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E4-81-216

E.Běták

ON THE POSSIBILITY OF THE BACKWARD ENHANCED PREEQUILIBRIUM EMISSION

Submitted to "Известия АН СССР, сер.физ."
and to the 31 Symposium on Nuclear
Spectroscopy and Nuclear Structure
(Samarkand, 1981)

1981

Nowadays popular preequilibrium models for nuclear reactions have been initiated mainly by Griffin's paper /1/. They are justified for the excitation energies above approximately 15 MeV /2/; but they are shown to produce good results in a rather wide energy interval, starting with an incident energy of 5 MeV /3/ and going far to the GeV region /4/. Many approaches have been developed in the course of time, emphasizing different aspects of the model considerations. It is rather interesting to trace the origins of the so-called hot-spot model (thermodynamic description of preequilibrium reactions) back to 1938, when Bethe suggested a creation of "local heating" (now commonly called hot spot) of the target nucleus, which evaporates particles before the equilibrium is reached /5/. Due to the high local temperature the emitted particles have higher energies than those corresponding to the compound nucleus. Of special interest is Bethe's note that "these 'too fast' particles will be emitted preferably in the backward direction" /5/. This seemed to be in contradiction with the experimental data acquired: all till now observed statistical nuclear reactions demonstrated dominance of the forward direction, especially near the high-energy edge of the particle spectrum, and the theoretical models nicely fitted the measured angular distributions. That is why original Bethe's prediction of angular distributions of preequilibrium particles has been supposed to be erroneous.

Let us have a look as to what are the conditions leading to the forward emission in the early stage of the reaction. Firstly, the momentum introduced to the composite system strongly favours the emission in the projectile direction. Secondly, a possible fast rotation of the system before the particle emission (important mainly in the heavy ion reactions) broadens the width of the angular distribution and shifts the position of its maximum, leaving the leading role for the forward hemisphere. If we are able to eliminate simultaneously the influence of both momentum and angular momentum on the reaction, we can expect fulfilling Bethe's prediction. In order to eliminate the rotation it is sufficient to consider only the central collisions (the s-wave); unfortunately, they are usually more than masked by higher partial waves. One of the possibilities how to isolate the s-wave contribution is the lowering of the incoming energy. This condition conforms with the requirement of low introduced momentum, but drastically worsens the conditions for applicability of preequilibrium statistical models. Therein, one needs a relatively high excitation energy as to justify the use of the level density concept. The minimum excitation energy required is estimated to be 10 - 15 MeV /2/, that should refer both to the composite and residual nuclei. Surprisingly, the model works nice enough at composite nuclear excitation energy as low as about 10 MeV /3,6/, that means still lower residual energy after the particle emission.

So, for the applicability of preequilibrium-model image and for obtaining the backward enhanced particle emission, one should try to fit the following conditions:

i/ The target should be with $A \gtrsim 40$ /2/; the nuclei with magic numbers are not welcomed;

ii/ The incident particle should be a nucleon with low energy (to ensure s-wave and little introduced momentum);

iii/ The binding energy of projectile (in the composite nucleus) must be higher than that of the ejectile (to have still some reasonable energy in the residual nucleus);

iv/ The emission of the outgoing particle must be treated unambiguously within the preequilibrium model, i.e., the ejectile must be a nucleon.

The conditions ii/ to iv/ select the (n,p) reactions (the (p,n) reactions have due to the Coulomb barrier vanishing cross sections at low incident energies). For the choice of the nucleus, we looked over the Tables of Isotopes /7/ and required:

i/ $A > 40$;

ii/ Neither of the target, composite and residual nuclei contains magic number of protons or neutrons;

iii/ The neutron binding energy in the composite nucleus is at least 10 MeV and it exceeds that of proton by at least 4 MeV.

There are 31 such nuclei in the Tables, all of them correspond to unstable targets. Fortunately, lifetimes of two possible targets are long enough (> 10 days) as to allow some measurements: ^{48}V and ^{56}Co.

Let us now estimate the cross section and the forward/backward asymmetry for the case of ^{48}V (n,p) reaction at E_n=0.5 MeV. As all the calculations are done near the limits of applicability of the preequilibrium models, they can serve only as guidenumbers and cannot be expected to fit the experimental data (when measured).

We shall assume that the first interaction of the incoming nucleon with the target nucleus gives rise to a localized hot spot on the nuclear surface. This hot spot emits backward, its angular distribution (in the extreme case) being

$$\frac{d\sigma}{d\Omega} \sim |\cos\vartheta|\;\Theta\left(\vartheta-\frac{\pi}{2}\right). \qquad (1)$$

The state after the first interaction, which we treat as the hot spot, can be interpreted in terms of the exciton model as a 3-exciton state. So we assume that the emission from the three-exciton state is peaked backward according to eq. (1). All the emission from more complex states is supposed to be isotropic in the c.m. system. Obviously, such a description is oversimplified. To bring it closer to reality, one must think of the mean free path. It is $\lambda \approx 6$ fm at our energies /8/. If we take as a reasonable approximation of the localized hot spot 1 fm (i.e., if the first interaction of a projectile with the target does not occur within the first 1 fm, the decay is treated as an isotropic one), the calculated asymmetry is decreased by a factor of 0.012. This will probably be the lower limit, as the nuclear surface plays a very important role in nuclear reactions /9/. Therefore as the upper limit we take the "hindrance factor" as obtained from the localization of the hot spot to dimensions less than the nuclear radius is. This procedure yields a factor of 0.14.

With these two factors we have calculated the spectra and angular distributions under three different assumptions:

a/ The single-particle level density is $g=A/13$ MeV^{-1}, no pairing corrections are used;

b/ The realistic single-particle level densities and classical pairing energy corrections enter the calculations;

c/ The realistic single-particle level densities and the Rosenzweig-corrected pairing /10/ are incorporated.

The proton spectra are rather sensitive to the inverse cross sections used. We followed the parametrization of Chatterjee and Gupta /11/ here. The absolute values of the (n,p) cross sections are high enough to be measurable ($>$ 100 mb), that might be encouraging at our energies. The Table summarizes the results of our calculations of asymmetry, defined as

$$A(\epsilon_p) = \frac{d^2\sigma(\vartheta = 180^\circ, \epsilon_p)}{d\epsilon_p \, d\Omega} \Big/ \frac{d^2\sigma(\vartheta = 0, \epsilon_p)}{d\epsilon_p \, d\Omega} , \qquad (2)$$

for both the values of localized hot spot probabilities and all three variants of calculations, presented for the peak of the spectrum and the high energy edge ($\approx$ 1 MeV from the end-point).

We see that the effect grows with increasing the outcoming energy (as was assumed by Bethe), its magnitude might make it available to measurements. Such an experiment would be an interesting test of Bethe's prediction.

Table

Backward-forward asymmetries at peak of the proton spectrum and at its high energy edge, as obtained for the ^{48}V (n,p) reaction. Numbers before parentheses correspond to the hot spot limited in size to the nuclear radius, and those within parentheses to its localization to 1 fm.

Variant of the calculation / Asymmetry	a	b	c
A (peak)	1.12 (1.01)	1.59 (1.04)	1.67 (1.05)
A (high energy edge)	1.38 (1.03)	1.67 (1.05)	1.67 (1.05)

The author is gratefull to R.V. Jolos, V.G. Kartavenko, P. Mädler and especially to V.D. Toneev for comments and discussions.

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Received by Publishing Department
on March 31 1981.