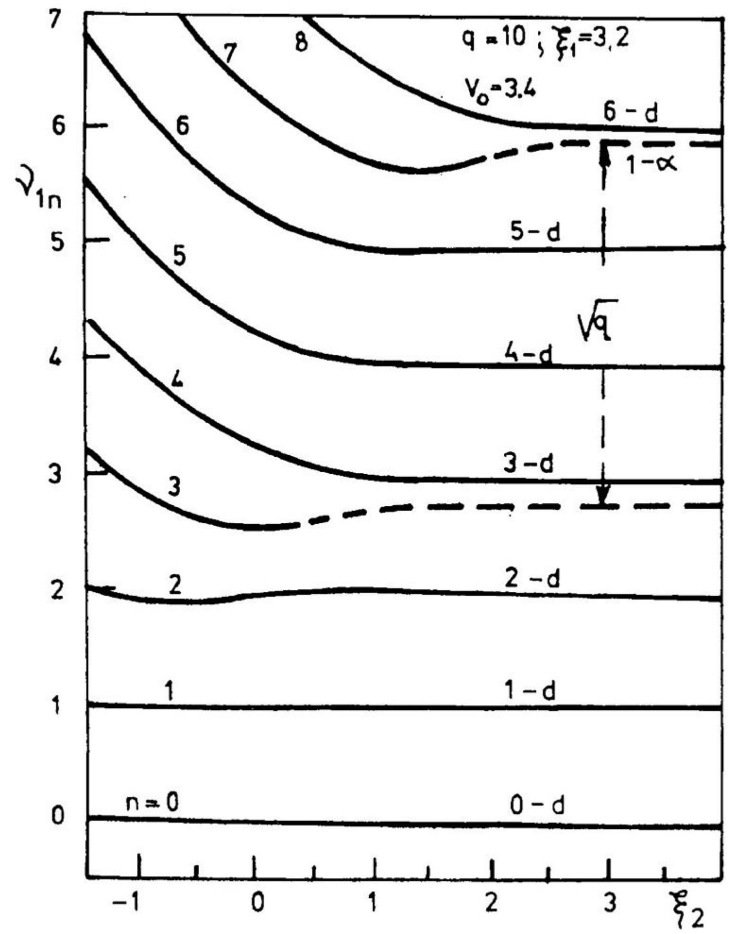

Fig. 2. The quantum numbers ν_{1n} defined by Eq. (13), obtained for $q = 10$, $v_o = 3.4$ and $\xi_1 = 3.2$ for various separation distances between the two centres (without spin-orbit and l^2-terms) for alpha decay of ^{212}Po.

and it is evident that $\epsilon_n = \sqrt{q}, 3\sqrt{q}, 5\sqrt{q}, \ldots (2n+1)\sqrt{q}, \ldots$ and $\nu_{1n} = (\sqrt{q}-1)/2, (3\sqrt{q}-1), \ldots, [(2n+1)\sqrt{q}-1]/2, \ldots$. If $q = 10$, one has $\nu_{1n} = 1.08$, 4.24, 7.40 , ... which is the case of the alpha particle for $v_o = 0$ (Fig. 4). When $v(x) = qx^2 + v_o$ the Schrödinger equation is

$$\frac{\mathrm{d}^2\psi(\xi)}{\mathrm{d}\xi^2} + \left[\frac{\epsilon - v_o}{\sqrt{q}} - \xi^2\right]\psi(\xi) = 0, \tag{26}$$

meaning that $\epsilon_\nu = \sqrt{q} + v_o, 3\sqrt{q} + v_o, \ldots (2n+1)\sqrt{q} + v_o, \ldots$; $\nu_{1n} = (\sqrt{q} + v_o - 1)/2, (3\sqrt{q} + v_o - 1)/2, \ldots$. For $q = 10$, $v_o = 3.4$, one gets exactly the alpha particle levels shown in Fig. 2: $\nu^\alpha_{1n} = 2.78$, 5.94, 9.10, ... In the same way, we can find the energy levels ϵ_n of the three-dimensional harmonic spherical oscillator with a frequency ω_1 or $\omega_2 = \sqrt{q}\omega_1$ and $v_o = 0$ or 3.4. In units of $\hbar\omega_1$, one has $\epsilon_n = N + 3/2$ for the daughter nucleus and $\epsilon_n = (N + 3/2)\sqrt{q} + v_o/2$ for the alpha particle, where the principal quantum number $N = \nu_{1n} + n_\perp$. For a given shell, N, the degeneracy is $(N+1)(N+2)$ and the magic numbers are $\sum_{N'=0}^{N}(N'+1)(N'+2) = (N+1)(N+2)(N+3)/3$. In our case, the results given in Table 2 are obtained.

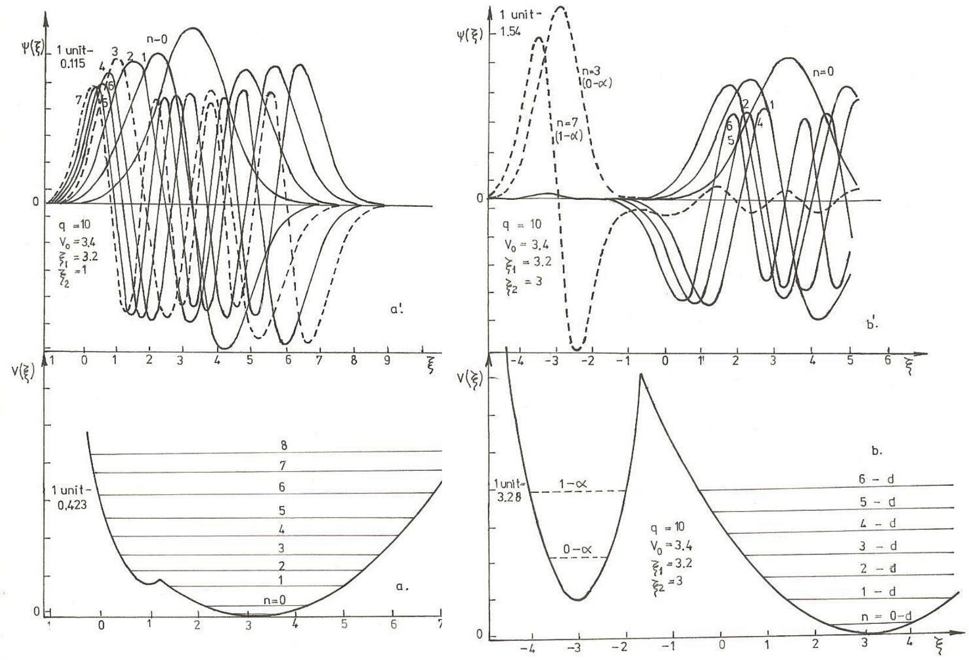

Fig. 3. (a, a') The wave functions for ξ_2 = 1 (see the text); (b, b') The wave functions for ξ_2 = 3 (see the text).

From this table one can see that the alpha particle level at 4.74 for $v_o = 0$ is lying closely to the $N = 3$ shell, but for $v_o = 3.4$ the alpha particle level at 6.44 is comparable with $N = 5$ shell in which the proton number $Z = 84$ has its Fermi level.

We conclude that such a model which simulates the nuclear dynamic effects on alpha decay enhances the single particle wave functions on the surface of the nucleous, i. e. the alpha reduced widths.

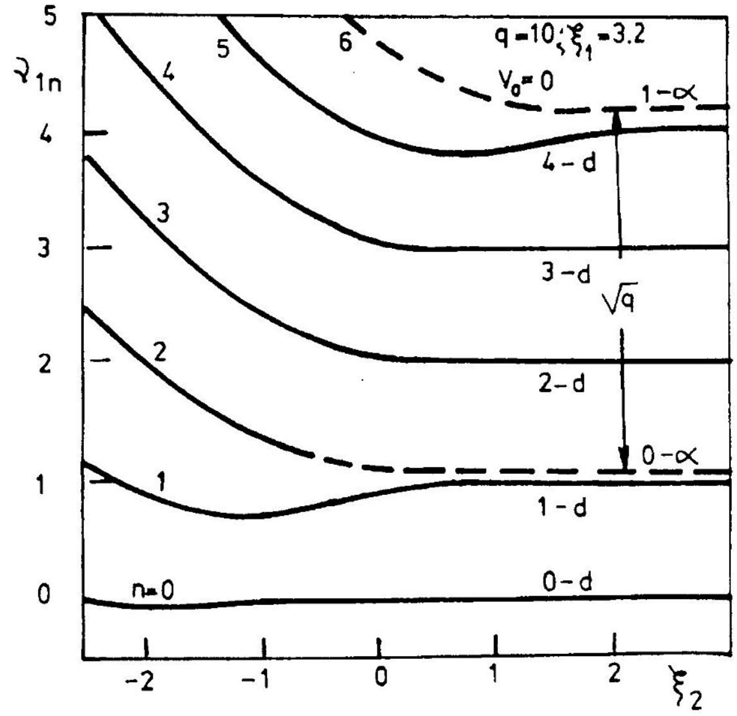

Fig. 4. The result for v_o = 3.4 is compared with the previous one [12] which corresponds to v_o = 0, q = 10, ξ_1 = 3.2.

TABLE 2.
The energy levels in units of $\hbar\omega_1$ for a three-dimensional spherical harmonic oscillator.

N	Degeneracy	Magic numbers	ϵ_n		
			$v_o = 0$, $q = 1$	$v_o = 0$, $q = 10$	$v_o = 3.4$, $q = 10$
0	2	2	1.5	4.74	6.44
1	6	8	2.5	7.90	9.60
2	12	20	3.5	11.60	12.76
3	20	40	4.5	14.22	15.92
4	30	70	5.5	17.38	19.08
5	42	112	6.5	20.54	22.24
6	56	168	7.5	23.70	25.40

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MODEL DVO–SREDIŠNJEG HARMONIČKOG OSCILATORA ZA JAKO ASIMETRIČNU FISIJU

Razvijen je ljuskasti model s vrlo asimetričnim dvo–središnjim harmoničkim potencijalom i različitim dubinama jama radi proučavanja dinamičkih učinaka na širine alfa raspada. Ograničavajući razmatranje na jednodimenzionalan problem, numerički se rješava Schrödingerova jednadžba i raspravlja ponašanje pripadne valne funkcije u blizini početne jezgre.