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THE JOINT INSTITUTE FOR NUCLEAR RESEARCH

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D. BLOKHINTSEV

# ON NUCLEAR MATTER FLUCTUATION

ЖЭТФ, 1957, т. 33, в 5, с 1295.

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D. Blokhintsev

In this article it is shown that the appearance of energetic fragments by the collision of fast nucleons with nuclei may be considered a result of the collision of nucleon with the fluctuation of nuclear matter.

## I. Introduction

During the process of the motion of nucleons within the nucleus short compact clusters of nuclei, in other words, the fluctuation of the density of a nucleus can arise. Being relatively removed from the other nucleons of a nucleus such clusters are atomic nuclei of lesser mass in the state of fluctuational compression.

Recently, while studying 675 MeV protons scattering on light nuclei, M.G. Mescheryakov and his collaborators found out the phenomena which confirm the existence of such fluctuations, at any rate, for the simpliest pair fluctuations, leading to the formation of the compressed deuton.

According to this it is necessary to remind of the fact that in a series of the earlier works (3,4) the attention was paid to the formation of the fragments with the energy higher than the potential barier during the collisions (fision) of nuclei with energetic nucleons,ie., fragments, the energy of the motion of which is considerably higher than that of binding as well as the barier height of a nucleon. However, the absence of quantitative data impeded the analysis of these phenomena.

Some authors groundlessly explained this interesting phenomenon at the expense of hypothetical long-range nuclear forces, others connected it with the existence of impair nuclear forces.

The experimental data concering the emergence of the energetic deuton out of light nuclei confirm the notim of the fact that the other fragments with the energy higher the potential barier as well, are also formed as a result of direct collision of a nucleon with a close group of nucleons, which has appeared because of the fluctuation of the density of nucleus.

Further, quantitative arguments for fluctuational origin of energetic deutons and other fragments with energy higher than the potential barier are advanced.

As far as the impair fordes are concerned, it is necessary to note, that the estimation of their magnitude does not give the ground to think that they are rather greater than pair forces (5). At the moment of close raprochement of nucleons interaction by pairs as well as collective interaction can be important. However, now there are no experimental data which should allow to throw light on all the details of this interaction, moreover, to determine relative contribution of interaction by pairs and collective interaction.

## 2. Energetic protons-dautrons interaction

As it was shown by the experiments (1,2) on 675 MeV protons scattering on dutons, except of scattered nucleons, undestroyed deutons of high energy (about 660 MeV), though relatively few of them, are observed. That means that during those collisions a nucleon transferes a deuton an important part of its momentum.

According to the idea of flictuation such collision takes place at the moment when both of the nucleons within a dauton are at a short distance R one from another and they interact very strongly.

In such a case it is possible for a nucleon to transfer its momentum to this close pair as a whole. The expected cross section for such special collision will be:

$$\sigma = \sigma_d \cdot W_d(R) \qquad (1)$$

where $\sigma_d$ is the full quasi-elastic collision cross section, and $W_d(R)$ is the probability of the fact that both of the nucleons of a deuton are at the distance less than R.

According to the order of the magnitude the distance R must be equal to the radius of nucleon strong interaction, that is $2-3\,\frac{\hbar}{Mc}$.
If we denote the deuton wave function by means of $\Psi_d(R)$ we shall have:

$$W_d(R) = 4\pi\int_0^R \Psi_d^2(r)\,r^2 dr = \frac{4\pi}{3}\Psi^2(0)R^3 \qquad (2)$$

In order to calculate $W_d(R)$ it is necessary to know the deuton wave function near r = 0.

The usual deuton asymptotic function $\Psi_d = \sqrt{\frac{\alpha}{2\pi}}\, e^{-\alpha r}/r$ ($\alpha^{-1} = 4{,}3\cdot 10^{-13}$ cm) does not suit absolutely for this purpose, because it turns into infinity when r = 0.

The deuton wave function has no nodes. Therefore we may approximate $u = r\Psi_d$ for large r(s) in the form of $\sqrt{\frac{\alpha}{2\pi}}\, e^{-\alpha r}$, and for small r(s)-in the form $u = \Psi(0)[r - \beta r^2 + \dots]$ and interlock functions and derivatives in the region of $r = b = \frac{1}{2\beta}$.

The quantity $2\beta$ has the meaning of a logarithmic derivative.

This gives us $\Psi(0) \sim \sqrt{\frac{\alpha}{2\pi}}\,\beta$.

Using Hülten function, the calculation leads to the same result, $\beta$ $\boxed{r\Psi_d = \sqrt{\frac{\alpha}{2\pi}}\left(e^{-\alpha r} - e^{-\beta r}\right)}$ being greater $\alpha$ several times according to the assembly of the known data. Not rating at the more than the order of the magnitude we shall put:

$$\Psi_d(0) = \sqrt{\frac{\alpha}{2\pi}}\,\beta \qquad (3)$$

where the quantity $\beta$ is considered determining the logarithmic deriva~~t~~tive of the deuton wave function, where $r = 0$.

From (2) and (3) we shall find:

$$W_d(R) = \frac{2}{3}\,\alpha\,\beta^2 R^3 \qquad (4)$$

If we express R by means of the units

$$\frac{\hbar}{Mc} = 2\,10^{-14}\ \mathrm{cm}$$

then

$$W_d(R) = 7\cdot 10^{-5} R^3 (\beta/\alpha)^2 \qquad (4')$$

While the experimental meaning of this quantity is

$$7\,10^{-3}$$

Therefore, $R^3(\beta/\alpha)^2 \sim 10^2$ which is quite reasonable.

Let us note that neither the theory "pick up", nor impulse" approximation are suitable for our case. Really, it is supposed in both of these methods that the (incident) nucleon interacts either with one nucleon, or with two of them, but independently. In our case under the transfered momenta are so great that the whole of the process is taking place at the expense of very high harmonics of the deuton wave function, i.e., at the expense of such states when both of the nucleons are near to each other and it is impossible to regard their collision with the third nucleon as taking place independently.

An estimation of the quantats W(R) for the other light nuclei is much more difficult.

We may determine quite approximately that, for instance, for tritium the magnitude $W_T(R)$ will be of the order $W_d^2(R)$ with the correction concerning the fact that the magnitude $\alpha_T$ for tritium will be $\sqrt{\frac{m_T \varepsilon_T}{m_d \varepsilon_d}}$ times greater $\alpha$. /Here, $\varepsilon_T$ is the binding energy of tritium, $\varepsilon_d$ of deuton, $m_T$ and $m_d$ are tritium and deutron reduced masses with respect to one nucleon extracted from the nucleus/.

This decrease of $\alpha'_T$ expresses the fact that tritium is a more closely bounded system than that of deuton.

By the same way $\alpha_{He}$ will be $\sqrt{\frac{m_{He}\varepsilon_{He}}{m_d \varepsilon_d}}$ times greater for $He$.

Using the expression, which has been founded, for $W_d(R)$ we will find $W_T \sim 2 \cdot 10^{-4}$, $W_{He} \sim 2 \cdot 10^{-5}$.

These value may be checked up experimentlally later on.

## 3. The Estimation of Fluctuations within Nuclei

Let the wave function of the nuclear $A = Z + N$ be

$$\Psi_A = \Psi_A(x_1, x_2 \dots x_Z, y_1, y_2 \dots y_N) \qquad (5)$$

where $x_1, x_2 \dots$ are proton coordinates and $y_1, y_2, \dots$ are neutron coordinates. As it is known, density operator, for example, of protons will be equal to:

$$\rho(x) = \sum_{k=1}^{Z} \delta(x - x_k) \qquad (6)$$

It is possible to introduce the density operator of the second order by the same way:

$$\rho(x, x') = \sum_{k \neq s}^{Z} \delta(x - x_k)\,\delta(x' - x_s) \qquad (6')$$

In the general case the density operator of the a-order, where z-protons and n-neutrons take part ($a=z+n$ ), will be:

$$\rho(x, x', \ldots x^{(z)}; y, y', \ldots y^{(n)}) =$$

$$= \sum_{k \neq s \neq \ldots} \delta(x-x_k)\delta(x'-x_s)\ldots\delta(y^{(n)}-y_n) \qquad (7)$$

An average value of this density is equal to:

$$\overline{\rho(x, x', \ldots y^{(n)})} = \int \Psi_A^* \rho(x, x', \ldots y^{(n)}) \Psi_A dx_1 dx_2 \ldots dy_N \qquad (8)$$

The exactly calculation of this integral demands the knowledge of the function $\Psi_A$.

However, it is possible to estimate taking into consideration the only fact that this integral must have the following form:

$$\overline{\rho(x, x', \ldots y^{(n)})} = M \cdot D(x, x' \ldots x^{(z)}; y, y', \ldots y^{(n)}) \qquad (9)$$

where D is the density of the probability of the fact that protons ( z ) and neutrons ( n ) are at the points $(x, x', \ldots y^{(n)})$, and the number M is equal to a number of the different permutations of protons and neutrons which should be suitable to realize this configuration

We are interested in the case when relative coordinates of these nucleons $\xi_1, \xi_2, \ldots \xi_{a-1}$ are placed within small volume $\Omega < R^3$.

Introducing still the coordinate of the centre of gravity of this group $X$ and integrating according to $\xi_1, \xi_2, \ldots \xi_{a-1}$ in the volume $\Omega$ and according to $X$ in the nuclear volume, we shall find:

$$\rho_a(\Omega) = M \cdot W_a(R) \qquad (10)$$

where

$$W_a(R) = \int_{\Omega} \Phi(\xi_1, \xi_2 \ldots \xi_{a-1} X)\, d\xi_1 \ldots d\xi_{a-1}\, dX \qquad (11)$$

is the probability of appearance of the group we are interested in and which is squeezed within a small volume $\Omega$.

This probability is close to the corresponding fluctuation probability in a free nucleus with the atomic weight $a = z + n$ because only short distances $R$ are important. It gives an possibility to determine this probability basing t on the experiments on the collision of a nucleon with a free nucleus. (A)[x]

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[x] L.S. Leksin and U.P. Kumekin (6) made an attempt to determine this probability for carbon (C) by the collision (P,C). They did not find out energetic protons, scattered backwards with carborn, as a whole, within the limits of their experiment.

Basing on the estimations made earlier for T and He we may suppose that the probability of the similar fluctuation for C is quite insignificant (worthless).

As far as the factor M is concerned for light nuclei it is equal to a number of (a series of) ways, by means of which it is possible to form the fragment, which we are interested in: in other words, the factor M is proportional, saying roughly, to $Z^2$.

And for those nuclei where the nuclear matter density is spread out like in a liquid drop, the number M will be equal to the number of fragments $a = z + n$ , which are contained within the nucleus, i.e., the number M is proportional to Z. In heavy nuclei it is necessary to take into consideration one more thing- the probability of the energetic fragment (yield) exit out of the nucleos P.

Supposing energetic fragments appear ~~(arise)~~ uniformly over the nuclear volume and move in the direction of the incident nucleon momentum with the free path ~~(range)~~

$$\ell = \frac{1}{n_o \sigma_a} \qquad (12)$$

where $n_0$ is the nucleon density in the nucleus, and

$$\sigma_a \sim \pi r_o^2 a^{2/3}$$

is the cross section of the fragment with the atomic weight a, it is not hard to find out that the fragrant yield probability out of the nucleus will be equal to:

$$P = \frac{3}{\eta}\left[\frac{1}{2} - \frac{1}{\eta^2} + \left(\frac{1}{\eta} + \frac{1}{\eta^2}\right)e^{-\eta}\right] \qquad (13)$$

where $\eta = \frac{D}{\ell}$, $D = 2r_0 A^{1/3}$

is the nuclear diameter. In particular, if $\rho_A \ll 1$,

then $\rho = \frac{\pi r_0^2}{\sigma} A^{-1/3} = \frac{1}{A}\frac{\sigma_A}{\sigma_0}$,

where

$$\sigma_A = \pi r_0^2 A^{2/3}$$

Now taking into considereation all the multipliers ~~(factors)~~, we will have for the cross section the fragment formation with the atomic weight $a$ from the nucleus with the atomic weight A the following expression:

$$\Sigma_a = \rho \cdot M \cdot \sigma_a W_a(R) \cong \frac{\sigma_A}{A} M \cdot W_a(R) \qquad (14)$$

and the yield/outcome of the fragment during one collision with the nucleus will be

$$q_a = \rho M \frac{\sigma_a}{\sigma_A} W_a(R) = \frac{M}{A} W_a(R) \qquad (15)$$

where $\sigma_A$ is the nuclear total cross section.

Specially for the deuton ($a = 2$) and for light nuclei $\rho \cong 1$ and the number M will be equal to the number of ways which are suitable to form the dauton by means of the nuclear nucleons; protons and neutrons have a parallel spin in the deuton, therefore We will get

$$M_d = 2\frac{Z \cdot N}{4} = \frac{1}{2} Z \cdot N.$$

As a result of this we have for deutons

$$\Sigma'_d = \frac{1}{2}\frac{Z \cdot N}{A} \cdot \sigma_A \cdot W_d(R) \qquad (16)$$

from light nuclei.

In the case of heavy nuclei, taking into consideration the nuclear forces saturation $M_d = Z \cdot n$ where n is the number of neutrons which are neighbouring to protons and which have the opposite (counter) spin. This number is $\approx$ 6.

Therefore, for heavy nuclei

$$\Sigma''_d = \frac{Z \cdot n}{A} \sigma_A W_d(R) \qquad (16')$$

The yield is almost constant in this case

$$q''_d = \frac{Zn}{A} W_d(R) \qquad (15')$$

Using the formulae (16) and taking into account ~~consideration~~ that $\sigma_d = 70 \cdot 10^{-27}\,cm^2$ and $W_d(R) \sim 7 \cdot 10^{-3}$ we will get the following figures in mm barns z)

| The element | Li | Be | C | O |
|---|---|---|---|---|
| $\Sigma_d$ | 1,4 | 2,1 | 3,6 | 5,8 |

As far as heavy nuclei are concerned, according to

(15') the expected deuton yield is: $q''_d \sim 2\%$ .

The obtained numbers are in satisfactory accordance with the results of the work (1),x).

The more convincing check-up may be received while studying the yield of deutons out of more heavy nuclei.

Let us notice one more thing that the estimation of the probability of fluctuation in tritium $W_T(Q) \sim 2 \cdot 10^{-4}$ leads to the conclusion that tritium yield must form 2-3% of the dauton yield. This conclusion does not contradict the results of the work. (I).

The quantitative calculations with the fragments which are more heavy than that of deutrons do not have the reliable theoretical basis. Therefore, it would be very interesting to measure the probability of great monumentum transfer by more complete nuclei then the dauton.

Then the possibility to estimate the yield exit of these fragments out of complete nuclei will appear.

In conclusion the author thanks M.G. Mescheryakov and L.G. Leksin for many valuable discussions.

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x/ Comparing these data with the data of the IIId table of the work (I) it is necessary to bear in mind that there the cross section for all the dautons is given, while we have the cross section only for fast deutons. According to the estimations made in (I) and (2), the difference must be brought to the multiplier 3. Therefore, our table is quite satisfactory corresponding with the data given in the table (I).

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