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To particle-release mechanism in nuclear reactions

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Manifestation of internal quantum states of emitter nucleus is recently revealed even at the case of compound reactions described within the statistical mechanism. Deviations from the prediction of models operating exclusively with macroscopic parameters are visible. Examples of such effects are given and discussed in this report. The factors of nucleon pre-arrangement and α-particle pre-formation influence the absolute rate of reactions and sometimes define quantum numbers of the emitted products.

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1. Introduction

Historically, direct mechanism of nuclear reactions is applied to such processes as elastic and inelastic scattering, Coulomb excitation, stripping, knock-out, and pick-up reactions. Application of the direct scenario requires a presence of the particle ready for emission together with a significant impact momentum by the projectile. The modern status of direct mechanisms has been in particular characterized in Ref. [1]. Naturally, the initial and final states of the reaction participants play a significant role and define the final observables. Follows an idea to probe the microscopic wave functions of stable or radioactive nuclei in the direct nuclear reactions.

However, sometimes, complicated multistep schemes are also attracted for description of the clearly direct processes. More essentially, there are wide classes of reactions traditionally treated within statistical and macroscopic mechanisms, for instance, at the case of excited compound nucleus formed past the projectile absorption and decayed then via emission of photons, nucleons, composite particles and fission fragments. The microstates of nucleons are typically neglected. Protons and neutrons inside a nucleus ascribed to be the two groups of fermions confined in the common potential well. That is equivalent to the charged gas or liquid filled in a vessel of definite size. The particle emission happens due to random fluctuations with transfer of thermal energy to the individual-nucleon kinetic energy. The compound nucleus is characterized by only macroscopic parameters, like excitation energy, level density, temperature, enthropy, radius, depth of the potential well, moment of inertia, rotational energy, deformation, and so on. Naturally, theory results are independent on the intrinsic microstates of the constituent nucleons.

Here is stressed now a possibility to deduce the microstructure manifestations from experimental studies of reactions normally attributed to the statistical mechanism. We are interested only with the processes at relatively low projectile energy: $E_p \leq 10$ MeV/amu, or several tens MeV, in total. The higher energy processes remain now beyond the discussion. Let us remind that the energies of about 100 MeV/amu and higher correspond to the intermediate energy range where the pre-equilibrium mechanisms are of importance. There were developed special theoretical approaches: the exciton model of pre-equilibrium emission [2] and coalescence mechanism of the complex particle formation [3]. At even higher energies in the range of GeV/amu and above, the generation of unstable elementary particles dominates and physical content is shifted to the field of subnucleon-structure processes unlike to the topics of nuclear reactions selected for the present report.

2. Microscopic manifestations in compound reactions

Recently in a course of experimental studies, it has been found a possibility to deduce the role of microstates in classical reactions at low energies, such as photon-induced processes at giant dipole-resonance (GDR) range and thermal neutron capture by isomeric states. These conclusions are new and three examples are characterized below in a form of separate subsections.

2.1 Yield of (γ, α) reactions influenced by the pre-formation factor

Series of (γ, α) reactions have been observed and characterized by the reliable activation method [4, 5]. In presence of the (γ, *n*) and (γ, *p*) reactions of higher yield, the activities produced in (γ, α) reactions were detected for several targets within mass range from A = 109 to 207. The background activities typically restrict the observation of (γ, α) products, but at the selected cases of favourable targets no disturbing backgrounds are created. Finally, seven such reactions were found and studied. Presence of γ lines belonged to the (γ, *n*) products in activation spectra supplies a natural calibration for the (γ, *p*) and (γ, α) yields. Such calibration allows to determine the probability of reactions with emission of charged particles because (γ, *n*) accumulates practically total cross section of the GDR photon absorption. Experiments were arranged using the bremsstrahlung radiation generated by 23 MeV electron beam at the microtron MT-25 in Dubna. There was obtained the (γ, *p*) to (γ, *n*) yield ratio of about (10^{-2} - 10^{-3}) for the series of reactions in this medium-mass range. At the same time, the (γ, α)/(γ, *n*) ratio appears to be as low as (10^{-4} - 10^{-5}) and even of about 10^{-6} for the ^{207}Pb target. Due to the low yield, a task of (γ, α) detection was difficult and the literature data were rare and scattered. Only after our careful measurements [4, 5] the (γ, α) yields at low photon energy were reliably determined.

The experimental results are shown in Fig. 1 demonstrating the regular yield decrease versus the target atomic number Z. The most intriguing remains a point, why (γ, α) is suppressed by two orders of magnitude compared to (γ, *p*) reaction. The Coulomb barrier for emission of alphas is definitely higher than of protons, but the great binding energy of α particles (^{4}He) produces an opposite effect. The effective barrier of emission (E_{th} + B_C) turns out to be practically similar both for protons and alphas. The B_C values were calculated using well known Bass equation [6] and E_{th} is just a mass difference of the exit and entrance channels of the reaction taken with modern nuclear-mass tables. The (E_{th} + B_C) parameter varies from 13 to 17 MeV for studied cases of proton and alpha emission. Correspondingly, the yields are decreased versus growing effective barrier. However, this parameter variation could not explain the suppressed probability of α emission by two and more orders of magnitude compared to the emission of protons. Obviously, the preformation factor is responsible for that. Proton in a nucleus is ready for emission while α must be formed at the first stage of reaction and then emitted.

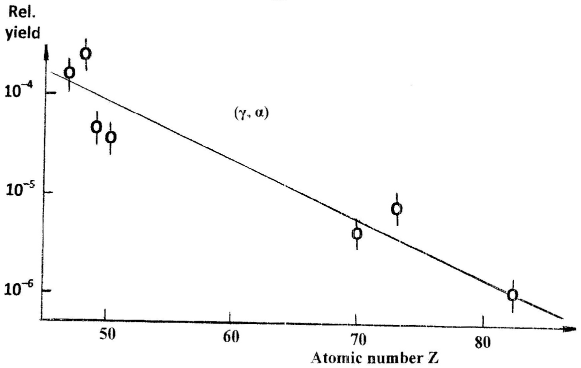

Fig. 1. Z-dependence of the (γ, α)-reaction yield. The points correspond to the following targets: ^{109}Ag, ^{113}Cd, ^{115}In, ^{119}Sn, ^{176}Yb, ^{181}Ta, and ^{207}Pb.

One has to remind the known theory models supposing that the nucleon status inside a nucleus is strongly modified compared to that of free nucleon in vacuum. Sometimes, a total α-clustering is supposed, or short-range nucleon correlations expressed in the formation of the multiquark objects, or content of interacting bosons in a nucleus. Observed now a necessity to insert the preformation factor for (γ, α) reaction may confirm that α clusters inside nuclei are present with low probability. In first approximation, the nucleons remain to be a group of non-interacting particles in accordance with the Pauli principle. This conclusion of our experiment corresponds to the nuclei of medium mass. Opposite, the light species, as known, are completely clustered. In addition, at the commented case, the photon absorption is driven by GDR. The latter resonance arises when the electromagnetic wave impacts a nucleus as some object of definite size and deformation. The nucleon status may be perturbed only slightly, they occupy in major the same microscopic orbits. The analogy to α decay of ground state nuclei is evident. Indeed, the preformation factor is attracted in many papers for description of α decay halflifes, same as in our case for (γ, α) reaction yield.

Unlike that, alphas are emitted [7] with cross sections comparable to the geometry cross section in reactions induced by low energy (10 MeV/amu) heavy ions. A high probability seems contradicting to our observation for (γ, α). Therefore, the special mechanism must be introduced. The projectile energy is not enough to suppose the massive production of α via the exciton mechanism of pre-equilibrium emission [2]. To resolve the contradiction, there was proposed in [5] the following scenario: at the nuclear contact, heavy projectile momentum immediately generates the directed flow of nucleons through the target volume. An internal coalescence mechanism is responsible for the formation of strongly bound clusters, in particular of α particles. Then, they are emitted preferentially in forward direction conserving the momentum transfered from the projectile. Thus, “direct” mechanism of α emission at low energies is turned out to be a two-step process including the nucleon prearrangement stage.

2.2 Structure selectivity for population of high-spin isomers

In Ref. [8], the relative yields of photon-induced (γ, *n*) and (γ, *p*) reactions were factorized versus independent barrier/threshold and spin factors. The systematic dependence was established for the yield as a function of the spin-difference parameter for final and initial reaction states. The literature and own data were involved in this systematics that contains, in total, the measured yield values for 35 reactions. Deduced regular function is shown in Fig. 2. The data processing did involve an exclusion of the threshold factor and also a new definition for the spin parameter. Compared to the literature, our innovation was the replacement of the straight spin-difference ($I_f - I_t$) by the difference of spin-square operators: $|I_f(I_f + 1) - I_t(\mathrm{I}_t + 1)|$, where I_f and I_t are the final state and the target spins, correspondingly. Such variant originates from the statistical model equation with the nuclear level density that exponentially decreases versus spin square I^2. Remind that in statistical model, a process probability is proportional to the level density ratio for the final and initial macrostates.

In Fig. 2, the spin dependence of the (γ, n) and (γ, p) reaction yields is shown in our modified formulation. One could see the point scattering at low values of the argument witout strong regular dependence and the exponential drop at higher values of the spin parameter. A scattering of points reflects the random origin of low spins created by combination of the microscopic nucleon momenta. The scattering is cooled down when the regular suppression of the level density by growing rotational energy is switched on. Cooling of random fluctuations due to the regular potential factors is well known for different systems. In addition, there are shown upper limits for several reactions and three other points deviating up from regularity by one order of magnitude. All of them correspond to the special class of reactions: "from isomer to isomer" when both the target and product nuclei are high-spin isomers. Such processes were originally observed in Ref. [9]. Established now selectivity of preferential population for similar in- structure levels contradicts to the widely discussed in literature structure mixing (*K*-mixing) at excitation energy near and above the neutron binding energy B_n. The structure mixing is real but incomplete. At least at some cases, the one order-magnitude selectivity is conserved for population of similar in-structure levels. Thus, the microscopic structure is manifested even in the reactions of statistical mechanism.

2.3 Enhanced transmission coefficients for neutrons with high orbital momentum

Over recent decade, the 100 barn and higher cross sections were observed for INNA reactions with high-spin ^{177m}Lu [10] and ^{178m2}Hf isomers [11]. The Inelastic Neutron Acceleration (INNA) process was introduced many years ago in the pioneering work [12]. The isomer excitation energy, in part, could be transfered to the kinetic energy of a scattered neutron with "acceleration" of it due to the transition from the isomeric to lower lying level in the target nucleus. INNA transition is not identical to the electromagnetic transition, nor to the acceleration by potential gradient. This especial process of nuclear origin is regulated by the emission probability for a neutron with definite orbital momentum l released due to the nuclear transition. Neutron transmission coefficients T_l , as known since 50th [13], are being drastically decreased for $l \geq 2$. So that, minor cross sections could be expected for INNA reactions because corresponding transitions from ^{177m}Lu and ^{178m2}Hf isomers require $l \geq 3$ taking into account the spin and parity conservation. Opposite, a great cross section is visible in experiments [10, 11].

Within statistical model, the neutron kinetic energy and angular momentum l_{out} are released in emission from excited nucleus due to random fluctuations of the thermal energy. The orbital momentum of a neutron inside the nucleus l_{in} is neglected in such models. In reality, the orbital momentum, being an integral of motion, must be conserved overall trajectory of a neutron from internal volume to the external space. The internal states of nucleons are well known according shell model and the occupation of definite orbitals in the unexcited nucleus is known. This is not much disturbed by the isomeric energy. Therefore, a neutron from the definite l_{in} orbit is emitted to the external space and reaches the l_{out} value appropriate for INNA transition.The mismatch between l_{in} and l_{out} strongly influences the probability of emission. At least, some additional exchange with the angular momentum between nucleons is required and prearrangement stage of the reaction must be accounted.

In Fig. 3a, transmission coefficients as a function of l are shown for the reaction of ^{180m}Ta depletion in (n, n') scattering both in classical approach and with modification due to the microscopic l_{in} distribution. The latter distribution for ^{180}Ta is shown in Fig. 3b according the Nilsson scheme reduced in [14]. In traditional model, the T_l values are great only for l = 0, 1 and 2, while at higher l, they degrade drastically. But, only about 30% of neutrons possess $l_{in} \leq 2$ and effective T_l must be reduced by a factor of about 3, as shown in Fig. 3a. For higher l values, T_l

is in opposite enhanced due to possible rearrangement of the nucleon orbital momentum before emission.

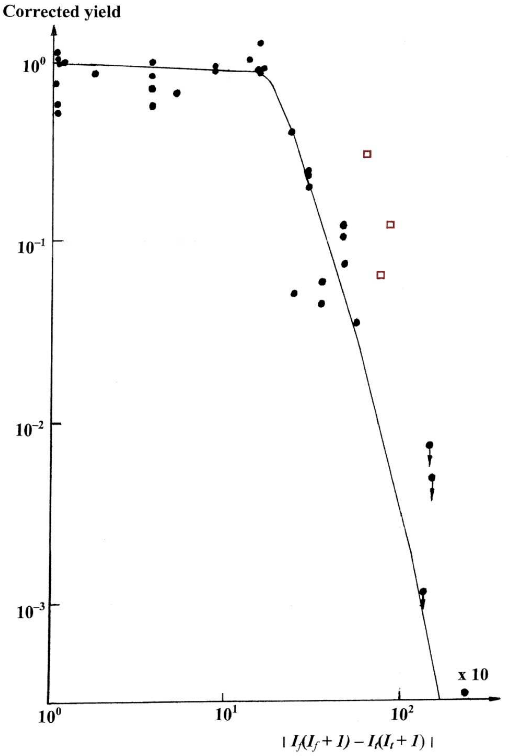

Fig. 2. Systematic dependence of the (γ, *n*) and (γ, *p*) yields from the spin parameter.

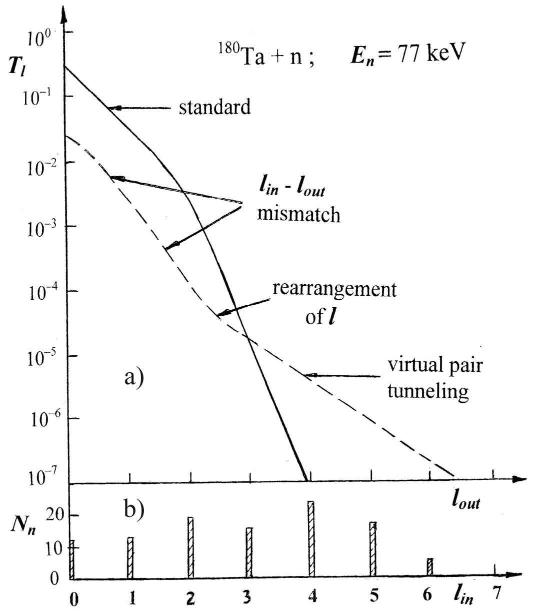

Fig. 3. In part a), the transmission coefficients $T_l\,(l_{out})$ are shown by solid line according the standard calculations and, schematically by dash line, with account of the orbital momentum rearrangement. In part b), the internal distribution of the neutron orbital momentum l_{in} inside the nucleus.

The final l_{out} is in part taken from the internal momentum that is neglected in standard approach. At highest l_{out} values, some additional quantum mechanism must be activated. The neutrons in bound nucleus are paired, and the sum orbital momentum of a pair is equal zero. It would be reasonasble to imagine the virtual tunneling of the pair through the centrifugal barrier with consequent splitting outside the nucleus. One of neutrons returns to its initial orbital inside and the second one is emitted with fixation of a great orbital mumentum. Definitely, the probability of such a scenario is suppressed by the virtual character of the process. But, when the regular T_l magnitude becomes minor, $\leq 10^{-6}$, the virtual process must contribute enough. Thus, Fig. 3 serves for illustration of the T_l coefficient modification with account of the microscopic *l* distribution inside the emitter nucleus.

3. Summary

The microscopic states of nucleons influence the particle emission even in reactions of the statistical mechanism. Accounts of the preformation and prearrangement factors for the reaction products will modify a theory predictions both for the reaction absolute rate and for the product distributions. Internal quantum numbers are manifested in the reaction-product states.

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