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THE TARGET NUCLEUS AS AN INDICATOR OF VARIOUS PROPERTIES OF THE HADRON-NUCLEON AND HADRON-NUCLEUS COLLISION PROCESSES

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1. INTRODUCTION

It is commonly believed now that the studies of the inelastic hadron-nucleus collisions at high energies might provide such information about the strong interactions of particles which cannot be obtained by investigating hadron-nucleon reactions alone. Recently, beautiful paper written by R.J.Blin-Stoyle has been published [1] in which it is shown that careful and accurate study of certain aspects of the properties of nuclei can continue to throw interesting light on various aspects of elementary particle interactions, the nucleus, as it were, acting as a laboratory in which they reveal themselves. Indeed, information about certain features of these interactions is only accessible in this way. This impressing idea has been developed consequently in low energy nuclear physics mainly, and described widely in the Blin-Stoyle unique book [2]. But, in my opinion, it has been never developed widely enough in high energy nuclear physics as complete and clear method of the target nucleus application in attepmts to elicit information about the hadron-nucleon strong interaction from the high energy hadron-nucleus collision studies. Although, some attempts have been made in the work of T. Ferbel to solve this problem too, as complete as it was possible [3].

In this article I would like to show that the atomic nucleus, being some "piece" of the nuclear matter, might be used in general in high energy physics as "a detector", like the block of material is usually applied as a detector of charged particles in nuclear radiation detection. My aim is to show how might the target nucleus be used in practice as a detector, or as an indicator, of properties of high energy hadron-nucleus or hadron-nucleon interaction processes. This work was undertaken with the hope that the possibility to apply the target nucleus as an detector shall open a new area for experimental studies of the intranuclear processes taking place at high energies and shall provide new experimental information about various interactions of particles, especially about the strong one; many of the existing experimental data can be considered then from the new point of view; various short living many-particle states might be probably investigated experimentally on this way too.

This paper is arranged as follows: after the introduction in section 1, in section 2 I present the heuristic considerations; in section 3 the description is given of some physical phenomenon which allows to use the target nucleus as a detector; in section 4 the general method of application of the target nucleus as a detector is shortly described; in section 5 examples of target nucleus application as such detector are presented; in section 6 the concluding remarks are given.

2. HEURISTIC CONSIDERATIONS

Any nuclear radiation detector consists of a block of some medium which might undergo various local changes when the radiation passes through it, and of the recording system of these changes. As the medium various materials may be used - in gaseous, liquid and solid state; as the recording systems the electronic units or the photographic cameras can usually serve. In some materials, as photonuclear emulsions or mica, various fast particles leave along their paths stable damages which become to be visible after appropriate chemical processing.

In any of the nuclear radiation detectors some physical process accompanying the passage of the particle of energy high enough through the material is used as a basis of action; such process should proceed in strictly determined manner and must be simply observed. For example: the basic principle of the operation of the ionization chamber and Geiger counter is that ionizing radiation passing through a gas-filled container produces positive ions and electrons in the gas which may be, for instance, argon. The basic principle of the operation of the cloud chamber is that a saturated vapour may not condense on a particle which is smaller than a certain minimum size, but may condense on the same size particle, if is electrically charged, being an ion, for instance, produced in ionization process accompanying the fast particle traversing the chamber filling material. Nuclear emulsion consists of grains of silver halides, mainly AgBr, dispersed in a gelatin; the reaction of this material to photons and to charged particles depends on the ionization produced in the sensitive grains, the ionization renders some grains developable; with charged particles, ionization results from the interaction between the atomic electrons and the field of the moving particles; with photons, electrons are ejected from atoms by photoelectric process.

It is clear therefore that before such "block" of the nuclear matter as the atomic nucleus can be considered to serve as the "detector" of the high energy particles traversing it and of various properties of hadron-nucleus and hadron-nucleon interaction processes, some physical effect caused by high energy hadrons traversing nuclear matter must be discovered and deeply elucidated; this effect should be going on in a strictly determined way and must be accompanied by simply observed "macroscopic" phenomenon.

Therefore, we have analysed many "visible" phenomena which accompany high energy hadrons in their passing through nuclear matter, in order to try use them as the basic of the target nucleus operation as a detector. After wide and accurate studies, performed in our group [4], we decide that the nucleon emission accompanying high energy hadrons traversing atomic nuclei might be used as such basic principle. This emission we have discussed in our special papers [5].

In the next section we shall present most important features of this phenomenon and we discuss the applicability of it as the basic principle of the target nucleus operation as a detector.

3. THE BASIC OPERATION PRINCIPLE OF THE TARGET NUCLEUS AS A DETECTOR

Fast nucleons, of kinetic energies from nearly 20 to nearly 400 MeV, are copiously emitted in high energy hadron-nucleus collisions, as we can conclude from the usually observed in experiments emission of the protons. The events are discovered in which the hadron induces such emission in colliding with the atomic nucleus without causing multiparticle creation, even if the hadron is of the kinetic energy high enough to be able to produce many particles as well [4]. These events were selected in the 180 litre xenon bubble chamber [6] exposed to the negative charged pion beam of 3.5 GeV/c momentum; various characteristics of the emitted protons in such special sample of hadron-nucleus collisions were analysed [4,5]. In such events the projectile hadrons deflect through some deflection angles θ_h in passing through nuclear matter in accompaniment by the nucleon emission. The plane in which the courses of the hadron lie, before and after the collision with the target nucleus, we call, as usually, the reaction plane. For any proton emitted from the reaction region, which we call "the reaction point", we ascribe the following angular characteristics: a) the zenith angle θ_p - the angle between the incident hadron course and the proton emission direction; b) the azimuth angle θ_p - the angle between the reaction plane and the proton emission plane, i.e., the plane in which the incident hadron course and the proton emission direction lie. The azimuth angle increases from its 0 to its 360 degrees value, if the proton emission plane is turned around the hadron course to the left from the position when both the deflected hadron and the emitted proton courses lie in the same semiplane. For any proton the kinetic energy has been estimated. For any hadron-nucleus collision event the deflection angle and the number of emitted protons were accurately estimated. The average accuracy of the proton kinetic energy measurement, using the range-energy relation, is nearly 4%. The average accuracy of the proton emission angle measurement is nearly 3 degrees; the accuracy of the pion deflection angle measurement amounts to nearly 1 degree.

From the analysis of these selected events it follows that:

1) The average multiplicity of the emitted fast protons equals $\bar{n}_p = 2.77 \pm 0.27$ and increases with the projectile deflection angle θ_h from $\bar{n}_p \doteq 0.5$ at $\theta_h \leq 10$ degrees to $\bar{n}_p \doteq 4.5$ at $30 \leq \theta_h \leq 40$ degrees; at higher values of θ_h it can be considered to be almost constant, being $\bar{n}_p \doteq 5.3$.

2) The ratio f between the number of protons emitted to the forward direction N_f and those emitted to the backward hemisphere N_b seems to be not depending on the proton multiplicity at $n_p > 1$, being in average $f = 1.80 \pm 0.20$; this ratio behaves itself similarly in the total sample of the pion-xenon nucleus collision events - in the sample of both, without multiparticle creation and those with it, being $f = 2.05 \pm 0.07$ [5].

3) The energy spectra of fast protons emitted forward and of those emitted in backward direction are lying in practically the same kinetic energy intervals 20-250 MeV; the shapes of the spectra in both these samples of events are practically the same [4].

4) The asymmetry is observed in the proton emission azimuth angle distribution. This asymmetry is expressed by the ratios a_1 and a_2:

$$a_1 = \frac{2N(0 \pm \Delta\phi)}{N(90 \pm \Delta\phi) + N(270 \pm \Delta\phi)}, \quad a_2 = \frac{2N(180 \pm \Delta\phi)}{N(90 \pm \Delta\phi) + N(270 \pm \Delta\phi)}, \qquad (1)$$

where $N(0 \pm \Delta\phi)$, $N(90 \pm \Delta\phi)$, $N(180 \pm \Delta\phi)$ and $N(270 \pm \Delta\phi)$ are the numbers of the protons emitted within some azimuth angle value limits $\pm\Delta\phi = 22.5$ degrees = const, starting from 0, 90, 180, and 270 degrees correspondingly. The confidence level of these data is still low, but they might be accepted to be an indication that the proton emission goes on from a limited part of the target nucleus [5]; it is observed the asymmetry a_2 which

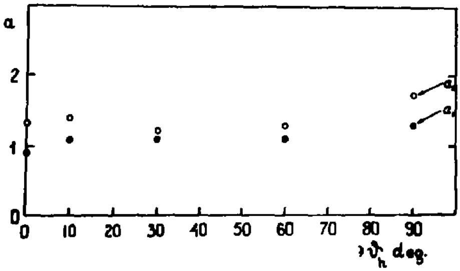

Fig.1. Azimuth asymmetry a_1 and a_2 dependence on the hadron deflection angle θ_h.

can be considered as appearing due to the existence of the additional nucleon emission caused by the recoil nucleon of energy high enough to be able to start such emission in nuclear matter. Both the values a_1 and a_2 change in definite manner with the increasing of the projectile deflection angle θ_h; it is shown in fig.1. The observed behaviour of these asymmetries with increasing the deflection angle of the projectile hadron indicates too that the nucleon emission follows the hadron course /5/.

5) The observed proton multiplicity distribution is inmonotonous /4/ two different smooth parts may be distinguished in it, one within the proton multiplicity values from 0 to 5 and the second one at the multiplicities larger than 5; this inmonotony disappears when the projectile deflection angle decreases - at $\theta_h \leq 30$ degrees the distribution is smooth. This inmonotony can be caused by the additional nucleon emission induced by the recoil nucleons of energies high enough to be able to do it; such recoil nucleons can appear sometimes along the projectile path inside nuclear matter /5/.

6) The proton multiplicity distribution is reproduced by the simple formula derived on the basis of the working hypothesis: a) High energy hadron traversing the nuclear matter causes monotonous emission of fast nucleons along its path; the number of emitted nucleons equals to the number of nucleons met in the neighbourhood to the path of this hadron; in particular, the number of the emitted protons equals to the number of the protons met /5/:

$$n_p = \pi \cdot D_0^2 \cdot \bar{\rho} \cdot \frac{Z}{A} \cdot \lambda = 2 \cdot \pi \cdot D_0^2 \cdot \bar{\rho} \cdot \frac{Z}{A} \sqrt{R^2 - \ell^2} , \qquad (2)$$

where D_0 denotes the nucleon diameter, $\bar{\rho}$ denotes the average nucleon density along the hadron path λ inside the target nucleus. R is the nucleus diameter, ℓ is the impact parameter, Z/A is the ratio between the proton number and the number of all the nucleons inside the target nucleus being accepted to be independent of the distance r from its center. b) This monotonous emission is usually disturbed by additional monotomous emission caused by the recoil nucleons, of energies high enough to be able to cause such emission too, which appear along the projectile hadron path with the intensity proportional to the path length. The formula for the proton multiplicity distribution has been derived in our work [5]: its general form is:

$$W(n) = W_0(n) \cdot e^{-\mu_s \cdot \bar{\lambda}(n) \cdot \bar{\rho}(n)} + \sum_{i=0}^{i=n-1} w_{in} \cdot W_0(i) \cdot [1 - e^{-\mu_s \cdot \bar{\lambda}(i) \cdot \bar{\rho}(i)}], \tag{3}$$

where W_0 is the function of the target nucleus radius R and the radial nucleon density distribution in it; μ_s is the coefficient accounting the existence of the single elastic scattering leading to the appearance of the recoil nucleon being of energy large enouth to be able to start the monotonous nucleon emission in nuclear matter in ones turn; w_{in} are the coefficients indicating the transition of the events which could be belonging to those with the proton multiplicity $i<n$ to those with the multiplicity n. The first term in the formula (3) describes accurately the proton multiplicity distribution of such hadron-nucleus collision events in which the monotonous nucleon emission takes place only (table 2 in my previous work [5] and fig.2 in this work). The second term has been expressed in our former works in various approximate manner [4,5].

The analysis of the total sample of the above-mentioned experimental facts, in spite of the low confidence level of some of these, shows that high energy hadrons of kinetic energies higher than some of $\epsilon_{h\,min}$ [4,5] cause monotonously fast nucleon emission in passing through nuclear matter. The emission starts from a vessel-shape spatial region situated along the hadron course; the number of emitted nucleons is proportional to the path length of the projectile inside the target nucleus [5], it equals the number of nucleons met in the neighbourhood to this path [4,5]. The nucleon emission intensity distribution of the special sample of the hadron-nucleus collision events being under consideration is determined by the geometry of the target nucleus, exactly speaking - by its dimensions and the radial nucleon density distribution in it [5]. It seems to be mostly probable that this emission goes on via some two or more nucleon intermediate systems [4,5].

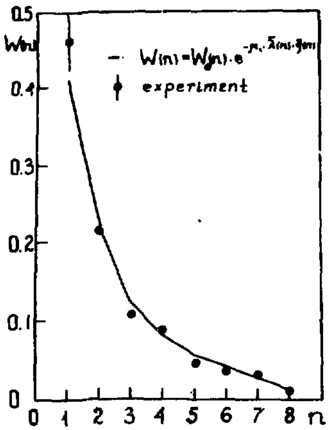

Fig.2. Proton multiplicity distribution in pion-xenon nucleus collision events at 3.5 GeV/c momentum in which pure monotonous nucleon emission takes place only. Solid curve presents the distribution predicted by the first term of the formula (3).

The properties of the nucleon emission process correspond well to the properties desired for any physical phenomenon which has to serve as a basic principle of the operation of any detector: the nucleon emission goes on in a strictly definite manner - it starts from the narrow vessel-shape region along the hadron course inside the target nucleus and its intensity is proportional to the path length of the hadron in nuclear matter; the protons are emitted copiously and are simply observed.

It should be noted that the proportionality of the number of emitted protons to the hadron path length in nuclear matter follows from the fast proton emission studies performed by means of the electronic techniques as well /7/.

The sample of the experimental facts presented above has been received in studying only one hadron-nucleus reaction at one definite momentum; namely, we have studied the pion-xenon nucleus special collision events at 3.5 GeV/c momentum. The question arises therefore: is this nucleon emission going on in the same manner at different energies when induced by the same incident hadrons, and if various hadrons of various energies pass through the nuclei? The analysis of fast proton emission observed in hadron-nucleus collisions registered in various chambers and in photonuclear emulsions shows that it goes on in the same manner at wide energy range of incident hadrons, from nearly 3 to nearly 400 GeV in proton-nucleus, and from nearly 3 to nearly 200 GeV in pion-nucleus collisions /5/.

Therefore, the fast nucleon emission in hadron-nucleus collisions is the phenomenon which we shall use as the basic for the target nucleus operation as a detector. In the next section practical method how the target nucleus should be used as a detector is shortly described.

4. THE METHOD OF APPLICATION OF THE TARGET NUCLEUS AS A DETECTOR

The application method of the target nucleus as a detector of the properties of the hadron-nucleus and hadron-nucleon interaction processes follows from the basic principle described in the foregoing section.

Firstly, the target nucleus should be applied in such conditions at which it is possible to observe effectively the emitted fast protons and to measure their angular and energy characteristics. As an example of such conditions is the target nucleus used in the bubble chamber filled with the medium consisting of one sort of the atoms - xenon, neon; if the chamber filling consists of many various atoms, there should be a possibility to identify what of atomic nucleus is colliding the incident hadron with.

Secondly, it must be possible to collect large sample of various types of the hadron-nucleus collision events.

The method of the target nucleus application consists in: a) The preparation of various possible characteristics of the emitted protons - proton multiplicity distributions of hadron-nucleus collision events, energy spectra, angular characteristics of the proton emission. b) The accurate analysis of the sample of such characteristics which has to be performed on the basis of the information about the fast nucleon emission process. c) The comparison of the characteristics with predictions of appropriate picture based on the monotonous nucleon emission process.

We have given above shortly a general application procedure. It is very difficult to give more clear description of this method without using some examples. Therefore, in the next section we give various examples of the target nucleus application as a detector; these examples are of more wide significance.

5. EXAMPLES OF THE TARGET NUCLEUS APPLICATION AS A DETECTOR

The examples presented here are based on the experimental material collected in investigating the hadron-nucleus collisions using the photographs of the 180 litre xenon bubble chamber [6] exposed to 3.5 GeV negative charged pion beam [4], the 2 meter propane bubble chamber exposed to 40 GeV negative charged pion beam [8], and nuclear emulsions irradiated in 3.6 GeV proton beam [9], in 200 GeV pion and proton beams [10], and in 400 GeV proton beam [11].

5.1. Example I

The problem to be solved firstly, using the target nucleus as a detector, is connected with the experimental value of the data from the hadron-nucleus collision investigations for the particle creation process elucidation in the hadron-nucleon high energy reactions, or, to put it bluntly: how is the multiparticle creation process in hadron-nucleon collisions going on? Do the colliding hadrons create some intermediate state, or states, which decay into the multiparticle channels after some time, after having left the target nucleus or the multiparticle channels appear immediately, just inside the target nucleus? If the first case takes place, how the intermediate state behaves itself in passing through nuclear matter.

First of all, let us specify which target nucleus should be used as a detector in solving the above-formulated problem. Secondly, let us determine the sort and energy of the hadrons which have to be used in investigations.

The target nucleus of dimensions as large as possible should be applied, in order to have a possibility for the incident hadron and of the products of its interactions inside the nucleus to pass relatively long paths in nuclear matter. The projectile hadron energies should be as large as it is needed for the intensive particle creation in the hadron-nucleon interactions, but these energies should be not too high, because the directions of the secondaries ejection must be widely spaced as far as possible. The last condition provides a possibility for the secondaries to interact with the nuclear matter inside the target nucleus, if they are created there; from many investigations of the elementary hadron-nucleon interactions, we conclude that such condition exists at energies of some gigaelectronovolts. We note that the condition limiting the projectile hadron energy value shall be removed, in many cases of the hadron-nucleon collision process investigation, when the multiparticle creation act goes on via some intermediate system.

Third condition which must be fulfilled is to have the possibility to detect effectively the emitted fast protons, and to estimate their emission intensity, energy spectra, and angular distributions.

All these conditions we meet with in the heavy liquid bubble chambers and photonuclear emulsions irradiated in various high energy particle beams. We can use therefore the existing experimental material in order to solve the above-formulated problems.

For this reason we use the data from the pion-xenon nucleus collision studies in the 180 litre xenon bubble chamber exposed to 3.5 GeV/c momentum negative charged pion beam. It should be pointed out that in the case under consideration this chamber is highly effective detector of 4π solid angle aperture for the charged secondaries and for the neutral pions [4].

Let us consider the average proton multiplicity $\bar{n}_p$ distribution in the pion-xenon nucleus collision events with various numbers n_π of emitted secondary pions, $n_{\pi^{+o-}} = 0,1,2,3,\ldots$. We see that $\bar{n}_p$ does not charge practically, if $n_{\pi^{+o-}}$ changes from 1 to 8, being $\bar{n}_p \doteq 3.2 \pm 0.3$ [4,12]; at $n_{\pi^{+o-}} = 0$ $\bar{n}_p \doteq 8$. The generated pions are usually of energies larger than $\epsilon_{h\,min}$ and, therefore, they should cause the monotonous nucleon emission in passing through nuclear matter; the experimental data show they didn't do it. Therefore, we have an indication that these pions appear outside the target nucleus, and the pion creation process might go on via some intermediate system.

Another information of great value in the considerations of the particle creation process in hadron-nucleon collisions gives the comparison of the experimental proton multiplicity distribution of the hadron-nucleus collision events registered in experiment with the predicted one. The precise reproduction of the experimental proton multiplicity distribution by the appropriate formula which has to describe it shall support simply initial conditions at which this formula was derived.

If we suppose that the multiparticle creation goes on via some intermediate state which follows the incident hadron course inside nuclear matter, and behaves themselves there as any hadron does it, we can apply the formula (3) in order to predict the proton multiplicity distribution in all the sample of the hadron nucleus collision events. It was not found necessary to repeat the argumentation used in applying this formula for the case under consideration; such argumentation is given in our papers [5]. The results presented there state good agreement of both the distributions, the predicted and the experimental one.

Therefore, we have new argumentation that the multiparticle creation act goes via some intermediate system; this system causes the monotonous nucleon emission as any high energy hadron does.

Our formula (3) should be applicable, therefore, for the description of the existing proton multiplicity distribution in the pion-carbon nucleus collisions at 40 GeV energy [8], and for the description of the existing grey prong multiplicity distributions in proton-nucleus and pion-nucleus collisions registered at various energies, from 3.6 to 400 GeV, in photonuclear emulsions[9-11]. Appropriate results are presented in figs.2 and 3 in our former work[5]. We see that the proton multiplicity distribution of high energy hadron-nucleus collisions might be described well using this simple formula. Therefore, we are able to state that the multiparticle creation act goes on via some intermediate state.

This intermediate state decays after having left the target nucleus. The lower limit of its life time might be estimated: $\tau = 2R/v$, where $2R$ is the target nucleus diameter, v - the incident hadron velocity. If $v \doteq c = 3.10^{10}\,\mathrm{cm\,s^{-1}}$ and $2R \doteq 27$ fm $2.7 \cdot 10^{-12}$ cm, we have $\tau = 9.10^{-23}$s. But, in our case $v \ll c$, then we can write that $\tau > 10^{-22}$s.

The events are observed in experiment[4] in which the incident hadron undergoes the deflection through large deflection angle, up to nearly 150 degrees, without multiparticle production. We can conclude therefore that the impact parameter d for the particle creation act in the hadron-nucleon collisions should be much smaller than the nucleon radius,

$$d \ll \frac{D_0}{2} .$$

5.2. Example II

We would like to know how the emission of the fast protons into the backward hemisphere is going on. Is it caused by the multiple scattering of the protons inside the target nucleus?

The deflection that a nucleon undergoes in traversing nuclear matter of a finite thickness may be caused either by a single collision or by many subsequent collisions. It can be proved that large deflections are more likely to occur in single collisions, while small deflections are generally caused by many collisions. In both the cases the probability for the proton to be deflected through some angle θ_p is proportional to its path length inside the nuclear matter.

We know that the thickness of the nuclear matter which is overcome by the high energy hadron in the hadron-nucleus collision is larger in the cases with larger proton multiplicity; it follows from the proportionality of the number of emitted protons to the nuclear matter thickness, formula (2). Therefore, the ratio between the number of the protons emitted to the forward hemisphere and those emitted to the backward hemisphere should decrease with increasing the proton multiplicity n_p, if the protons come from the target nucleus region in the neighbourhood to the hadron trajectory. This ratio is

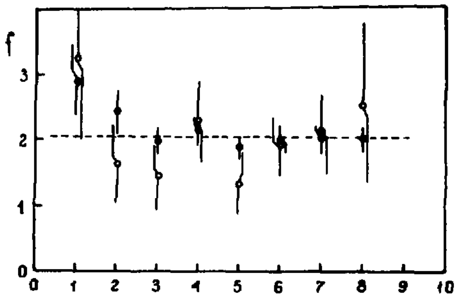

Fig.3. The ratio $f = \frac{N_f}{N_b}$ between the numbers of protons emitted to the forward hemisphere N_f and those emitted to the backward hemisphere N_b, in the pion-xenon nucleus collisions at 3.5 GeV/c momentum [4]. ● - all pion-nucleus collision events, O - the pion-nucleus collision events without multiparticle creation, dotted line - corresponding average value.

presented in fig.3; it is almost constant in both the classes of the pion-nucleus collisions: those with the multiparticle creation acts and those without multiparticle creation.

We might state, therefore, that the backward emission of the fast protons is not caused by the backward proton scattering inside nuclear matter; some different mechanism should be applied for the explanation of this emission into the backward hemisphere.

6. CONCLUSIONS

We might summarize the whole discussion in a few words: the target nucleus can serve as a detector of various properties of the hadron-nucleon and hadron-nucleus collision processes.

It was not found necessary to give now numerous samples of such detector applications; it was attempted only to show that the target nucleus in fact can operate as the detector.

Now, our aim is simple: to look for the direct methods to receive wide and new experimental information about the hadron-nucleon collision processes. We are trying to open new ways and alleys for further experimental investigations of the particle creation and particle interaction processes. For such studies new methods must be applied in which the target nucleus as a detector should play an important role. We hope to be true the sentence expressed in the review article of W.Busza [13]: "The nucleus is the only tool available which allows, in direct way, the experimental study of such intriguing topics as: the space-time development of the particle production; the interaction of resonances with nucleons; and perhaps even the interaction of almost free quarks".

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