SPLASHING OUT – A POSSIBLE MECHANISM OF PREEQUILIBRIUM EMISSION

S.T. BELYAEV and B.A. RUMYANTSEV
Institute of Nuclear Physics, Novosibirsk, USSR

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A dynamical model of preequilibrium emission is suggested which predicts and enables one to calculate the correlation effects, e.q. the angular anisotropy with forward-backward symmetry, the energy – and angular – correlations of secondaries in (n, 2n) reaction.

1. Statistical (evaporation) energy and angular isotropy of secondaries (for not very large angular momenta transferred) are characteristic peculiarities of compound nucleus reactions. Experimental spectra demonstrate more and more clearly deviations from this picture which on the other hand cannot be attributed to accompanying direct reactions[‡1]. That is why the search of nuclear reaction mechanisms occurring at the compound-nucleus-formation stage (preequilibrium emission) is of interest. In the model of Griffin [1] the compound nucleus formation is considered as consecutive stages of partial equilibrium (e.g. first of two particles one hole (2p1h), then in (3p2h)-space and so on). The relative phase space in the continuum determines emission at each stage. Qualitatively this model predicts an increased fraction of fast particles[‡2] but (due to its statistical nature) not an angular asymmetry. To account for the latter as well as other correlation effects one needs more detailed dynamical models of preequilibrium emission.

2. Here we want to stress that the very fact of a projectile capture is necessarily accompanied by coherent (non-statistical) excitation of two-quasiparticle collective states [2]. We shall call this mechanism "splashing out".

The effect is in a way similar to bremsstrahlung generation during the capture of a charged particle. The capture itself, irrespective of its mechanism, varies the current (the generalized characteristic of the system as a whole) causing radiation. For the reaction via compound nucleons statistical relaxation of the initial capture state ("heating" of the system) is inevitably accompanied by the rearrangement of the selfconsistent field (the generalized characteristic of the nucleus) which in its turn causes a dynamical excitation of two-quasiparticle (collective) modes. In this case (in contrast to the bremsstrahlung) statistical and dynamical mechanisms of excitation act in the same system. Thus one can speak of independent excitation of those collective (two quasiparticle) modes whose interaction with the "thermal background" is sufficiently small. Here we consider only particle-hole modes with a particle in the continuum ("preequilibrium emission"). A real collective excitation in discrete spectrum will be considered separately (see [3]).

3. Let $\delta U(\alpha,t)$ be a distortion of the self consistent potential caused by the formation of a compound nucleus via the entrance channel α. Then the probability to excite the particle-hole state $|\omega\rangle$ with energy ω is ($\hbar = 1$)

$$P(0 \to \omega) = \left| \int_{-s}^{\infty} \mathrm{d}t \exp(-\mathrm{i}\omega t) \langle \omega | \delta U(\alpha,t) | 0 \rangle \right|^2 . \quad (1)$$

If ω is only a small fraction of the total excitation energy[‡3], then the non-statistical correction to the reaction cross section $\sigma(\alpha|\alpha')$ can be approximated as

$$\delta\sigma(\alpha|\alpha') = \sigma_c(\alpha) P(0 \to \omega_{\alpha'}) \quad (2)$$

‡1 Angular anisotropy with forward-backward symmetry, an excess of fast particles.

‡2 A large number of free parameters (choice of the first stage, independent normalization of the spectrum at each stage) hamper quantitative predictions.

‡3 The opposite case is reached in the semidirect process [4] when the particle-hole mode exhausts the main part of the excitation energy and the "thermal-background" is reduced to a neutron (captured) on one of the orbitals.

where $\sigma_c(\alpha)$ is the capture cross section via the channel α.

To make the next step we have to analyse the time dependence and the structure of the distortion potential δU. The compound nucleus formation can be qualitatively described as follows. Very fast (during the time $\tau_e \sim r_0/v_F \sim \epsilon_F^{-1}$ where r_0, ϵ_F, v_F are the range of the forces, energy and velocity at the Fermi-surface) the projectile is captured by the nucleus.

After the period of the intrinsic nucleon motion $\tau \sim R_0/v_F \sim A^{1/3}/\epsilon_F$ the capture will be felt by all nucleons. So the time τ can serve as a measure of the increment of the distortion field δU, which then relaxed slowly ($\tau_r \sim \Gamma_{s.p.}^{-1} \sim A^{2/3}/\epsilon_F$) to the statistical equilibrium. Such a time-variation of δU can easily produce a particle-hole excitation up to the energy $\omega = \epsilon_p + \epsilon_h \lesssim \tau \sim \epsilon_F A^{-1/3}$.

From (1) and (2) one gets for the reaction of the type of (n,n').

$$\delta\sigma(\epsilon)\,\mathrm{d}\epsilon \approx \sigma_c \sum_h \frac{|\langle \mathrm{ph}|\delta U|0\rangle|^2}{(\epsilon_p+\epsilon_h)^2+\tau_r^{-2}}\,\Theta((\epsilon_p+\epsilon_h)\tau)\,\rho(\epsilon)\,\mathrm{d}\epsilon \tag{3}$$

where $\rho(\epsilon)$ is the density of states in continuum ($\epsilon_p = B + \epsilon$, B is the binding energy), the function $\Theta(x) \approx 1$ for $x \leqslant 1$ and decreases rapidly for $x > 1$. For a rough estimate we take $\delta U \sim U/A \sim \epsilon_F/A$ $\epsilon_p + \epsilon_h \sim \epsilon_F/A^{1/3}$; $\Sigma_h \ldots \to \ldots xA^{1/3}$. Then for the ratio of the cross sections of the (n,n')-reaction via our mechanism ("splashing out") and the usual one ("evaporation") we find

$$\sigma_{spl.}/\sigma_{ev} \approx (T/\epsilon_F)^{3/2}(T/\epsilon)^{1/2}\exp(\epsilon/T) \tag{4}$$

giving dozens of percent for $\epsilon/T \sim 3-5$ (T is the nucleus temperature).

4. The initial distortion of the selfconsistent field δU naturally depends on the quantum numbers of the entrance channel. This fact results in angular anisotropy and other correlation effects in the cross section (3). Let δU be expanded in spherical harmonics

$$\delta U = \sum_{lm} \delta U_{lm}(k_i)\, Y_{lm}(n) \tag{5}$$

where the tensor δU_{lm} is constructed with the use of the projectile momentum k_i. From eqs. (3), (5) one gets the expression of the form

$$\frac{\mathrm{d}\delta\sigma}{\mathrm{d}k_f} = \sum_{l=0}^{l_{max}} \delta\sigma_l(k_i;k_f)\,P_l(\cos\theta) \tag{6}$$

where k_f is the momentum of the outgoing particle, $\cos\theta = (k_i k_f)/k_i k_f$, $l_{max} = 2k_f R_0$. Note that odd Legendre polynomials in eq. (6) arise only from the interference of harmonics with different parity in expanison (5).

5. The capture of the projectile results in the distortion not only of the average nuclear field but of the pairing potential as well. The latter is equivalent to the "external perturbation" of the form (ν and $\tilde{\nu}$ are time conjugated states)

$$\delta\Delta = \sum_{\nu\nu'} \langle\nu|\delta\Delta(r)|\nu'\rangle\, a_\nu^+ a_{\tilde{\nu}'}^+ + \mathrm{h.c.}$$

capable of "splashing out" the nucleon pair. If the distortion $\delta\Delta(r)$ is assumed to be of δ-surface type (Δ_0 = const inside the nucleus) then the probability to emit the neutron pair with momenta k and k' is given by

$$\frac{\mathrm{d}P(k|k')}{\mathrm{d}k\,\mathrm{d}k'} = \frac{|\langle k|\delta\Delta(r)|-k'\rangle|^2}{(\epsilon+\epsilon')^2+\tau_r^{-2}} \sim j_0^2(qR_0). \tag{7}$$

Here $q = |k + k'|$ and $j_0(x)$ is the spherical Bessel function. Eq. (7) shows that emitted particles are correlated with each other (equal energies and opposite directions are preferable) but not with the projectile.

6. For a numerical calculation one needs a more precise definition of the distortion potential δU. Neglecting relaxation processes one may use time-dependent Hartree-Fock approximation for the density matrix ρ

$$\mathrm{i}\delta\dot{\rho} = [S(\rho);\rho]; \qquad S_1(\rho) = \epsilon_1 + \mathrm{Tr}_2(V_{12}\rho_2). \tag{8}$$

Here $S(\rho)$ is the selfconsistent HF-Hamiltonian, V_{12} the two-nucleon interaction. Using the stationary solution $[S(\rho^0);\rho^0] = 0$ as the basic approximation we obtain for the time-dependent correction $\delta\rho(t)$

$$\mathrm{i}\delta\dot{\rho} = [\rho^0;\delta\rho] + [S(\delta\rho);\rho^0]. \tag{9}$$

Let ρ^0 and S^0 be referred to the initial (say, even-even) nucleus. Then eq. (9) describes both corrections due to the extra nucleon $\delta\rho'(t)$ and to the collective excitation of the even-even core $\rho_n \exp(-\mathrm{i}\omega_n t)$ (in

RPA). The general solution of eq. (9) is of the form

$$\delta\rho(t) = \sum_n a_n \rho_n \exp(-i\omega_n t) + \delta\rho'(t). \quad (10)$$

We are interested in the solution of (10) with the initial condition at $t = 0$, when $\delta\rho(0)$ describes the captured nucleon[‡4]. Then the quantity a_n is the amplitude of probability for the eigen mode n of the core with the energy ω_n to be excited during the capture.

After simple calculations we find[‡5]

$$a_n = -i \int_0^\infty dt \, \mathrm{Tr}(\delta S(t)\rho_n) \exp(-i\omega_n t - \gamma t); \quad \gamma = +0 \quad (11)$$

$$\delta S_1(t) = \mathrm{Tr}_2(V_{12}\delta\rho_2(t))$$
$$\delta\rho(t) = \exp(-iS^o t)\delta\rho(0)\exp(iS^o t) \quad (12)$$

For comparison with eq. (3) one has to identify ρ_n with the wave functions of the particle-hole pair (with the particle in the continuum).

7. All the information on the entrance channel is contained in the quantity $\delta\rho(0)$, specified by the dynamics of the capture process. However, a reasonable parametrization of $\delta\rho(0)$ can be obtained in the quasiclassical approximation. If $\delta\rho(0)$ arise from the capture of a projectile with the momentum $\boldsymbol{k}$ it can be represented as

$$\delta\rho(r|r') = \exp(i\boldsymbol{k}(r-r'))\delta\rho(\boldsymbol{k}/R); \quad R = (r+r')/2 \quad (13)$$

where $\delta\rho(\boldsymbol{k}|R)$ is in fact the distribution function. Assuming for simplicity the absorption at the surface ($R = R_o$) we obtain

$$\delta\rho(r|r') = \frac{\delta A}{4\pi R_o^2}\delta(R - R_o)\exp(i\boldsymbol{k}(r-r')) \times \sum_l [\Sigma_l(kR_o)/\Sigma_o(kR_o)]\, P_l(\cos\theta)$$

where θ is the angle between $\boldsymbol{k}$ and the radius to the "capture point" at the surface. The quantities Σ_l are proportional to the attachment coefficients. The right hand side of eq. (14) is normalized over the nucleon number in the projectile δA. Using eq. (14) as the initial distortion $\delta\rho(0)$ one can find then the probability of the preequilibrium splashing out from eqs. (11) and (12).

8. A few remarks should be made in conclusion. (i) The results obtained are formally valid for projectiles with energy high enough when the main part of the excitation energy is spent on the "heating" and the "splashed out" particles get only its small fraction. However, the phenomenon itself remains when the initial energy decreases and in the limit transferring smoothly into the "semidirect" process (see footnote ‡3). (ii) The "splashed out" particles can be observed (recognized by energy spectrum and angular distribution) against the "evaporation background" if their energies are high enough ($\epsilon \gtrsim 3T$, see eq. (4)). (iii) The angular- and energy-correlations of secondaries in reaction (n,2n) are of great interest for the test of the mechanism (see sect. 5). (iv) The characteristic feature of the "splashing out" reaction is a peculiar scaling property: the same initial perturbation $\delta\rho(0)$ irrespective of the captured particle leads to the same emission.

‡4 Note that this solution is not reduced to $\delta\rho'$ alone since $\delta\rho'$ describes the odd nucleon in the equilibrium with the self-consistent field. The part in $\delta\rho'$ describing the core polarization cancels at $t = 0$ with the first term in the right hand side of eq. (10).

‡5 The physics of the solution is clear. The initial distortion of the density matrix undergoes dynamical time evolution governed by the HF-Hamiltonian S^o (statistical relaxation is neglected, see sec. 3.). The self-consistent quantity $\delta S(t)$ plays the role of $\delta U(t)$.

References

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