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Cold fission as cluster decay with dissipation

E. Stefanescu* and W. Scheid
Institut für Theoretische Physik der Justus-Liebig-Universität, Giessen, Germany

A. Sandulescu† and W. Greiner
Institut für Theoretische Physik der Johann Wolfgang Goethe-Universität, Frankfurt am Main, Germany

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For cold (neutronless) fission we consider an analytical model of quantum tunneling with dissipation through a barrier $U(q)$ evaluated with a M3Y nucleon-nucleon force. We calculate the tunneling spectrum, i.e., the fission rate as a function of the total kinetic energy of the fragments. The theoretical results are compared with the experimental data obtained for the fine structure of two cold fission modes of ^{252}Cf: ^{148}Ba$+$^{104}Mo and ^{146}Ba$+$^{106}Mo. Taking into account the dissipative coupling of the potential function $U(q)$ and of the momentum p with all the other neglected coordinates, we obtain a remarkable agreement with the experimental data. We conclude that the cold fission process is a spontaneous decay with a spectrum determined by the shape of the barrier and an amplitude depending on the strength of the dissipative coupling. [S0556-2813(96)03805-8]

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I. INTRODUCTION

In a recent paper [1], using Lindblad's master equation [2], we obtained an analytical expression for the spectrum of the quantum tunneling [3] through a barrier between two wells. For cold fission we considered a barrier with an internal part of a parabolic form, corresponding to a harmonic oscillator with mass m and zero-point vibration energy $E_0=\hbar\omega_0/2$, and an external part of a Coulomb form close to the height of the barrier U_M. For the decaying energy we took the Q value of the corresponding fragmentation mode. For the dissipative coupling we assumed the simplest form: an operator linear in the coordinate q and the momentum p. We showed that besides the proper tunneling with energy conservation, usually described by Gamow's formula, two additional processes are present: an environment-assisted tunneling and a spontaneous decay. This approach is based on the definition of a tunneling operator V as the nondiagonal part of the Hamiltonian in the basis of localized states $\Psi_0(q)$ inside and $\Psi_i(q)$ outside the barrier. The above effects are due to three kinds of transitions through the potential barrier, corresponding to the three spectral terms obtained from the theory of perturbations: the second-order term of the tunneling operator, the second-order mixed terms of the tunneling operator and of the dissipation operator, and the first-order term of the dissipation operator. The first term corresponds to the usual Gamow description. The second and third terms are an effect of the coupling of the physical system to the dissipative environment by its coordinate q and momentum p. We found that, for rather strong dissipation of energy in the Coulomb part of the barrier, only the last term is dominant. We stress that this term is quite different from Gamow's term, describing a very broad spectrum as it is encountered in the cold fission of some very heavy nuclei [4]. In that model the characteristics of the dissipation spectrum depend only on the shape of the nuclear barrier and on the friction parameter λ.

In the present paper, we generalize the previous results including the potential function $U(q)$ and the momentum p instead of q and p in the dissipative coupling. We evaluate the tunneling spectrum, i.e., the tunneling rate as a function of the total kinetic energy of the fragments, by assuming that the excited levels of the fragments which are not included explicitly in the calculations could be described as a dissipative environment. In this way, we reduce the whole description to a one-dimensional case, i.e., to the radial distance between the fragments. We believe that such a phenomenological description is quite appropriate for the cases when the number of the excited states of the fragments is very large and cannot be treated explicitly.

We derive a quantum master equation depending on the momentum p, on the tunneling operator V, and four openness parameters λ_{qV}, D_{qq}, D_{VV}, D_{qV}. For these four phenomenological parameters we obtain three fundamental constraints and an uncertainty relation. We calculate the tunneling spectrum and obtain dissipation terms depending on the matrix elements of the momentum p and of the tunneling operator V. We show that from the condition of the cold processes, the number of the phenomenological parameters can be reduced to only two: D_{qq} which determines the amplitude of the dissipative spectral component and D_{VV} which determines a decrease of the transition probabilities around the Q value. As a result, only transitions with energy loss are favored and the spectrum takes the shape of a large, shifted peak, very similar to the experimental spectrum. We apply our model to a fission barrier with dissipation processes associated only with the Coulomb part where the fragments get strongly accelerated behind the classical turning point. We evaluate the barrier with the M3Y nucleon-nucleon force [5] and show that the experimental spectra of some fission modes of ^{252}Cf [6] can be described by the dissipation term of the tunneling spectrum.

*Permanent address: Research Institute for Electronic Components, 72996 Bucharest, Romania.

†Permanent address: Department of Theoretical Physics, Institute of Atomic Physics, Bucharest-Magurele, P.O. Box MG-6, Romania.

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II. MASTER EQUATION FOR SYSTEMS WITH POTENTIAL DIFFUSENESS

The proper tunneling, as it was usually defined and understood [7–9], is an effect of the time evolution of the system wave function from the initial ''localized'' state Ψ_0 in the first well to the ''localized'' states Ψ_i in the second well. Evidently, the most direct method of studying such processes is based on the Schrödinger equation. This method has also been generalized for open systems by introducing additional dissipative terms in the Schrödinger equation [9], but generally, this procedure violates the uncertainty principle. The open systems cannot be rigorously described by Schrödinger-type equations, i.e., by pure states [3], because a dissipative coupling always generates transitions in any basis of states or, in other words, for such systems the Hamiltonian and the density matrix are not diagonal. An open quantum system can be described rigorously only by a master equation where, for every pair of noncommuting observables, a friction coefficient and three diffusion coefficients are introduced [2,14].

In the following we consider Lindblad's quantum master equation [10]

$$\frac{d\rho}{dt}=-\frac{i}{\hbar}[H,\rho]+L(\rho), \tag{1}$$

with the dissipation term

$$L(\rho)=\frac{1}{2\hbar}\sum_j([X_j\rho,X_j^\dagger]+[X_j,\rho X_j^\dagger]), \tag{2}$$

where the openness operators

$$X_j=b_jp+c_jV(q),\quad j=1,2, \tag{3}$$

are linear combinations of the momentum p and the tunneling operator V. The master equation (2) describes the non-Hamiltonian evolution of the system [11–14], due to the coupling of the momentum p and of the tunneling operator V [1,3], with the not explicitly considered degrees of freedom of the dissipative environment. The ''tunneling'' operator V is in fact the ''coupling'' operator from the resonance reaction theory [15], where this operator couples the eigenstates corresponding to the two parts of a potential barrier.

We should like to stress that in this way we consider an Ohmic dissipation [16] which is linear in the momentum operator, but not in the coordinate operator. More than that, in comparison to the previous dissipation introduced by the operators q and p [2], the dissipative coupling of the operator V, which essentially depends on the potential, introduces a diffuseness of the barrier due to the environment.

The Hamiltonian H is of the form

$$H=H_0+V(q),$$

$$H_0=\frac{p^2}{2m}+U_0(q),\quad V(q)=U(q)-U_0(q). \tag{4}$$

Here, H_0 is the diagonal part of the Hamiltonian H in the representation of the localized states, while $V(q)$ is a small perturbation appearing due to the many degenerate configurations of the system embedded in an environment of fission channels. This perturbation does not change the energy E_0 of the system, but introduces nondiagonal components responsible for the tunneling through the potential barrier. In [3] we showed that this operator has the matrix elements of the form

$$V_{0i}\simeq\frac{\hbar^2}{2m}[\Psi_0'(q_M)\Psi_i(q_M)-\Psi_0(q_M)\Psi_i'(q_M)], \tag{5}$$

where q_M is the coordinate corresponding to the maximum value U_M of the barrier. For the three operators of the system $q,\ p,$ and $V,$ we have the commutation relations

$$[q,p]=i\hbar, \tag{6}$$

$$[q,V]=0, \tag{7}$$

$$[p,V]=-i\hbar\frac{dU}{dq}-[p,H_0]. \tag{8}$$

With these relations and by introducing the expression (3) in (2), the operator $L(\rho)$ becomes

$$L(\rho)=L_{pp}(\rho)+L_{VV}(\rho)+L_{pV}^{\lambda}(\rho)+L_{pV}^{D}(\rho), \tag{9}$$

with

$$L_{pp}=-\frac{D_{qq}}{\hbar^2}[p,[p,\rho]], \tag{10}$$

$$L_{VV}=-\frac{D_{VV}}{\hbar^2}[V,[V,\rho]], \tag{11}$$

$$L_{pV}^{\lambda}=-\frac{i\lambda_{qV}}{2\hbar}([p,V\rho+\rho V]-[V,p\rho+\rho p]), \tag{12}$$

$$L_{pV}^{D}=\frac{D_{qV}}{\hbar^2}([p,[V,\rho]]+[V,[p,\rho]]), \tag{13}$$

where the openness parameters have the expressions

$$D_{qq}=\frac{\hbar}{2}\sum_j b_j^*b_j, \tag{14}$$

$$D_{VV}=\frac{\hbar}{2}\sum_j c_j^*c_j, \tag{15}$$

$$\lambda_{qV}=\sum_j\frac{b_j^*c_j-b_jc_j^*}{2i}, \tag{16}$$

$$D_{qV}=-\frac{\hbar}{2}\sum_j\frac{b_j^*c_j+b_jc_j^*}{2}. \tag{17}$$

From the relations (14) and (15) we notice that

$$D_{qq}\geqslant 0,\quad D_{VV}\geqslant 0. \tag{18}$$

At the same time, from a Schwartz inequality, we obtain

$$D_{qq}D_{VV}-D_{qV}^2\geqslant\frac{\hbar^2\lambda_{qV}^2}{4}. \tag{19}$$

The above three relations (18) and (19) are fundamental constraints.

We define the variances

$$\Delta_{pp}=\langle p^2\rangle-\langle p\rangle^2,\quad \Delta_{VV}=\langle V^2\rangle-\langle V\rangle^2, \tag{20}$$

$$\Delta_{pV}=\left\langle\frac{pV+Vp}{2}\right\rangle-\langle p\rangle\langle V\rangle. \tag{21}$$

From the inequality $\Sigma_j\mathrm{Tr}(\rho V_j^\dagger V_j)\geqslant\Sigma_j\mathrm{Tr}(\rho V_j^\dagger)\mathrm{Tr}(\rho V_j)$ we obtain the following uncertainty relation:

$$D_{qq}\Delta_{pp}+D_{VV}\Delta_{VV}-2D_{qV}\Delta_{pV}\geqslant\frac{\hbar\lambda_{qV}}{2i}\langle[p,V]\rangle. \tag{22}$$

Consequently, it appears that quantum tunneling with dissipation is a rather complex phenomenon which, in the approximation (3) of the openness operators X_j, is described by four phenomenological parameters satisfying four inequalities (18), (19), and (22).

This phenomenon includes two processes: a transition through the nuclear barrier with energy conservation (proper tunneling) and an excitation of the fragments when some part of the kinetic energy, corresponding to the coordinate q, is transferred to internal degrees of freedom of the fragments (spontaneous decay with dissipation).

III. TUNNELING SPECTRUM

We consider the density operator $\rho^{(0)}=|0\rangle\langle 0|$ of the initial state $|0\rangle$, corresponding to the first well and the diagonal matrix elements $\rho_{ii}(t)\doteq\langle i|\exp[(i/\hbar)H_0t]\rho\exp[-(i/\hbar)H_0t]|i\rangle$, corresponding to the states $|i\rangle$ of the second well. Taking into account the expression (4) of the Hamiltonian, the master equation (1) takes the following form in the interaction picture:

$$\frac{d\rho'}{dt}=-\frac{i}{\hbar}[V',\rho']+L'(\rho'), \tag{23}$$

where

$$\rho'(t)=\exp\left(\frac{i}{\hbar}H_0t\right)\rho\exp\left(-\frac{i}{\hbar}H_0t\right), \tag{24}$$

$$V'(t)=\exp\left(\frac{i}{\hbar}H_0t\right)V\exp\left(-\frac{i}{\hbar}H_0t\right), \tag{25}$$

$$L'(\rho';t)=\exp\left(\frac{i}{\hbar}H_0t\right)L\exp\left(-\frac{i}{\hbar}H_0t\right). \tag{26}$$

We solve the master equation (23) in a second-order approximation of the theory of perturbations of the Hamiltonian H_0 with the tunneling operator V and the dissipation operator L, taking into account that L is of second order in the matrix elements. We obtain

$$\rho'(t)=\rho^{(0)}+\rho_V'(t)+\rho_L'(t)+\rho_{VV}'(t), \tag{27}$$

where

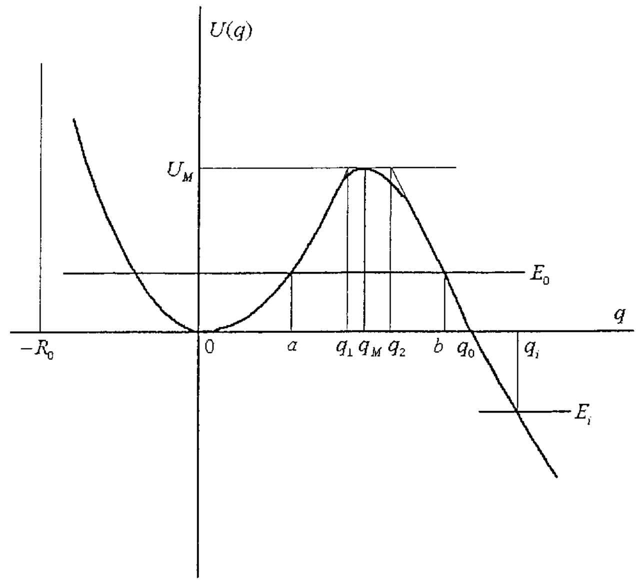

FIG. 1. The fissionlike barrier $U(q)$ with the height $U_M=U(q_M)$, with an internal part $q<q_1$, approximated by a parabola, a top part $q_1<q<q_2$, approximated by a constant, and an external part $q>q_2$, approximated by a Coulomb potential.

$$\rho_V'(t)=-\frac{i}{\hbar}\int_0^t dt'[V'(t'),\rho^{(0)}], \tag{28}$$

$$\rho_L'(t)=\int_0^t dt'L'(\rho^{(0)};t'), \tag{29}$$

$$\rho_{VV}'(t)=-\frac{1}{\hbar^2}\int_0^t dt'\int_0^{t'}dt''[V'(t'),[V'(t''),\rho^{(0)}]]. \tag{30}$$

Here we distinguish two types of additive terms: the terms depending on V, describing the usual tunneling, and the terms depending on L, describing a decay with dissipation. Using the notation (for a,b,q_M see Fig. 1):

$$s_{0i}=\int_a^b\Psi_0(q)\frac{d\Psi_i}{dq}dq, \tag{31}$$

$$\omega_i=\frac{E_i-E_0}{\hbar}, \tag{32}$$

$$\Omega_{0i}=\frac{V_{0i}}{\hbar}\simeq\frac{\hbar}{2m}[\Psi_0'(q_M)\Psi_i(q_M)-\Psi_0(q_M)\Psi_i'(q_M)]<0, \tag{33}$$

and the closure relation

$$|0\rangle\langle 0|+\sum_i|i\rangle\langle i|=1, \tag{34}$$

we obtain the transition rate from the initial state $|0\rangle$ in the first well to the state $|i\rangle$ in the second well:

$$\Gamma_{0i}(t)=\frac{\langle i|\rho'(t)|i\rangle}{t}$$
$$=\Omega_{0i}^2\frac{\sin^2(\omega_i t/2)}{(\omega_i/2)^2 t}$$
$$+2(D_{qq}s_{0i}^2+D_{VV}\Omega_{0i}^2+\lambda_{qV}\hbar\Omega_{0i}s_{0i}). \quad (35)$$

In this expression we distinguish two components of the tunneling spectrum: The first very narrow component with the width proportional to $1/t$ represents Gamow's tunneling term. The second component has a width depending on the energy variation of the transition elements of the observables and describes the spontaneous decay with dissipation. For cold processes, we assume the relation $D_{qV}=0$, similar to the thermal equilibrium condition $D_{qp}=0$ [2]. For the diffusion coefficients D_{qq} and D_{VV} we take their minimum values allowed by the relation (19). In this case the last term of the expression (35) has the form

$$\Gamma_i^D=2(\sqrt{D_{qq}}s_{0i}+\sqrt{D_{VV}}\Omega_{0i})^2$$
$$=2D_{qq}\left(s_{0i}+\eta\left|\frac{s_{0i}}{\Omega_{0i}}\right|_{\omega_i=0}\Omega_{0i}\right)^2. \quad (36)$$

In this last expression we replaced the potential diffuseness D_{VV} by the parameter

$$\eta=\sqrt{\frac{D_{VV}}{D_{qq}}}\left|\frac{\Omega_{0i}}{s_{0i}}\right|_{\omega_i=0},$$

which takes the value $\eta=1$ when $\Gamma_i^D(\omega_i=0)=0$ for any fission mode.

From the expression (35) we notice that, due to the diffusion terms which are positive, tunneling is enhanced, while due to the friction term which is negative ($\Omega_{0i}<0$), tunneling is suppressed. However, from the expression (36) we see that, due to the fundamental constraints (18) and (19), the positive diffusion terms cannot be smaller than the friction term and, as a result, the total effect of dissipation consists in an enhancement of the quantum tunneling.

In our application we have taken the fact into account that the potential barrier depends on the deformations of the fragments and that these deformations depend on the excitations of the fragments. Here we consider a potential barrier for fragments in the ground state, so that the only coordinates, taking energy in the fragmentation process without altering the barrier, are the rotational ones. We consider an experiment where the rotational levels are populated during the fragmentation process (side feeding) and after that, the fragments decay by emission of γ rays with energies corresponding to the energy differences between these levels (γ-ray cascades).

IV. DECAY THROUGH THE FISSION BARRIER

In this paper we use an analytical model, where only some essential parameters of the barrier (Fig. 1) are considered [1]: the zero-point vibration energy $E_0=\hbar\omega_0/2$, the height of the barrier U_M, the Q value, the reduced mass m, the electric charges Z_1e, Z_2e, and the "initial" distance between the fragments, $R_0\approx\frac{3}{4}R$, where R is the radius of the initial nucleus.

In this case, it is supposed that the barrier $U(q)$, $q=r-R_0$, has an internal part of a parabolic form,

$$U(q)=\frac{m\omega_0^2q^2}{2} \quad \text{for } q\in(-\infty,q_1), \quad (37)$$

a plateau

$$U(q)=U_M \quad \text{for } q\in(q_1,q_2), \quad (38)$$

and a Coulomb part

$$U(q)=Q'\frac{q_0-q}{R_0+q} \quad \text{for } q>q_2, \quad (39)$$

where $Q'=Q-E_0$, $q_0=r_0-R_0$, $r_0=\beta/Q'$, $\beta=KZ_1Z_2$, and $K=e^2/4\pi\epsilon_0$. From these relations we can determine the turning points $a=\alpha^{-1/2}$ where $\alpha=m\omega_0/\hbar$, $b=\beta/Q-R_0$, and the limits of the plateau $q_1=(U_M/\alpha E_0)^{1/2}$, $q_2=\beta/(Q'+U_M)-R_0$. We also consider the value $q_M\in(q_1,q_2)$ where the "real" barrier reaches its maximum value U_M.

Calculating the actual potential with the double-folding integrals of the M3Y nucleon-nucleon force in steps of 0.1 fm in the domain from the maximum to the Coulomb part of the barrier, we obtain an almost perfect correspondence with the analytical model. The actual barrier is very sharp (with a width $\simeq 1-2$ fm), and only near the point of the maximum of the potential do we find small deviations from the Coulomb curve. At the same time, the parabola considered for the inner part of the barrier goes nearly up to the maximum value of the potential. In fact we do not know exactly this part. The only approximate part of this model, the constant plateau around the maximum value U_M of the barrier (see Fig. 1), does not alter the results.

Using the potential determined with the double-folding procedure of the M3Y nucleon-nucleon force [5], we calculate the WKB wave functions for two fission modes of ${}^{252}_{98}$Cf: ${}^{148}_{56}$Ba+${}^{104}_{42}$Mo and ${}^{146}_{56}$Ba+${}^{106}_{42}$Mo. With these two wave functions $\Psi_0(q)$ and $\Psi_i(q)$ we calculate the matrix elements (31) and (33). With these matrix elements we can obtain the transition rates $\Gamma_{0i}(t)$ from the expression (35). This expression contains two terms: The first term, depending on time, describes the proper tunneling with energy conservation, while the second term, constant in time, describes transitions through the potential barrier due to the dissipative part of the master equation. However, the experimental data do not contain events with energy conservation corresponding to the proper tunneling, but only events with energy loss described by the second term of the expression (35) or (36). This term describes transition processes $|\Psi_0\rangle\rightarrow|\Psi_i\rangle$ when, at the same time, some part of the energy is transferred to rotational levels (side feeding).

We compare the decay spectra obtained from the expression (36) with the experimental side feeding of the rotational levels of the fragments which give information on the direct population of these levels by cold fragmentations of ^{252}Cf and on the γ cascades from the excited levels of each fragment [6]. The experimental side feedings of the rotational

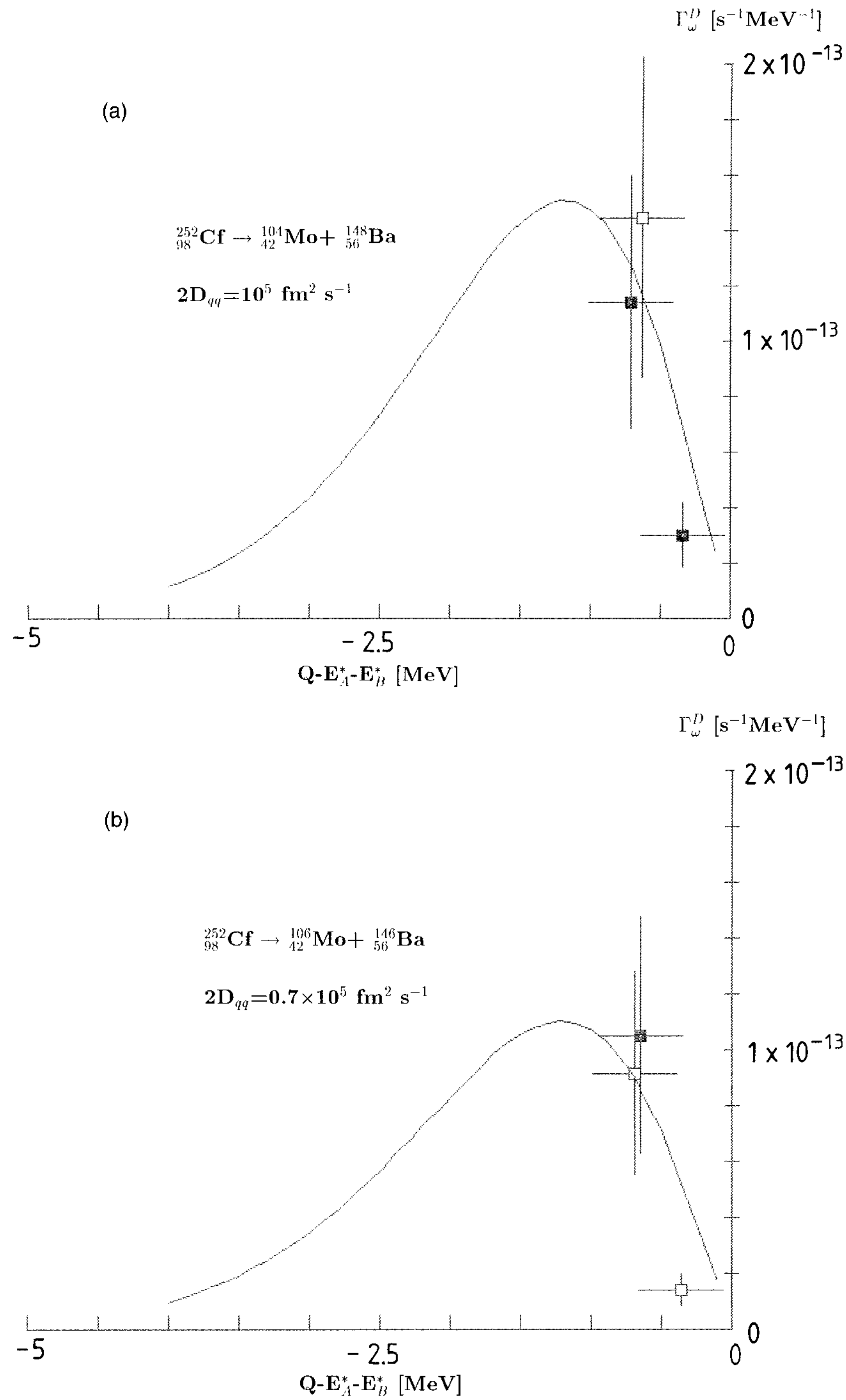

FIG. 2. Comparison of the calculated spontaneous decay spectrum $\Gamma_\omega^D = (1/\hbar\Delta\omega)\Sigma_i\Gamma_i^D$ $[\omega_i \in (\omega - \Delta\omega/2, \omega + \Delta\omega/2)]$ with the experimental fine structure data for two cold fission modes of $^{252}_{98}$Cf: (a) ^{104}Mo+^{148}Ba, (b) ^{106}Mo+^{146}Ba. The open (solid) squares correspond to the heavy (light) two fragments A (B) with the corresponding total kinetic energy $Q - E_A^* - E_B^*$, where E_A^*, E_B^* are the excitation energies of the heavy and respectively the light fragment. From the present theory we expect decays to larger excitation energies. Up to now, experimentally the rotational bands have been mainly observed. Probably the states with a larger spin are not observed since in cold fragmentations we expect that only states with very low spin are populated.

levels for the two fission modes of ^{252}Cf are obtained as differences of the γ-ray intensities corresponding to the transitions populating and depopulating these levels.

We should like to mention that for neutronless (cold) fission, only the first two to three rotational levels are populated. This indicates that, as we expected, the fragmentation process is along the symmetry axis and very slow. When two to four neutrons are emitted, more rotational levels are populated, namely, up to angular momenta 8–10 $\hbar$ [19]. Consequently, the present experimental data [6] confirm directly the cold fragmentation process. The present cold fission yields are very large, about 10^{-3}. Consequently, these yields sum up all the cold fragmentations from higher excited states. Probably, the γ cascades to the ground states are populating only the levels with low spin values.

In Fig. 2 we represent the spectrum of the total kinetic energy together with the theoretical results obtained from the expression (36) with $\eta = 1$ for which we obtain minimum values close to zero excitation energy. The experimental values represent the fission rates on the rotational levels (fine structure) or the level populations for a fission half-life $\tau_{\mathrm{Cf}} = 2.54$ yr and for the branching ratios B for the two fragmentation modes: $B(^{148}\mathrm{Ba} + ^{104}\mathrm{Mo}) = 7.7 \times 10^{-4}$ and $B(^{146}\mathrm{Ba} + ^{106}\mathrm{Mo}) = 5.6 \times 10^{-4}$. With the free parameter D_{qq} we fit the amplitudes. The coefficient D_{qq}, being proportional to the amplitude of the spectrum, could be considered as an intensity of the dissipative coupling, while the coefficients b_j in expression (14) of D_{qq} are the coupling coeffi-

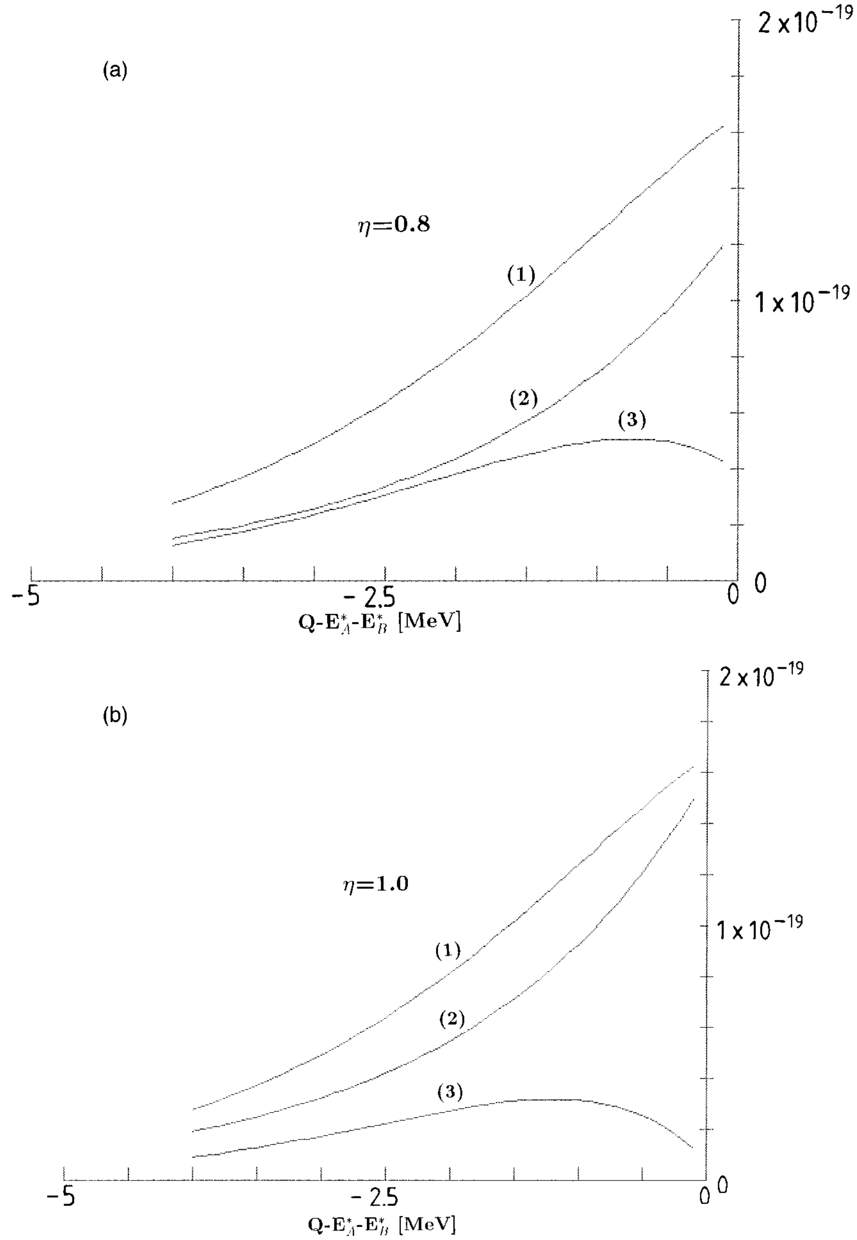

FIG. 3. The term $s_{0i}+\eta|s_{0i}/\Omega_{0i}|_{\omega_i=0}\Omega_{0i}$ [curve (3)], giving the shape of the decay spectrum Γ_i^D, is obtained as a difference of the two terms s_{0i} [curve (1)] and $\eta|s_{0i}/\Omega_{0i}|_{\omega_i=0}|\Omega_{0i}|$ [curve (2)] (calculations for the fission mode ^{252}Cf$=^{148}$Ba$+^{104}$Mo): (a) $\eta=0.8$, (b) $\eta=1.0$, (c) $\eta=1.2$.

cients or ''amplitudes'' of the momentum p with the dissipative environment according to expression (3). We use the notation with the indices q for this parameter resulting from the coupling coefficients of p because the variance of the coordinate q is proportional to D_{qq} [2,14].

The form of the spectrum entirely depends on the shape of the barrier. The upper limit of the spectrum depends on the variation with the transition energy of the tunneling matrix element Ω_{0i}, while the lower limit depends on the variation of the matrix element s_{0i} with the energy. In order to understand such a behavior we represent the two matrix elements and the sum

$$s_{0i}+\eta\left|\frac{s_{0i}}{\Omega_{0i}}\right|_{\omega_i=0}\Omega_{0i}$$

in Fig. 3. We notice that the shape of this peak in Fig. 3 is due to a slower variation of the transition element s_{0i} with the final energy E_i than the variation of the transition element Ω_{0i}. As one can notice from expression (36), the spectrum depends on two parameters: the diffusion coefficient D_{qq} and the parameter η or, equivalently, the potential diffuseness D_{VV}. These two parameters are independent in the frame of Lindblad's theory of open systems, and consequently, we could have spectra with various values of η for a given D_{qq}. However, experimentally we obtain only spectra with very low transition rates in the neighborhood of the point $E_i=0$, when $\eta=1$ [Fig. 3(b)].

In Fig. 2 we notice that the theoretical results indicate transition rates to energies much lower than the energies experimentally obtained. Such transitions really exist [17,18], but they correspond to processes with neutron emission, i.e., to fragments with other deformations for which the potential barrier is no longer the same. In the experiment considered in [17] and [18] only one fragment was measured [19,20], the other fragment being merely considered his partner, and, in this case, rotational levels up to angular momenta 8–10 $\hbar$ were obtained. In the new experiment [6], when both frag-

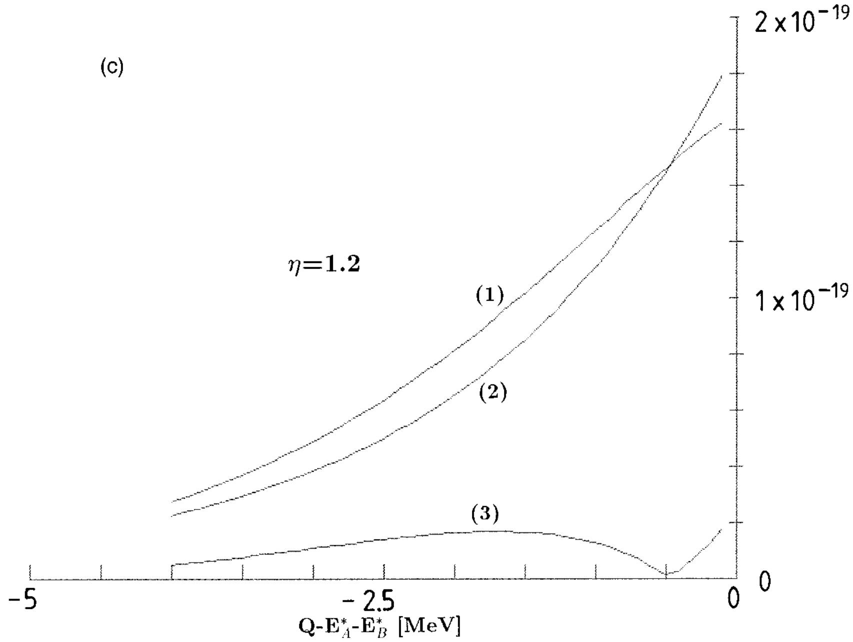

FIG. 3 (*Continued*).

ments were measured, only rotational levels up to 2–4 $\hbar$ were observed. It seems that the fragments with higher angular momenta correspond to partners emitting neutrons. We conclude that this discrepancy appears only due to the nature of this barrier which depends on the shape of the final fragments, not due to the model adopted which is correct for a single barrier. When the total kinetic energy loss increases over a certain limit, the excitation energy takes a value that neutrons are evaporated and, as a result, these events are eliminated in this experiment with measurements in triple coincidence, identifying both fragments.

V. CONCLUSIONS

In this paper we show that due to dissipation the proper tunneling with energy conservation can be covered up by the spontaneous decay with a shifted spectrum. This process is an effect of the dissipative coupling of the momentum p and of the potential function $U(q)$. Although for these operators friction and diffusion processes are present, the diffusion is dominant due to the fundamental constraints, leading to an enhancement of the tunneling process. From the comparison of the theoretical results with the experimental data we conclude that the cold fission rate is determined by the coupling of the observables p and V with the rotational coordinates of the fragments, treated in this paper as a dissipative coupling. Evidently, the theoretical spectrum, calculated for a certain barrier, describes the experimental data only in the energy domain corresponding to this barrier. When the excitation energy leads to neutron evaporation, the matrix elements must be recalculated for the corresponding new barrier. New measurements of γ transitions in odd-odd configurations will allow us to develop a new kind of nuclear spectroscopy with heavy fragments.

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