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POTENTIAL BARRIER CRITERION AND STARS IN EMULSIONS

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Nuclear emulsions were bombarded with 660-Mev protons and the resulting disintegrations of nuclei in the emulsions studied. The nuclei investigated were carbon, introduced as diamond specks, the light nuclei (C, N, O) of the emulsion and the heavy ones (Ag, Br). Analysis of disintegrations in carbon indicates that there is no significant difference in the mechanisms associated with the production of stars which do or do not contain slow ($R \leq 50\,\mu$) particles. It was found that if the potential barrier criterion were used to pick out stars due to C, N and O nuclei, there would be a 19% admixture of stars due to Ag and Br.

1. INTRODUCTION

IN studying disintegrations of nuclei in emulsions when these are bombarded by various particles, one of the first questions to arise concerns the nature of the disintegrated nucleus.

Disintegrations in emulsions can be divided into two fundamental classes: those in light (C, N, O) nuclei and those in heavy ones (Ag, Br). This division can be made using the potential barrier criterion, as follows. If, after the cascade process in the initial nucleus, the remaining intermediate nucleus is a heavy one, then the potential barrier inhibits the emission of particles with energy less than a certain threshold (9 Mev for particles with $Z = 2$ and 4.5 Mev for particles with $Z = 1$). Hence all stars containing a track less than $50\,\mu$ long (which corresponds to an α particle with energy 9 Mev) must correspond to the disintegration of a light nucleus. It is very unlikely that a heavy nucleus would emit such a low energy particle.

The fundamental work on the disintegration of light nuclei in emulsions has been carried out using this potential barrier criterion. However, a careful analysis of whether this criterion is actually justifiable leads to serious objections.

1. At high excitation energies, deformation of the nuclear surface can lead to lowering of the potential barrier. On the other hand, in principle such a nucleus could decay into unstable fragments, which then decay like a light nucleus, i.e., with the emission of low energy α particles.

2. In a nucleon-bound nucleon collision, the residual nucleus is not highly excited. In interactions of this sort, on light nuclei, slow particles will not be emitted.

3. At sufficiently high excitation energies of light nuclei there is no reason to suppose that low energy particles would be emitted during the disintegration; the higher the energy of the incident particle, the more likely it will be that the decay will not produce low energy particles.

In view of the above, it becomes desirable to take a critical look at the potential barrier criterion, together with experimental data based on it, especially at high energies of the bombarding particles (several hundred Mev and higher).

2. DISINTEGRATIONS OF LIGHT NUCLEI SUCH THAT THERE ARE NO TRACKS SHORTER THAN $50\,\mu$

To study the interaction of 660-Mev protons with carbon, we introduced[1] a suspension of diamond dust into a nuclear emulsion. The diamond particles are transparent, so that the interesting disintegrations could easily be picked out.

Analysis of carbon nucleus disintegrations[2] leads to the conclusion that 51% of the disintegrations are not accompanied by tracks of length $R \leq 50\,\mu$. (In the following, disintegrations unaccompanied by short tracks will be called L_2 disintegrations, while those which do have tracks of length $R \leq 50\,\mu$ will be called L_1 disintegrations.) In his study of C, N, and O due to protons with energy 1 Bev, Philbert[3] found that 55% of the disintegrations were L_2. Comparing this number with the fraction of L_2 disintegrations that we observed, we find support for the conjecture made above that the fraction of L_2 disintegrations increases with increasing energy of the bombarding particle.

Thus the potential barrier criterion eliminates more than half of the disintegrations of light nuclei.

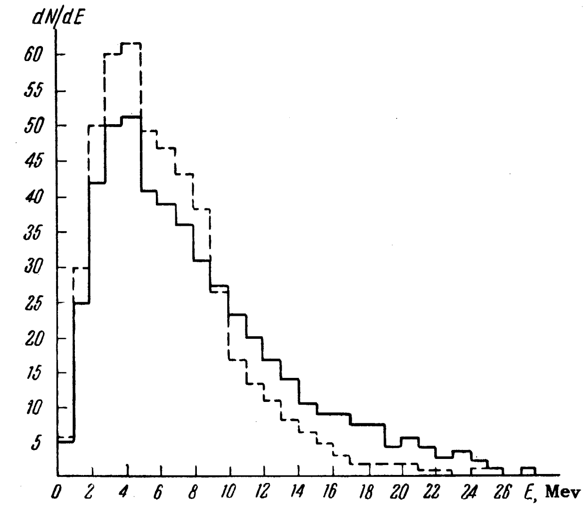

FIG. 1. Energy distribution of α particles from the disintegration of C^{12}. Solid curve – all disintegrations, dotted curve – L_1 disintegrations.

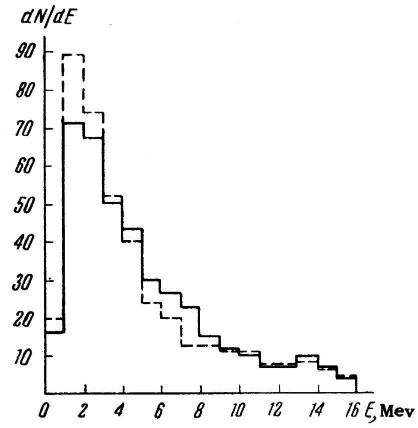

FIG. 2. Energy distribution of protons from disintegration of C^{12}. Solid curve – all disintegrations, dotted curve – L_1 disintegrations.

It is interesting to compare the results for the groups L_1 and L_2.

The energy distributions of α particles and protons from C^{12} stars are shown in Figs. 1 and 2. The solid line refers to all stars, while the dotted one refers only to the group L_1. The spectra in each group are normalized to the same total number of particles. Both the α particle and the proton spectra differ somewhat for the two groups. This difference is apparently due to the way the L_1 group is defined, and does not reflect a real difference between the mechanisms for disintegration in the groups L_1 and L_2. This conclusion is supported by the angular distributions in Figs. 3 and 4. The angular distributions are for the same particles, α's and protons, whose energy distributions were given in Figs. 1 and 2. Figures 3 and 4 show that the angular distributions for groups L_1 and $L_1 + L_2$, and hence for L_1 and L_2, are the same.

Our conclusion, that there is no real difference between the mechanisms for formation of stars with short tracks and those which do not have short tracks, is directly opposite to the conclusion drawn by Philbert and Vigneron,[4] who studied stars made by 1-Bev protons. In their work, L_2 stars were those having a number of tracks $n \leq 8$, total charge $Z \leq 9$, not containing the recoil nucleus. For L_1 disintegrations, the forward/backward ratio for black tracks was 1.91, while for L_2 disintegrations the corresponding number was 1.35. It was on this basis that Philbert and Vigneron drew their conclusion that there was a difference between the disintegration mechanisms in the two groups. However, their method for defining the L_2 disintegrations raises doubts, since this group will certainly contain stars on heavy nuclei, not containing the recoil nucleus. That this admixture to the group L_2 existed may be shown by the fact that the forward/backward ratio for heavy nuclei is 1.36. In the case of the interaction of 660 Mev protons with light and heavy nuclei in emulsions, the preliminary results presented in Sec. 3 show that, using the definition of L_2 disintegrations adopted by the author, the number of disintegrations of Ag and Br is 1.5 to 2 times greater than the number of disintegrations of light nuclei.

On the other hand, it is possible that the difference between the conclusion drawn in reference 4 and the one drawn here is due to the difference in proton energy. At 1 Bev, meson production is more important than at 660 Mev, and it is by the absorption of mesons that Philbert and Vigneron explain their results.

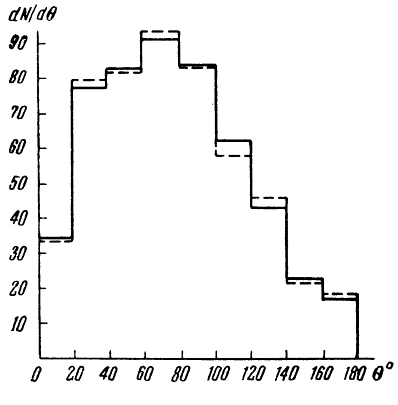

FIG. 3. Angular distribution of α particles from disintegration of C^{12}. Solid curve – all disintegrations, dotted curve – L_1 disintegrations.

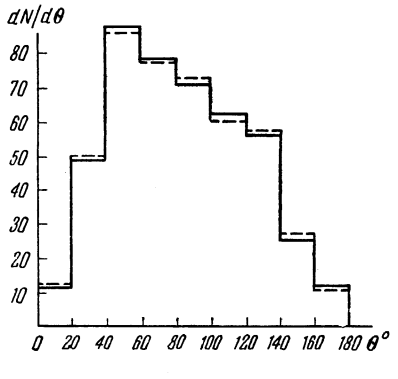

FIG. 4. Angular distribution of protons from disintegration of C^{12}. Solid curve – all disintegrations, dotted curve – L_1 disintegrations.

In addition to comparing the energy and angular distributions in the groups L_1 and L_2, we also compared the types of reactions. The results are shown in the table.

Type of disintegration*	Percent disintegrations	
	L_1	L_2
$2p2\alpha$	50 ± 8.0	38 ± 6.0
$4p\alpha$	18.7 ± 4.5	14.3 ± 3.7
3α	13.8 ± 4.0	2.4 ± 1.5
$p\alpha$ Li	7.5 ± 2.5	14.3 ± 3.7
$2p$ Be	6.2 ± 2.3	11.9 ± 3.4
$6p$	0	9.5 ± 3.0
$2p2\alpha\pi^+$	2.5 ± 1.5	2.4 ± 1.5
$3p$ Li	1.3 ± 1.0	4.8 ± 2.2
$5p$Li π^-	0	2.4 ± 1.5

*Reactions leading to C^{10}, C^{11}, B^{10}, and B^{11} are not considered. The cross sections for these reactions are given in reference 2.

From this table, it appears that there is no difference between the groups L_1 and L_2 as far as types of reaction are concerned, except for stars of type 6p, which appear only in group L_2, and stars 3α, which belong primarily to L_1.

The mean excitation energies for disintegrations in groups L_1 and L_2 are 37 Mev and 55 Mev respectively. The mean excitation energy of 43 Mev is in good agreement with the 42 Mev given by Monte Carlo calculations on the interaction of 660 Mev protons with carbon.

The difference between the mean excitation energies in groups L_1 and L_2 is due to the uneven distribution of 6p and 3α stars over the two groups and the substantial difference between the mean nuclear excitation energies for these two types of stars.

3. ADMIXTURE OF HEAVY-NUCLEUS STARS HAVING TRACKS OF LENGTH $R \leq 50\mu$

The use of the potential barrier criterion to pick out disintegrations of light nuclei introduces a certain admixture of heavy nucleus disintegrations (Ag and Br). To estimate the magnitude of this effect, we studied the disintegration of light and heavy nuclei induced by 660 Mev protons incident on a NIKFI-R type emulsion, registering particles of minimum ionization. All disintegrations were divided into two classes: those with track lengths $5\mu \leq R \leq 50\mu$, and all other (tracks of length $R < 5\mu$ were due to recoil nuclei). Disintegrations of C, N, or O and disintegrations of Ag or Br entered into both of these groups.

Let T_1 be the number of heavy-nucleus stars which do have tracks of length $5\mu \leq R \leq 50\mu$, and T_2 be the number which do not. As mentioned above, L_1 and L_2 are the corresponding numbers for light nuclei. To find T_1, T_2, L_1 and L_2 we can use the following system of equations:

$$L_1/L_2 = C_1, \quad L_1 + T_1 = C_2, \quad L_2 + T_2 = C_3,$$
$$\frac{L_1 + L_2}{T_1 + T_2} = \frac{\sigma_{aC}n_C + \sigma_{aN}n_N + \sigma_{aO}n_O}{\sigma_{aBr}n_{Br} + \sigma_{aAg}n_{Ag}}, \tag{1}$$

where C_1, C_2 and C_3 are experimental constants, σ_{aC}, σ_{aN}, σ_{aO}, σ_{aBr}, σ_{aAg} are the cross sections for absorption of 660 Mev protons by C, N, O, Br and Ag, while n_C, n_N, n_O, n_{Br} and n_{Ag} are the numbers of C, N, O, Br and Ag atoms per unit volume of emulsion.

Analysis of C^{12} disintegrations gives the ratio $L_1/L_2 = 0.96$. C_2 and C_3 were obtained by counting the number of disintegrations having short tracks, and those where all the tracks were longer than 50μ. Since the plates were scanned in two dimensions, all one prong stars and most two prong stars with "gray" tracks were not counted. Hence the number of stars we found in the emulsion must be corrected for the unobserved stars corresponding to the reactions (p, pxn) and (p, 2pxn) on the nuclei C, N, O, Ag, and Br. Taking into account unobserved one and two prong stars, we had 2190 disintegrations. Of these, 450 had tracks with length $5\mu \leqslant R \leqslant 50\mu$ while 1740 had only tracks with $R > 50\mu$. The absorption cross section for the various nuclei in the emulsion were taken from a curve of σ_a against atomic number for 650 Mev protons, as constructed from the data of Moskalev and Gavrilovskiĭ.[5] Substituting our values of C_1, C_2 and C_3 into (1), and the values of σ_a and n for the nuclei in the emulsions, we obtain the following values for the numbers of stars in the sub-groups L_1, L_2, T_1 and T_2:

Number of disintegrations with short tracks and on light nuclei	$L_1 = 264$
Number of disintegrations without short tracks and on light nuclei	$L_2 = 276$
Number of disintegrations with short tracks and on heavy nuclei	$T_1 = 186$
Number of disintegrations without short tracks and on heavy nuclei	$T_2 = 1264$

Comparing T_1 and T_2, we find that the potential barrier criterion breaks down in 12.8% of Ag and Br disintegrations. However, we are mostly interested in how many heavy nuclei are admixed to the group of light nuclei with short tracks.

The following is the distribution of the short track distributions $L_1 + T_1$ by number of prongs:

Number of prongs	2	3	4	5	6	7	8	9	10	11	12	13
Number of disintegrations	12	68	90	108	58	42	38	12	12	4	4	2

All stars with 9 or more prongs we consider to belong to Ag and Br, since all tracks with $5\mu \leq R \leq 50\mu$ we take to belong to α particles, except of course for the case $Z > 2$ (over a short range it is impossible to distinguish between singly and doubly charged particles).

For carbon, we found that 10% of the disintegrations of type L_1 have tracks with length $R < 5\mu$. If the same fraction holds for C, N, and O (it is at least not less than 10%), then the number of L_1 disintegrations having tracks with length $R < 5\mu$ is 26. There are 110 tracks in the group $L_1 + T_1$ with tracks of length $R < 5\mu$. Then 84 of the disintegrations with tracks of length $R < 5\mu$ must be due to the nuclei Ag and Br. Furthermore, of the 332 stars remaining in the group $L_1 + T_1$, having $n \leq 8$ prongs and not containing tracks with $R < 5\mu$, 20 have total charge $Z > 9$ and hence must be disintegrations of heavy nuclei.

Hence we conclude that the number of light nuclei disintegrations satisfying the potential barrier criterion and having total charge $Z \leq 9$ is 312 $[450 - (84 + 34 + 20)]$. Actually, (1) gives 264 as the number of L_1 disintegrations. Hence, application of the potential barrier criterion for picking out disintegrations of light nuclei would have included 48 stars satisfying the criterion $\Sigma Z \leq 9$ but due to Ag and Br. The admixture, 19%, so obtained may be an under-estimate since we assumed that the fraction of C, N, and O disintegrations with track lengths $R < 5\mu$ is the same as for C^{12}. Actually, the number of such disintegrations in a mixture of C, N, and O nuclei might be somewhat larger.

Our value, 12.8%, for the fraction of Ag and Br disintegrations which do not satisfy the potential barrier criterion is in good agreement with the value (15%) obtained by Philbert[3] for 1-Bev protons. As is to be expected, increasing the energy of the incident particle makes it more likely that the heavy nucleus emit a slow α particle.

In conclusion the author would like to express his deep gratitude to A. P. Zhdanov for his constant interest in this work, to L. I. Shur and I. V. Ryzhkova who invested much time and effort in preparing the emulsions for the experiment with carbon and to G. M. Subbotina for help in working over the experimental material.

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