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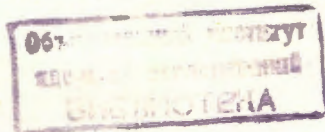
ALPHA DECAY AS  
A FERMI LIQUID PROCESS

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**ALPHA DECAY AS  
A FERMI LIQUID PROCESS**



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## Альфа-распад как ферми-жидкостный процесс

Предлагается новая модель теории альфа-распада на языке неприводимой амплитуды образования альфа-частицы в четырех-частичном канале. Была введена новая универсальная константа, определяемая связью между состоянием типа Ферми-жидкости и альфа-кластерным состоянием. Константа была получена при фитировании теоретической ширины разрешенного альфа-перехода с экспериментальными данными из распада  $^{210}\text{Ra} \rightarrow \alpha + ^{206}\text{Rn}$ . Были рассмотрены несколько разрешенных и неразрешенных альфа-переходов в районе ядер свинца. Полученные данные хорошо согласуются с экспериментом.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

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## Alpha Decay as a Fermi Liquid Process

A theory of the  $\alpha$ -decay in terms of irreducible amplitude of the  $\alpha$ -particle formation in the four particle channel ( $T_{4 \rightarrow \alpha}$ ) is proposed. By introducing a new universal constant determined by the coupling interaction between the many body Fermi liquid state and the  $\alpha$ -cluster state we have calculated the  $\alpha$ -widths for some favoured and unfavoured  $\alpha$ -transitions in the translead region. Good agreement with the experimental data is obtained.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna 1979

## 1. INTRODUCTION

An analysis of the existent  $\alpha$ -decay models<sup>/1-5/</sup> shows that the nucleus was treated therein as a Fermi gas object. This observation results from the way the  $\alpha$ -particle has been treated in these models. Thus, the constituent nucleons of the  $\alpha$ -particle either fly away independently<sup>/2-4/</sup> from the nucleus and subsequently gather together (cluster) to form an  $\alpha$ -particle, or the corresponding  $\alpha$ -width formula uses, in some way, the perturbation approach.

The R-matrix theory<sup>/6/</sup> does not get along this line, but it encounters difficulties in defining the internal region nuclear states and the channel radius which are to a great extent artificially introduced.

All these models lead to constantly lower values of the theoretical  $\alpha$ -widths with respect to the experimental data<sup>/1,2,5/</sup>.

The previous models propose themselves to transport to the continuum a group of four particles, from the mother nucleus, but they do not consider the mechanism of formation of the cluster. However, in our opinion it is more important to describe the  $\alpha$ -clustering because, once we have done it, the  $\alpha$ -decay process reduces to the well known problem of the barrier penetration:

The nuclear states involved in the  $\alpha$ -decay models are described by the shell model with residual interactions where small momenta and energies participate. The same kind of interactions were also used in perturbation theories<sup>/2-4/</sup> for the  $\alpha$ -transition operator. However, during the  $\alpha$ -decay four nucleons, initially distributed over the whole mother nucleus, undergo a transition to a state in which they occupy a small volume. Such a transition can take place with a significant probability only if large enough momenta are transferred to the four nucleons. At the same time the energy involved in the  $\alpha$ -decay is quite small. Therefore, it is clear that some other interactions must be responsible for the  $\alpha$ -particle clustering inside the nucleus. They cannot act in the frame of a Fermi gas model.

The nucleus is a system of strong interacting particles, where the mean distance between the nucleons is of the same order of magnitude as the range of the nuclear forces. This fact tells us that, the nucleus has to be treated as a Fermi liquid with strong correlations among the nucleons. The possibility of clusterization is equivalent to the coexistence of two different kinds of states in the nuclei. One kind of states describes the nucleus as a Fermi liquid drop in which the particles are more or less uniformly distributed over the whole nuclear volume. The other kind of states describes two Fermi liquid fragments ( $\alpha$ -particle and daughter nucleus) in relatively weak interaction (a cluster state).


The decay of the cluster state is allowed or forbidden mainly by the barrier.

The presence of the above-mentioned two states can be also found in the stable nuclei. Such a picture could explain why in the high energy nuclear reactions with different projectiles (p, d,  $\alpha$ , light nuclei) one can observe a large yield of  $\alpha$ -particle emission [22-24].

It is natural to assume that the clusterization is a surface phenomenon. At the nuclear surface the density is relatively low and the clusterization is favoured. The collisions of the  $\alpha$ -particle with the neighbouring nucleons far inside the nucleus lead to a very improbable existence of the  $\alpha$ -cluster in that region. The  $\alpha$ -scattering experiments are described by using a rather large imaginary part of the optical potential which shows that the  $\alpha$ -particles are melted inside the nucleus. The large incompressibility of the nuclear matter excludes the presence of inhomogeneities like  $\alpha$ -clusters far inside the nucleus.

These arguments exclude the channel state wave functions with a resonant behaviour. However, the total wave function of the system has a resonant character [1].

Assuming that the nucleus is a Fermi liquid, one can expect that the  $\alpha$ -decay is a strong collective phenomenon taking place in two steps: the clusterization and the barrier penetration. The clusterization process is a transition between the many-body Fermi liquid state to the  $\alpha$ -cluster state. The transition operator must be determined by a new quantity, namely the irreducible amplitude of the particle formation in the four particle channel [1]:

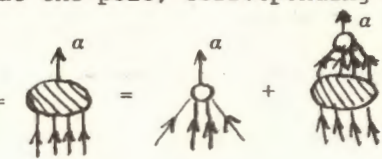
$$T_{4 \rightarrow \alpha} = \text{diagram} \quad (1)$$


An analogous situation occurs in the description of the pairing correlations in nuclei, where irreducible amplitudes [7] in the particle-particle channels are introduced.

By assuming a model for the amplitude (1) we have calculated the  $\alpha$ -widths for some favoured and unfavoured  $\alpha$ -transitions between spherical nuclei in the translead region. A unique constant determined by fitting the favoured  $\alpha$ -transition  $^{210}\text{Ra} \rightarrow \alpha + ^{206}\text{Rn}$  to the experiments was used.

## 2. MODEL FOR THE IRREDUCIBLE AMPLITUDE OF THE $\alpha$ -PARTICLE FORMATION IN THE FOUR PARTICLE CHANNEL

In the framework of the many-body theory an equation for the four particle Green function can be deduced in the usual way [7]. The equation for the residue of this Green function at the pole, corresponding to the decaying state is

$$T_{4 \rightarrow \alpha} = \text{diagram} = \text{diagram} + \text{diagram} \quad (2)$$


where

$$T_{4 \rightarrow \alpha}^{(0)} = \text{diagram} \quad (3)$$


is the irreducible four particle amplitude from which the contribution from the s.p. states around the Fermi sea is excluded.

In the following we will propose a model for  $T_{4 \rightarrow \alpha}^{(0)}$  and neglect the second term in eq. (3). The amplitude  $T_{4 \rightarrow \alpha}^{(0)}$  must have a universal character, determined by the properties of the nuclear matter (through the density dependence), i.e., by the states deep inside the Fermi sea:

$$T_{4 \rightarrow \alpha}^{(0)} \cong \kappa (e_n \cdot \nabla) \rho(\mathbf{R}) \delta(\xi_1) \delta(\xi_2) \delta(\xi_3) t. \quad (4)$$

Here  $e_n$  is a unit normal to the nuclear surface,  $\nabla$  is the gradient operator,

$$\rho(\mathbf{R}) = \langle A+4 | \hat{\rho}(\mathbf{R}) | A+4 \rangle; \hat{\rho}(\mathbf{R}) = \sum_{\mathbf{r}} \phi_{\mathbf{r}}^*(\mathbf{R}) \phi_{\mathbf{r}}(\mathbf{R}) a_{\mathbf{r}}^{\dagger} a_{\mathbf{r}} \quad (5)$$

in the nuclear matter density, where  $|A+4\rangle$  stands for the initial state wave function,  $\phi_{\mathbf{r}}$  - for the single particle wave function and  $a_{\mathbf{r}}^{\dagger}(a_{\mathbf{r}})$  - for the fermion creation

(absorption) operator of a nucleon in (from) the state  $|r\rangle$ .

$\xi_i$  are the internal Jacobi coordinates of the  $\alpha$ -particle. The  $\delta(\xi_i)$  functions describe the packing process of the four nucleons in a small volume of the order of the  $\alpha$ -particle volume. The  $t$ -operator selects the terms containing two protons and two neutrons from among the four fermion orbitals.

The constant  $\kappa$  must have a unique value for all the  $\alpha$ -transitions.

Our model is still in a preliminary stage, mainly because we have neglected the second term in eq. (2). By solving eq. (2) one could also attempt to calculate the  $\alpha$ -decay energy, but this problem is as complicated as the similar problem of the binding energy. Therefore in our calculations experimental  $\alpha$ -decay energies are used. Generally speaking, the second term in eq. (2) leads to a rescattering of the four nucleons of the cluster over the whole nuclear volume and so it can be expected to be nonessential for the  $\alpha$ -decay.

The amplitude (4) in the second quantization form can be written as follows:

$$T_{4 \rightarrow \alpha}^{(0)} = \sum_{s_4 s_a} T_{s_4 s_a}^j (R) b_{s_a}^{j\mu} A_{s_4 j\mu} \quad (6)$$

Here

$$A_{s_4 j\mu} = ((a_\nu a_\nu')_{j_p} (a_\omega a_\omega')_{j_n})_{j_\mu} \quad (7)$$

where  $\nu\nu'(\omega\omega')$  stand for the s.p. proton (neutron) orbitals, (e.g.,  $\nu \equiv \{n_\nu l_\nu j_\nu\}$ ),

$$\langle \hat{R}, \xi_a | b_{s_a}^{j\mu} | 0 \rangle = ((Y_{l_a}(\hat{R}) \psi_{s_\xi}(\xi_1, \xi_2, \xi_3))_{L_a} X_{s_p s_n s_a}(\hat{S}_1 \hat{S}_2 \hat{S}_3 \hat{S}_4))_{j_\mu} \quad (8)$$

is the  $\alpha$ -cluster wave function, where

$$\psi_{s_\xi m_\xi}(\xi_1, \xi_2, \xi_3) = \langle \beta \xi_1, \beta \xi_2, \beta \xi_3 | n_{\xi_1} l_{\xi_1} n_{\xi_2} l_{\xi_2} (l_{\xi_1} l_{\xi_2})_{l_{\xi_3}} n_{\xi_3} l_{\xi_3}; l_{\xi_3} m_{\xi_3} \rangle \quad (9)$$

is the spatial part and

$$X_{s_p s_n s_a}(\hat{S}_1 \hat{S}_2 \hat{S}_3 \hat{S}_4) = \langle \hat{S}_1 \hat{S}_2 \hat{S}_3 \hat{S}_4 | \frac{1}{2} \frac{1}{2} (S_p) \frac{1}{2} \frac{1}{2} (S_n), S_a \sigma_a \rangle \quad (10)$$

is the spin part.

The quantities  $T_{s_a j}^j (R)$  are the reduced matrix elements  $\langle S_a j | T_{4 \rightarrow \alpha}^{(0)} | S_4 j \rangle$ , when eq. (4) is used.

### 3. ALPHA DECAY WIDTH

Starting from eq. (14) of ref.<sup>1/</sup> (or eq. (15) of ref.<sup>8/</sup>) the complicated transition R-operator can be factorized by inserting the correlations in both the channel and initial state wave functions:

$$R = \Omega^{(A+a)} T_{4 \rightarrow \alpha} \Omega^{(A+4)} \quad (11)$$

The  $\alpha$ -decay width can be written<sup>1/</sup> as follows:

$$\begin{aligned} \Gamma_\alpha &= 2\pi \sum_c |\langle A+a, c | T_{4 \rightarrow \alpha} | A+4 \rangle|^2 \approx \\ &\approx 2\pi \kappa^2 \sum_c \left| \sum_{c'} \Omega_{cc'}^{(A+a)} \int_0^\infty dR u_{c'}(R) \rho'(R) g_{c'}^{s_i j_i}(R) \right|^2, \end{aligned} \quad (12)$$

where the following notation has been used:

$$|S j_\mu\rangle = \Phi_{S j_\mu} = \Omega_{S j_\mu}^+ | \vec{0} \rangle \quad (13)$$

for the nuclear state wave functions,

$$|A+a, c\rangle \equiv \eta |u_\Sigma\rangle \equiv \sum_{c'} \Omega_{cc'}^{(A+a)} A \left( \frac{1}{R} u_{c'}(R) (b_{s_a l_a}^+ \Omega_{s_f j_f}^+) \right) | \vec{0} \rangle \quad (14)$$

for the correlated channel wave function, in which  $c$  stands for the group  $\{s_a, l_a, j_f, s_f\}$  of quantum numbers and  $A$  for the antisymmetrization operator of the channel partners,

$$|A+4\rangle \equiv \Omega^{(A+4)} |BSEC\rangle \equiv \Omega_{s_i j_i}^+ | \vec{0} \rangle \quad (15)$$

for the initial state wave function,

$$\begin{aligned} g_c^{s_i j_i}(R) &= R \langle \phi_a (Y_{l_a} \Phi_{s_f j_f})_{j_i \mu_i} | \delta(\xi_1) \delta(\xi_2) \delta(\xi_3) | \Phi_{s_i j_i \mu_i} \rangle = \\ &= \sum_{s_4} R \langle s_a l_a | \delta(\xi_1) \delta(\xi_2) \delta(\xi_3) | s_4 l_a \rangle \times \end{aligned} \quad (16)$$

$$\times \langle f | [(\Omega_{s_f j_f} A_{s_4 l_a})_{j_i}, \Omega_{s_i j_i}^+] | \vec{0} \rangle.$$

We also used eqs. (4) and (6) with

$$T_{s_4 s_a}^{\ell_a}(\mathbf{R}) = \rho'(\mathbf{R}) \langle s_a \ell_a || \delta(\xi_1) \delta(\xi_2) \delta(\xi_3) || s_4 \ell_a \rangle, \quad (17)$$

where  $\rho'(\mathbf{R})$  is the first derivative of the nuclear density (5). The channel radial wave function  $u_c(\mathbf{R}) \equiv u_{c\Sigma}(\mathbf{R}) \equiv u_\Sigma$  can be obtained from the total function (14) which is a solution of the following scattering equation

$$(\epsilon - P)K(P|A + a) = 0, \quad (18)$$

where

$$P = \eta N^2 \eta^+, P + Q = 1, P^2 = P, PQ = 0 = QP, Q^2 = Q, \quad (19)$$

$$K = H + HQ \frac{1}{\epsilon - H} QH, \quad (20)$$

and /10,11/

$$N^{-2} = 1 - K = \eta^+ \eta. \quad (21)$$

From eq. (18) we can extract the equation

$$(\epsilon - N\eta^+ K\eta N) |\bar{u}_\Sigma\rangle = 0, \quad (22)$$

where we have defined a new channel radial wave function

$$|\bar{u}_\Sigma\rangle = N^{-1} |u_\Sigma\rangle \quad (23)$$

with the same normalization condition

$$\langle \bar{u}_\Sigma | \bar{u}_\Sigma \rangle = \delta(\epsilon - \epsilon') \quad (24)$$

as for the channel functions (14).

It is easy to see that the renormalized Hamiltonian  $N\eta^+ K\eta N$  from eq. (22) can be obtained by a folding procedure /9/ including the exchange terms. We can obtain afterwards the channel radial wave function  $u_c(\mathbf{R})$  by using the integral eq. (23) and the  $N$  operator /10,18/ from eq. (21).

#### 4. NUMERICAL CALCULATIONS

To compute the overlap integral  $g_c^{s_1 j_1}(\mathbf{R})$  (16) and the densities  $\rho(\mathbf{R})$  (5), we need the structure of the initial and final nuclear states (13). For the favoured (g.s.  $\rightarrow$  g.s.)  $\alpha$ -transitions in the double even nuclei we have used the BCS-wave functions. It is known that the pairing correlations are very important in  $\alpha$ -decay /11/. We included them by the following procedure /13-15/. The level scheme is recalculated for each nucleus, including all the bound levels and the quasibound levels with the widths up to 100 keV. Then, the pairing coupling constants  $G_p$  and  $G_n$  are fitted to reproduce the experimental pairing energies /12/.

It must be noticed that excluding the quasibound levels the theoretical values decrease by a factor of  $\approx 2$  /15/.

As an example of unfavoured transition we have chosen the decay of  $^{210}\text{Bi}$  to  $^{206}\text{Tl}$ , because these nuclei differ from double magical  $^{208}\text{Pb}$  by only one proton and one neutron and, thus, their structure can be fairly well described. We used the nuclear structure from ref. /16/, where the configuration mixing is introduced to reproduce the low-lying level energies and the corresponding gamma and beta transitions.

To compute the radial channel wave function we neglected the exchange terms in the folding potential (i.e.,  $N = 1$  /10,18/). Thus, for the potential occurring in the renormalized Hamiltonian of eq. (22) the direct term obtained by folding an Yukawa-type effective interaction has been analysed:

$$V_{\text{Fold}}(\mathbf{R}) = \int d^3x_1 d^3x_2 \rho_1(x_1) \rho_2(x_2) \sum_s \kappa_s(E) \frac{e^{-\mu_s |x_1 - x_2 - \mathbf{R}|}}{|x_1 - x_2 - \mathbf{R}|} = \sum_s 16\pi^2 \kappa_s(E) \int_0^\infty x_1^2 dx_1 \rho_1(x_1) \int_0^\infty x_2^2 dx_2 \rho_2(x_2) F^{(\mu_s)}(x_1, x_2, \mathbf{R}), \quad (25)$$

where

$$F^{(\mu)}(x_1, x_2, x_3) = \{ \text{sign } Z_1 (1 - e^{-\mu |Z_1|}) + \text{sign } Z_2 (1 - e^{-\mu |Z_2|}) + \text{sign } Z_3 (1 - e^{-\mu |Z_3|}) - (1 - e^{-\mu |Z|}) \} (4\mu^2 x_1 x_2 x_3)^{-1}$$

with

$$Z_1 = -x_1 + x_2 + x_3, Z_2 = x_1 - x_2 + x_3, Z_3 = x_1 + x_2 - x_3, Z = x_1 + x_2 + x_3,$$

$$\kappa_0(E) = e^2; \kappa_1(E) = 1528.75 \text{ MeV} \cdot \text{fm}; \kappa_2(E) = -784.4 \text{ MeV} \cdot \text{fm};$$

$$\mu_0 = 0, \mu_1 = 4 \text{ fm}^{-1}, \mu_2 = -2.5 \text{ fm}^{-1}.$$

The parameters  $\kappa_s(E)$ ,  $\mu_s$  were taken from ref.<sup>/19/</sup>. They were obtained by fitting the even-state G-matrix elements of the Reid interaction and assuming the odd-state interaction of a purely OPEP type. No imaginary part has been used. The case  $S=0$  ( $\kappa_0, \mu_0$ ) corresponds to the Coulomb part of the folding potential.

Unfortunately, the calculations of the channel radial function with the potential (26) are very cumbersome, therefore we compared the folding potential with the potential obtained by summing two single proton and two single neutron (fig. 1) shell model potential:

$$V_4 = 2V_p + 2V_n. \quad (26)$$

Assuming that the exchange terms from eq. (24) lead to the decrease<sup>/25,26/</sup> of the difference between the folding potential and the potential (26) in the surface region, in the calculations we have used the potential  $V_4$ .

In figs. 2 and 3 we have plotted the overlap integral (16), the derivative ( $\rho'$ ) of the nuclear density of the initial nucleus (5) and the radial channel wave function for the favoured  $^{210}\text{Ra} \rightarrow \alpha + ^{206}\text{Rn}$  and  $^{210}\text{Bi}(1^-) \rightarrow \alpha + ^{206}\text{Tl}(1^-)$   $\alpha$ -transitions using the set of Woods Saxon parameters taken from ref.<sup>/17/</sup>. These functions were also calculated with the s.p. Woods-Saxon's parameters obtained from the scattering experiments<sup>/20/</sup> and a small difference is obtained. This is shown in fig. 2 also. From these figures we conclude that the integrand from eq. (12) is relatively large in the surface region only.

The calculated ratios  $\Gamma_{\text{exp}}/\Gamma_{\text{theor}}$  for some favoured and unfavoured  $\alpha$ -transitions are given in the table. The value of the universal constant  $\kappa$  from eq. (4) fitted to

Table

The calculated  $\Gamma_{\text{exp}}/\Gamma_{\text{theor}}$  ratios with  $\kappa = 1.044 \cdot 10^7 \text{ MeV fm}^{14}$  and Woods-Saxon parameters from ref.<sup>/20/</sup>

Mother nucleus	A	$I_i^{\pi_i}(E(\text{MeV})) \rightarrow I_f^{\pi_f}(E(\text{MeV}))$	$\Gamma_{\text{exp}}/\Gamma_{\text{theor}}$
Ra	208	$0^+(g.s) \rightarrow 0^+(g.s)$	0.56
	210	$0^+(g.s) \rightarrow 0^+(g.s)$	1.00
	212	$0^+(g.s) \rightarrow 0^+(g.s)$	1.56
	214	$0^+(g.s) \rightarrow 0^+(g.s)$	2.95
Rn	202	$0^+(g.s) \rightarrow 0^+(g.s)$	0.31
	206	$0^+(g.s) \rightarrow 0^+(g.s)$	1.60
	210	$0^+(g.s) \rightarrow 0^+(g.s)$	1.56
Bi	210	$1^-(g.s) \rightarrow 1^-(0.304)$	1.54
		$1^-(g.s) \rightarrow 2^-(0.266)$	1.26
		$9^-(0.205) \rightarrow 1^-(0.304)$	7.10
		$9^-(0.265) \rightarrow 2^-(0.266)$	0.2

the favoured transition  $^{210}\text{Ra} \rightarrow \alpha + ^{206}\text{Rn}$  is equal to  $1.044 \cdot 10^7 \text{ MeV fm}^{14}$ . We can see that the calculated  $\alpha$ -widths for both favoured and unfavoured  $\alpha$ -transitions are in agreement with the experimental data. Here we have chosen the  $\alpha$ -transition, where the involved nuclear states have the best known structure. The fluctuations of the ratio  $\Gamma_{\text{exp}}/\Gamma_{\text{theor}}$  (see the table) are not large and they could be removed either by taking into account higher order terms in eq. (2) and/or by improving the description of nuclear structure and channel wave function.

Of course, calculations in the actinide region have to be done in addition. Such calculations are on the way.

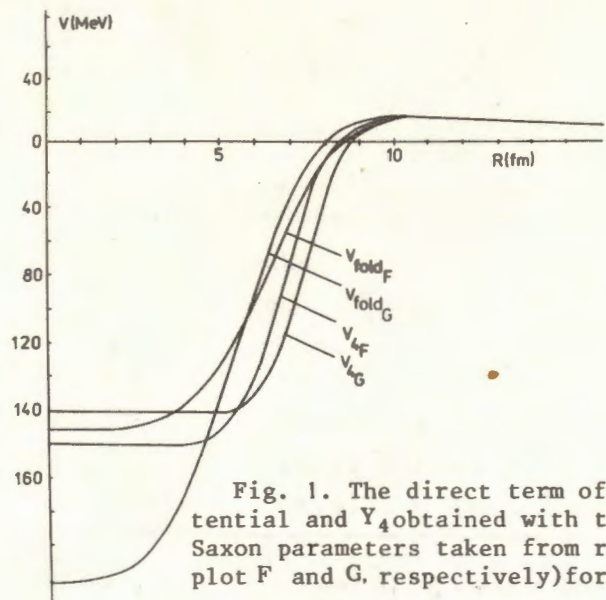


Fig. 1. The direct term of the folded potential and  $Y_4$  obtained with the set of Woods-Saxon parameters taken from refs. <sup>17,20</sup> (on the plot F and G, respectively) for the  $\alpha$ -<sup>208</sup>Pb channel.

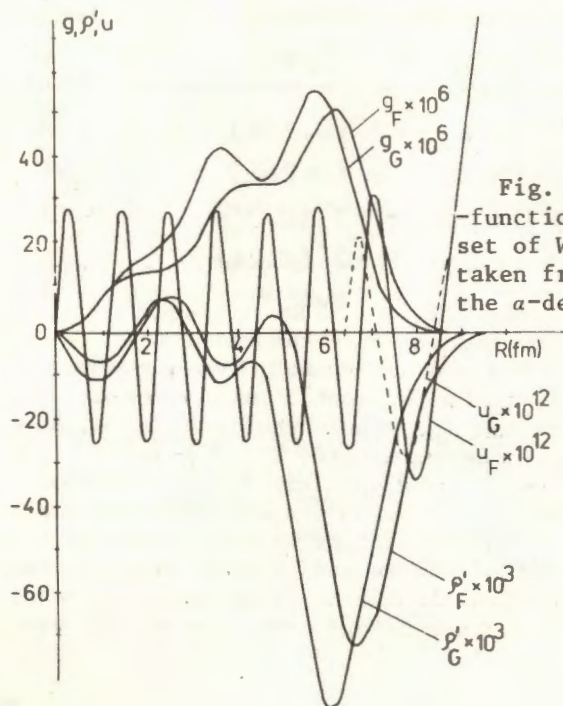


Fig. 2.  $g_c^{s_i, j_i}$ ,  $\rho'$  and  $\mu_c$ -functions obtained with the set of Woods-Saxon parameters taken from refs. <sup>17,20</sup> for the  $\alpha$ -decay of <sup>210</sup>Ra.

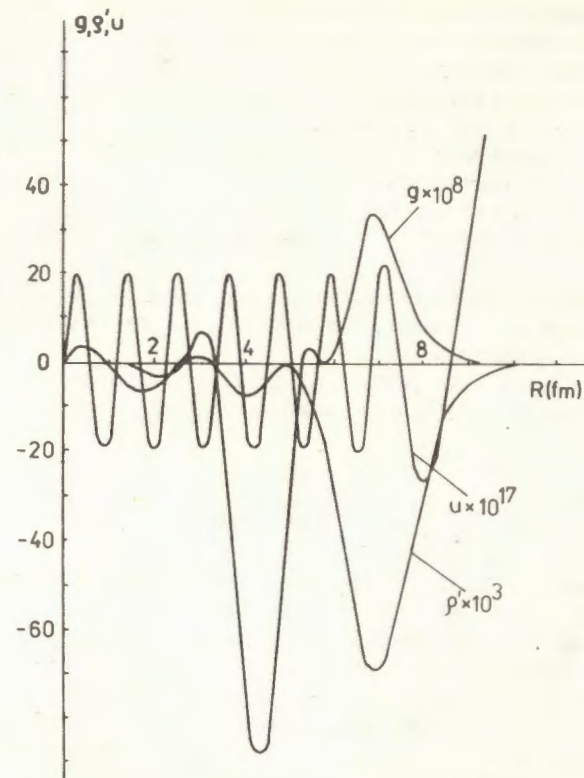


Fig. 3. The same as in the fig. 2, but with the Woods-Saxon parameters taken from ref. <sup>17</sup> for the  $\alpha$ -decay of <sup>210</sup>Bi( $1^-$ ) to <sup>206</sup>Tl( $1^-$ ).

## 5. CONCLUSIONS

In this work we have proposed a new picture to describe the  $\alpha$ -decay phenomenon. First, we assume the coexistence of two kinds of states in the nuclei: the Fermi liquid states and the cluster states. The  $\alpha$ -decay phenomenon takes place in two steps: the clusterization and the barrier penetration. The clusterization process is a (phase) transition between the Fermi liquid state and an  $\alpha$ -cluster state. The barrier penetration process is practically the way the  $\alpha$ -cluster state decays.



Our model is in a preliminary stage. The second term in eq. (2) has to be also analysed, especially to study the  $\alpha$ -decay energy. In order to be self-consistent we should also calculate the  $\alpha$ -decay energy and obtain the  $\alpha$ -decay width on this basis.

The exchange part of the folded potential might also give a significant contribution to the  $\alpha$ -decay width.

Such calculations are on the way, but they lead to complicated expression for the potential, hard to be computed

A coupled channel analysis (especially for deformed nuclei) has to be done, to obtain a realistic radial  $\alpha$ -channel function.

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