UDC 539.17, 530.145

TIME RESONANCES (EXPLOSIONS) IN HIGH-ENERGY NUCLEAR REACTIONS

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It is shown, that the exponential decrease of the energy spectra, accompanied in a certain degree by slight oscillations, with final-fragment energy in high-energy nuclear reaction, independently from fragments, targets, projectiles and projectile energies, can be explained under some conditions at the range of strongly overlapped compound-resonances by a new phenomenon of time resonances (explosions). These time resonances (explosions) correspond to the formation of a few high-excited non-exponentially decaying nuclear clots (partial compound nuclei consisting of certain small groups of target and projectile nucleons).

1. For not very heavy projectiles (from p to ^{20}Ne) with projectile energies above 1 - 10 Gev/nucl there had been observed structureless, exponentially decaying inclusive (and not only inclusive) energy spectra, often accompanied by slight oscillations, throughout the studied range of projectiles and projectile energies, targets and registered final fragments (see, for example, [1 - 8]). For heavier projectiles these phenomena were observed even for smaller energies (see, for instance, [9]).

2. It is well-known that, if we take the reaction amplitude $f_{\alpha\beta}(E)$ in the form

$$f_{\alpha\beta} = \frac{C_{\alpha\beta}}{E - E_r + i\Gamma/2} \tag{1}$$

($C_{\alpha\beta}$ is an almost constant or a smooth function of the final-particle kinetic energy E in the region (E_r - Γ/2, E_r + Γ/2); in general, it depends on the angular coordinates of the emission direction, E_r and Γ being the resonance energy and width respectively), we obtain the following expression

$$I(t) = (\Gamma / \hbar)\exp(-\Gamma t / \hbar) \tag{2}$$

in the vicinity of the compound nucleus for the emission probability $I(t)$ under the condition

$$\Gamma << \Delta E << E_r \tag{3}$$

(ΔE is the energy spread).

If we take the reaction amplitude $f_{\alpha\beta}(E)$ in the form

$$f_{\alpha\beta}(E) = C_{\alpha\beta}{}^{n} \exp(-E\tau_n/2\hbar + iEt_n/\hbar), \tag{4}$$

where τ_n and t_n are constants (with the time dimension), τ_n and t_n determine the exponential dependence on energy for the correspondent cross section and the linear dependence on energy for the amplitude phase respectively, $C_{\alpha\beta}{}^{n}$ is a constant or a very smooth function (inside ΔE) of the final-particle energy E, then the correspondent cross section and the emission probability under the condition

$$\Delta E << 2\hbar/\tau_n \tag{5}$$

will be

$$\sigma_{\alpha\beta} = |f_{\alpha\beta}|^2 = \text{const}\cdot \exp(-E\tau_n/\hbar) \tag{6}$$

and

$$I(t) = \frac{(\tau_n/2\pi)}{(t - t_n)^2 + \tau_n{}^2/4}, \tag{7}$$

respectively.

The evolution of compound-nucleus surviving (at instant t during the life and decay after the formation) can be described by the following function:

$$L^c(t) = 1 - \int_{(0)}^{t} \mathrm{d}t\, I(t). \tag{8}$$

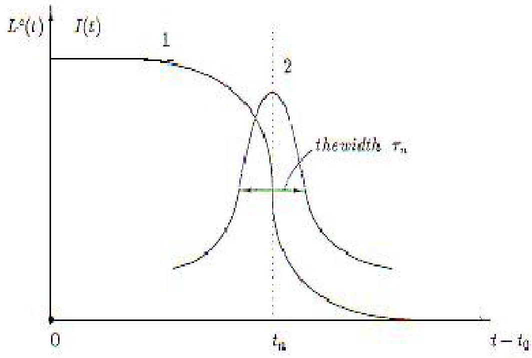


Fig. 1. $L^c(t)$ (curve 1) and $I(t)$ (curve 2).

From (7) and (8) one can deduce the strongly non-exponential form of $L^c(t)$ and $I(t)$, like depicted in Fig. 1.

When $f_{\alpha\beta}$ has a more general form like

$$f_{\alpha\beta}(E) = \sum_{n=1}^{\nu} C_{\alpha\beta}{}^{n} \exp(-E\tau_n/2\hbar + iEt_n/\hbar) \quad (9)$$

with several terms ($\nu = 2, 3, \ldots$), the cross section $\sigma_{\alpha\beta} = |f_{\alpha\beta}|^2$ contains not only exponentially decreasing terms but also oscillating terms with factors

$$\cos[E(t_n - t_{n'})/\hbar] \quad \text{and} \quad \sin[E(t_n - t_{n'})/\hbar].$$

In the case of two terms ($\nu = 2$) in (9) formula (9) can be rewritten as

$$\sigma_{\alpha\beta} = |C_{\alpha\beta}{}^{1}|^2 \exp(-E\tau_1/\hbar) + |C_{\alpha\beta}{}^{2}|^2 \exp(-E\tau_2/\hbar) + \\ + 2\mathrm{Re}\,\{ C_{\alpha\beta}{}^{1} C_{\alpha\beta}{}^{2*} \exp[iE(t_1 - t_2)/\hbar - E(\tau_1 + \tau_2)/2\hbar]\}, \quad (10)$$

(where the terms with ΔE are neglected if the conditions

$$\Delta E t_n << E\tau_n \quad \text{and} \quad \Delta E\tau_n << Et_n$$

are supposed).

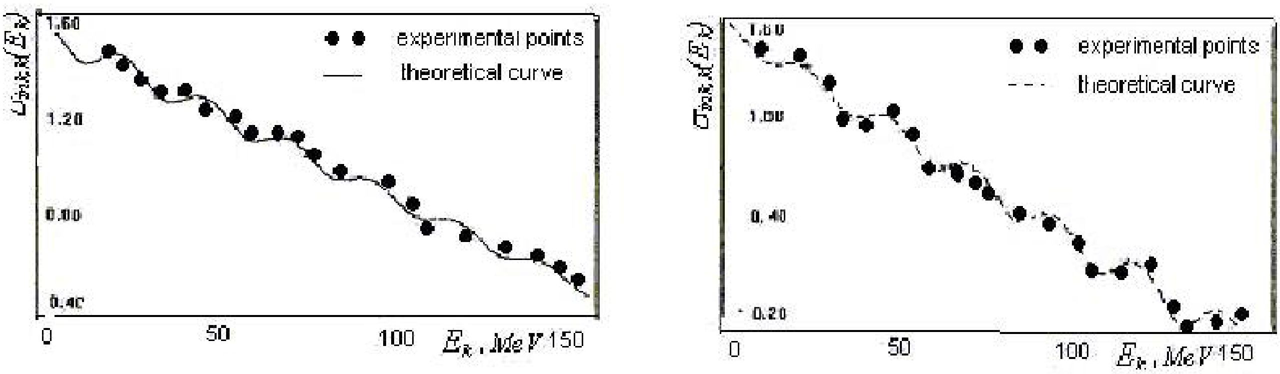
3. For analysis of observed experimental spectra of a single final fragment one has to sum (or average) the expressions like (6) and (9) over the subsets of final states (with different quantum numbers $JS\Pi$, orbital quantum numbers L etc) and channels, sometimes coherently and usually incoherently. It does not matter and does not change the final expressions if we make the simplifying assumption that all the involved amplitudes have the same E-dependence for the both $|f_{\alpha\beta}|$ and $\arg f_{\alpha\beta}$.

In particular, for inclusive energy spectra of the k-th final fragment we shall use the following expression:

$$\sigma_{inc,k}(E_k) = |\sum_{n=1}^{2} C_n \exp[(it_n - \tau_n/2)E_k/\hbar]|^2 =$$

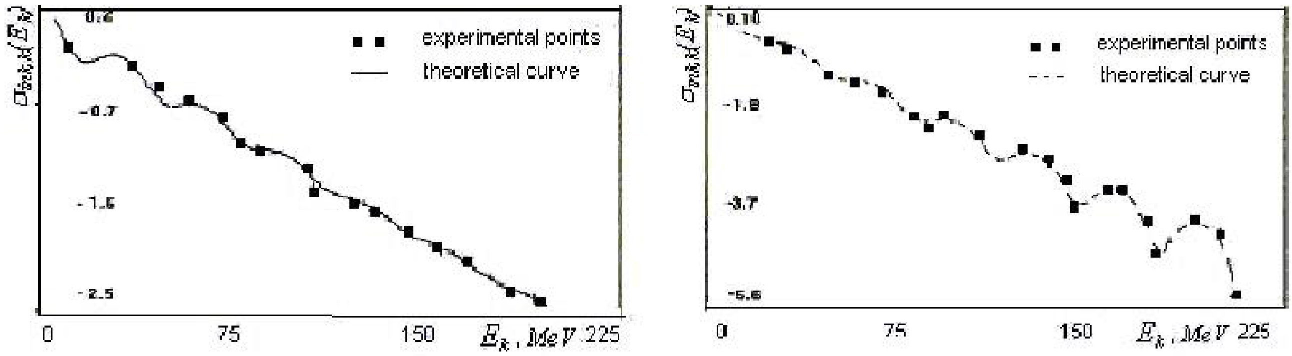
$$= \sum_{n=1}^{2} |C_n|^2 \exp(-E_k\tau_n/\hbar) + 2\,\mathrm{Re}\,C_1^{*} C_2 \exp\{[i(t_2 - t_1) - (\tau_1 + \tau_2)/2]E_k/\hbar\}. \quad (11)$$

In Figs. 2 and 3 some calculated inclusive energy spectra $\sigma_{inc,k}(E_k)$, in arbitrary units and in semi-logarithmic scale, are presented in comparison with the experimental data from [4, 6, 9] (see also [8]).



a *b*

Fig. 2. Inclusive process $p + C \rightarrow {}^7Be$ (2.1 GeV protons):
a - $C_1 = 0.36$, $C_2 = 0.04$ ($\theta = 90°$); *b* - $C_1 = 0.05$, $C_2 = 0.35$ ($\theta = 160°$).



a *b*

Fig. 3. Inclusive process $^{20}Ne + Al \to p$ (393 *MeV/* nucleon):
a - C_1= 0.1, C_2= 5.9 (θ= 90°); *b* - C_1= 0.2, C_2= 5.8 (θ= 150°).

In Figs. 2 and 3, θ is the detected angle of the *k*-fragment emission.

The values of τ_1, τ_2 and $t_2 - t_1$, which were found from fitting the theoretical curves with the experimental data.

The parameters of time resonances for some inclusive spectra:

Reaction	Projectile energy, *GeV*/nucl	τ_1, 10^{-23} s	τ_2, 10^{-23} s	t_2 - t_1, 10^{-22} s
$p + C \to {}^7Be$	2.1	10.45	17.0	5.95
$^{20}Ne + Al \to p$	0.393	0.1	0.99	1.7

4. Let us explain the time-resonance structure at the range of overlapped compound-nucleus *energy resonances*, basing on the papers [10 - 13]. For sufficiently high energies, if one neglects bound-state, anti-bound-state and threshold singularities, the *S*-matrix can be described by the Simonius formula [14]

$$\hat{S} = \hat{U}\hat{S}_{res}\hat{U}^T, \quad \hat{S}_{res} = \prod_n \left(I - \frac{i\Gamma_n \hat{P}_n}{\varepsilon - \varepsilon_n + i\Gamma_n / 2} \right), \tag{12}$$

where the indexes *JSΠ* are omitted for the simplicity, the unitary background (non-resonant) matrix *U* and the resonance projection matrix $\hat{P}_n$ ($\hat{P}_n = \hat{P}_n^{\,+} = \hat{P}_n^{\,2}$, Trace $\hat{P}_n$ = 1) slowly changing with the total energy ε or are almost independent on ε, $\hat{U}^T$ being the matrix transposed to $\hat{U}$.

Under the simplest Baz'-Newton conditions (which are described in []) when fluctuations of $\hat{P}_n$ can be neglected ($\hat{P}_n = <\hat{P}>$), the S-matrix (12) acquires the following form:

$$\hat{S} = \hat{S}_b - \hat{a}\left(1 - \prod_n \frac{\varepsilon - \varepsilon_n - i\Gamma_n / 2}{\varepsilon - \varepsilon_n + i\Gamma_n / 2} \right) \tag{13}$$

with $\hat{S}_b = \hat{U}\hat{U}^T$ and $\hat{a} = \hat{U} < \hat{P} > \hat{U}^T$.

For unresolved ($\Delta E >> \rho^{-1}$, Γ) and strongly overlapped ($\pi\Gamma\rho >> 1$) resonances the compound-nucleus *S*-matrix $\hat{S}^c$ is

$$\hat{S}^c \to \hat{a}\prod_n \left(\frac{\varepsilon - \varepsilon_n - i\Gamma/2}{\varepsilon - \varepsilon_n - i\Gamma/2}\right) \tag{14}$$

and the energy-averaged compound-nucleus cross section $<\sigma^c_{\alpha\beta}>_{\Delta\varepsilon}$ is proportional to $|a_{\alpha\beta}|^2$

$$<\sigma^c_{\alpha\beta}>_{\Delta E} \sim <|S^c_{\alpha\beta}|^2>_{\Delta\varepsilon} = <|a_{\alpha\beta}|^2>_{\Delta\varepsilon} \cong |a_{\alpha\beta}|^2, \tag{15}$$

(where ΔE is defined by $\Delta\varepsilon$ and the energy resolution of the detector of final fragments).

The correspondent to (15) energy-averaged compound-nucleus time delay and variance of the compound-nucleus delay distribution are defined by the following relations

$$<\tau^c> = <\sum_n \frac{\hbar\Gamma_n}{(\varepsilon-\varepsilon_n)^2+\Gamma_n^2/4}>_{\Delta E} = 2\pi\hbar\rho \tag{16}$$

$$D\tau^c_{\alpha\beta} = \frac{\hbar^2 <(\partial|a_{\alpha\beta}|/\partial E)^2>_{\Delta E}}{<|a_{\alpha\beta}|^2>_{\Delta E}} \tag{17}$$

(at the continuum approximation $\sum_n \to \int \rho d\varepsilon$). (Here and afterwards we write $<\tau^c>$ and $D\tau^c$ without indexes $\alpha\beta$).

If $a_{\alpha\beta}$ has a form like (4) and (5), when $\hbar/\tau_n >> \Delta E$ for small ΔE, for strongly overlapped resonances (with $\pi\Gamma\rho >> 1$) we rewrite (15) like (6) in the following form:

$$\sigma_{\alpha\beta} = |a_{\alpha\beta}|^2 \sim \exp(-E\tau_n/\hbar) \tag{15a}$$

and write the following relation

$$<\tau^c>^2, \exp(-\pi\rho\Gamma) << \frac{\hbar^2 <(\partial(a_{\alpha\beta}(/\partial E)^2>_{\Delta E}}{<(a_{\alpha\beta}(^2>_{\Delta E}}. \tag{18}$$

Under the same conditions,

$$D\tau^c \cong \tau_n^2. \tag{17a}$$

If $\tau_n << 2\pi\hbar\rho$ (it is possible when $\Delta E >> \rho^{-1}$) then

$$D\tau^c \cong \tau_n^2 << (<\tau^c>)^2 \tag{20}$$

and we have a narrow time resonance (explosion) as a physical phenomenon.

Similarly, under more general conditions when there are several independent non-fluctuating projectors $\hat{P}_\nu = <\hat{P}^{(\nu)}>$, $\nu = 1, 2 \ldots \eta$ (η being much less than the number of resonances), one can obtain after the same considerations the result (9) and (10) for $\sigma_{\alpha\beta}$ with oscillating terms.

Under the more realistic Lyuboshitz conditions of statistically equivalent channels of compound-nucleus decays when either mean values or fluctuations of $\hat{P}_n$ are similar in all open channels, it can be shown that for strongly overlapped resonances when $\pi\rho\Gamma/N >> 1$ (N is the number of open reaction channels)

$$<\tau^c> = 2\pi\hbar\rho / N \tag{21}$$

and also

$$D\tau^c << <\tau^c>^2.$$

If, further, one extents the simple version of the Hauser-Feshbach formula for cross sections of compound-nucleus reactions (see, in particular, [15]) into the region of high-energy processes then for the same conditions one can be easily convinced that

$$<\sigma^c_{\alpha\beta}> = \frac{T_{\alpha\alpha}T_{\beta\beta}}{\sum_{\gamma=1}^N T_{\gamma\gamma}} W_{\alpha\beta} \to N^{-1} \cong \exp(-E\tau_n/\hbar),$$

with $\hat{T} = \hat{1} - <\hat{S}><\hat{S}^*> \to \hat{1}$ and $W_{\alpha\beta} \cong 1$,

$$2\pi\rho\Gamma/N \to \infty$$

too (in the evident supposition of the exponential growth of N with energy).

So, also under the Lyuboshitz conditions for the region of strongly overlapped resonances, an exponential decreasing of final-fragment energy spectra correspond to a narrow time resonance (explosion) as a physical phenomenon.

Therefore there are certain situations at the range of strongly overlapped compound-resonances when one can observe one or several time resonances (explosions) in the cross sections.

Nevertheless, for weakly overlapped energy resonances (when $\pi\rho\Gamma/N << 1$ under the Liuboshitz conditions) or well-separated energy resonances (when $\pi\rho\Gamma << 1$ under the Baz'-Newton conditions) there is no time resonance (no explosion) even notwithstanding an exponential behavior of energy spectra ($\sigma_{\alpha\beta}(E)$). In fact, it was shown that for those cases the mean time delay is

$$<\tau^c> = \hbar\Gamma$$

and if

$$\Gamma << \Delta E << \hbar/\tau_n$$

then $<\tau^c> >> \tau_n$ and $D\tau^c \cong <\tau^c>^2$ (which correspond to a mean exponential decay function $L^c(t)$).

In intermediate cases when $<\tau_c> \cong \tau_n$ there is a more complicated situation which demands a special study.

5. Now we formulate our conclusions:

The phenomenological time-evolution approach, developed here, is based on general properties of time-energy transformations and general results of joint time and statistical energy-resonance analysis of nuclear reactions.

Presented here time-resonance (explosion) phenomenological description can also be combined with any semi-microscopic model, in particular, elaborated on the base of the fireball or intra-nuclear cascade models.

In section 4 the certain situations at the range of strongly overlapped compound-resonances were revealed (in particular, conditions $\pi\Gamma\rho >>1$, $\pi\rho\Gamma/N >>1$ etc) when one can observe one or several time resonances (explosions) in the cross sections *de facto*. So, time resonances (explosions) can appear only on the base of strongly overlapped standard energy compound-resonances as a particular phenomenon. In this case the only clear experimental indication for appearing of a time resonance (explosion) is the exponential decreasing of inclusive energy spectra (with some oscillations at the case of several coherent time resonances [for the same involved amplitudes]).

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ВРЕМЕННЫЕ РЕЗОНАНСЫ (ВЗРЫВЫ) В ВЫСОКОЭНЕРГЕТИЧЕСКИХ ЯДЕРНЫХ РЕАКЦИЯХ

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Показано, что экспоненциальное убывание энергетических спектров с ростом энергии конечных фрагментов, сопровождаемое иногда легкими осцилляциями, независимо от фрагментов, мишеней, бомбардирующих частиц и энергий бомбардирующих частиц можно при определенных условиях в области сильно перекрывающихся компаунд-резонансов объяснить новым явлением временных резонансов (взрывов). Эти временные резонансы (взрывы) отвечают образованию нескольких высоковозбужденных неэкспоненциально распадающихся ядерных комплексов (частичных составных ядер, состоящих из некоторых малых групп нуклонов мишени и бомбардирующей частицы).

ЧАСОВІ РЕЗОНАНСИ (ВИБУХИ) В ВИСОКОЕНЕРГЕТИЧНИХ ЯДЕРНИХ РЕАКЦІЯХ

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Показано, що експоненційне спадання енергетичних спектрів зі зростанням енергії кінцевих фрагментів, що іноді супроводжується легкими осциляціями, незалежно від фрагментів, мішеней, бомбардуючих частинок та енергій бомбардуючих частинок можна при певних умовах в області компаунд-резонансів, що сильно перекриваються, пояснити новим явищем часових резонансів (вибухів). Ці часові резонанси (вибухи) відповідають утворенню декількох високозбуджених ядерних комплексів (часткових складених ядер із деяких малих груп нуклонів мішені та бомбардуючої частинки), що розпадаються неекспоненційно.