СООБЩЕНИЯ
ОБЪЕДИНЕННОГО
ИНСТИТУТА
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ

Дубна

E1-96-121

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HADRONS AS PROBES FOR EXPLORATION INTO INTRANUCLEAR MATTER

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1996

1. INTRODUCTION

The subject matter in this work is to present some answer for the commonly known question — difficult but mostly fascinating of the problems in nuclear physics: how to untangle the mystery of intranuclear matter properties, in a model-independent way, from nuclear collisions of strongly interacting probes with atomic nuclei?

Rutherford has introduced a method for investigating the constituents of matter by means of beams of electrically charged particles directed onto thin slabs of materials; the importance of it is not diminished today. Almost 80 years ago H.Geiger and E.Marsden, two Rutherford's students directed a beam of fast alpha particles onto thin slabs of gold. Using a screen of fluorescent material, they then counted the number of particles scattered at various angles as a result of encounters with the gold atoms [1].

The exploration of atomic nuclei is undeniably fascinating; it started from the work of Rutherford [2] in which he analysed how alpha particles are scattered from atoms in thin metal foils and concluded that the atom is not a homogeneous body but consists of negatively charged electrons surrounding an evidently small massive, positively charged atomic nucleus.

Accurate measurements of the matter distribution in target nuclei involve the interactions of probe projectiles with them and these interactions should be of either electromagnetic or nuclear nature. The scattering of high-speed charged particles by nuclei of atom is one of the most promising methods of attacking this problem. Such measurements were performed in R.Hofstadter's experiments about 40 years ago [3—6].

After the Hofstadter's works, it is clear that our knowledge about the nuclear matter distribution is substantial, but so is our ignorance. The works of Hofstadter and his associates at Stanford have shown that: many aspects about nuclear matter distribution are now so firmly established that it has been possible to use them in order to investigate other physical quantities. Although there is inadequate direct evidence on the neutron distribution, however the indications are quite strong that the neutron distribution does not differ by much from the proton distribution. It becomes to be clear that the only probes of the whole matter distribution must be strongly interacting; we can think of electron scattering as determining the distribution of protons only in the nucleus.

Our main purpose in this paper is to discuss the techniques and methods for determining the properties of whole intranuclear matter, and assess its reliability. Some of reviews of the techniques which have been used to determine the ground states of matter distribution in finite nuclei will be useful [7].

The considerations here will be based on information about hadron collisions with atomic nuclei and about the hadron passages through intranuclear matter layers; appropriate data are obtained experimentally [8—17].

Our preliminary data on the processes in question indicate that the main purposes in the investigations are: to elaborate effective method of fast hadrons applications as probes for exploration of the atomic nuclei and of the intranuclear matter properties. It may be worked out just now. We can in fact explore the processes taking place inside atomic nuclei, within the sizes from about 10^{-13} up to about 10^{-12} cm within the time intervals from about 10^{-23} up to about 10^{-22} seconds.

2. OPERATIONAL PRINCIPLE OF HADRONIC PROBES APPLICATION FOR EXPLORATION OF THE ATOMIC NUCLEI INTERIOR

In absence of the strong interaction theory, experimental investigations of the intranuclear matter properties by means of hadronic probes should be based on some simply observable and experimentally perfectly recognized a nuclear phenomenon. The hadron passage through atomic nucleus found some years ago [8], can be employed as such basic phenomenon. This passage is some nuclear analogue of the well-known electromagnetic process — of the passage of charged particle through layers of materials. The hadron passage through layers of intranuclear matter proceeds accompanied by the emission of fast nucleons with kinetic energies from about 20 up to about 500 MeV, from the target nucleus; this emission is observable effectively enough, with about 100% of efficiency.

In passing through layers of intranuclear matter, a definite part of the target nucleus is involved only — the channel with the diameter $2R_h$ centered on the hadronic probe course [8]; R_h is the strong interaction range approximately as large as the nucleon diameter D_o is, $R_h \approx D_o$. The emission of the observable «fast» nucleons (protons) proceeds in a definite manner — the number or multiplicity n_N of the emitted nucleons is almost strictly defined by the hadronic probe path length covered in intranuclear matter [8]. The finding of the hadron passage through layers of the intranuclear matter allows one to hope that:

a) Any hadron may serve as effective probe of exploration into intranuclear matter;

b) Experimental investigations in a new branch of physics — in the intranuclear physics — will start.

3. THE ATOMIC NUCLEI AS SLABS OF INTRANUCLEAR MATTER

In a numerous sample of collisions of a hadron with a definite spatially unpolarized massive atomic nucleus, the target can be treated as a spherical object of intranuclear matter with a definite maximum thickness $\lambda_{\max} = D$, where D is the nucleus diameter, $\langle \lambda \rangle$ the mean thickness, and $\lambda(b)$ the thickness at the distance b from the nuclear centre or, in other words, at the impact parameter b [18]. It is convenient to express these thicknesses and the distance b in nucleons/S, where S is an area which can be as large as $\pi D_o^2 \approx 10$ fm^2, D_o is the nucleon diameter; such a length or thickness unit is similar to that in g/cm^2 used frequently in measurements of the thicknesses of the layers of materials with inhomogeneous densities.

The quantities $\langle \lambda \rangle$ and $\lambda_{\max}$ in dependence on the mass number A of various atomic nuclei are given on Fig.1. These quantities and the quantity $\lambda(b)$ can be evaluated [19,20] on the basis of experimental data obtained in the Hofstadter's works [3—6].

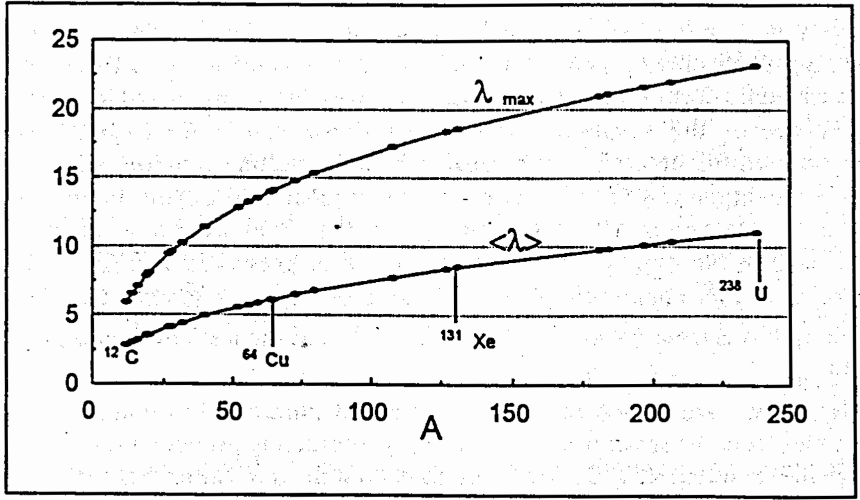

Fig.1. The maximum thickness $\lambda_{\max}$ and the mean thickness $\langle \lambda \rangle$ of the atomic nuclei with mass number A, in [nucleons/S], $S \approx 10$ fm^2

Any spherical object can be treated as consisting of a sample of axially centered disc-shaped slabs of various radii and thicknesses; the target-nucleus can be treated as a sample of axially centered such disc-shaped slabs of intranuclear matter.

A numerous sample of hadron-nucleus collisions can be regarded as a collection of subsamples of the collisions of hadrons with the disc-shaped slabs of intranuclear matter of definite thicknesses $\Delta\lambda(\Delta b)$ depending on Δb. In any of collisions the target nucleus is destroyed, but new identical nucleus is involved in any of them.

Thus, any of the subsamples of collisions with a definite multiplicity of emitted nucleons can be treated as an interaction of a homogeneous beam of identical hadrons with a slab of intranuclear matter of definite thickness [18].

4. THE PROBES FOR EXPLORATION OF THE INTRANUCLEAR MATTER

After the analysis of the methods of nuclei exploration reviewed shortly in section 1, one is led to the conclusion that the only probes of the whole matter studies inside atomic nuclei must be strongly interacting — hadronic. In order to obtain information about the electrically charged component in the intranuclear matter (protons) it will be useful to use charged hadrons — pions and nucleons, first of all. A particle that has certain momentum p also has associated with it the De Broglie's wavelength Λ; the formula that relates this property is $\Lambda = h/p$, where h is Planck's constant (Fig.2). The accuracy to which a particle may be located is limited by the associated wave. The accuracy Δx to which the location of an unknown structure can be recognized by the probe is governed by the momentum transfer q experienced in the hadronic probe collision with the object under localization; the resulting relation is $\Delta x = h/q$ (Fig.3). In other words, our ability to distinguish fine details in the target nucleus depends on making q as large as it is possible in order to make the Λ as small as possible (Fig.3). The relation $\Lambda - p$ is presented in Fig.2; for the hadron with the momentum p values from about 2 up to about 9 GeV/c, the wavelength Λ is from about 10^{-14} up to $2\cdot10^{-15}$ cm; the nucleon radius is about 10^{-13} cm.

Hence we are led to the problem: how to untangle intranuclear matter properties from the scattering of the strongly interacting probes with nuclei, in a model-independent way. Before to discuss about the nuclear probes, let us write a few words about the electromagnetic probes, too. Accurate measurements of the matter distribution in target nuclei involve the interactions of probe projectiles with them and these interactions can be of either electromagnetic or

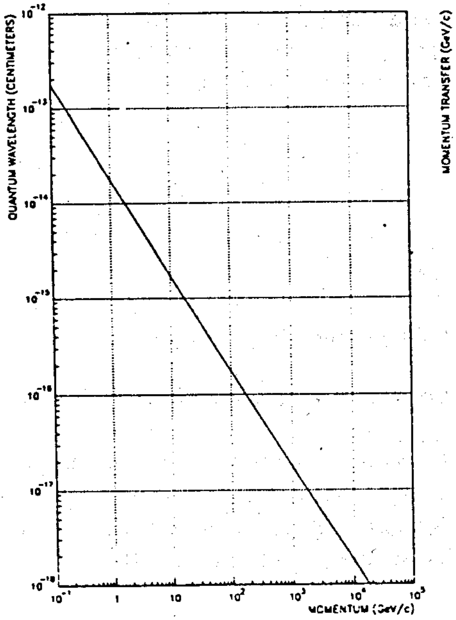

Fig.2. The L.De Broglie's wavelength Λ in dependence on the particle momentum p [GeV/c].

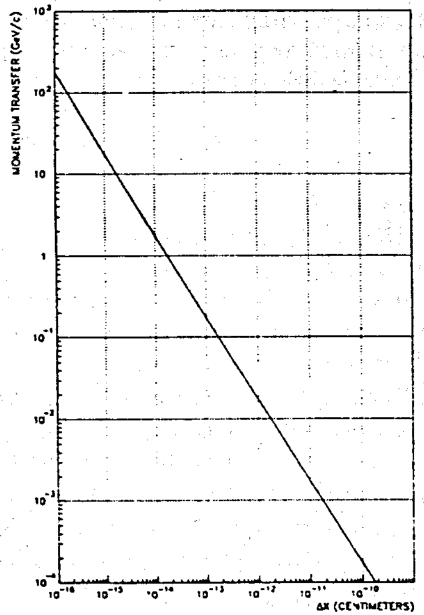

Fig.3. The relation $\Delta x = h/q$

nuclear nature. As we know so much more about electromagnetic ones, it was tempting to conduct investigations mainly with electron beams, but unfortunately, information about the distributions of electrically charged constituents in intranuclear matter could be obtained this way only.

Because of our great knowledge of the mechanism of electromagnetic interactions we were able to state with considerable confidence that a nucleus could be represented by a central electrostatic potential and deduce the properties of the potential comparing our predictions with the experimental results. But no such clear prescriptions can be given in the case of nuclear interactions.

4.1. The Electromagnetic Probes

The scattering of high energy charged particle by atomic nuclei is one of the most promising methods of attacking the ptoblem when the distribution of the charged component in the intranuclear matter is needed only. Such measurements were performed in R.Hofstadter's experiments [3—6]. In such experiments, conclusive information could be obtained very exactly since the relationships between charge and magnetic moment distributions and the electromagnetic potentials due to these are well known from Maxwell's theory.

4.2. The Strongly Interacting Probes

So as things stand now, in the absence of an adequate nuclear force theory, we proposed [11] employ some nuclear phenomenon occurring plentifully in hadron-nucleus collisions as the physical principle of a new method for exploration of intranuclear matter properties by means of strongly interacting probes falling on atomic nuclei. The phenomenon should be simply observable and conclusively recognizable.

In our opinion, the passage of hadrons through the atomic nucleus satisfies the desired conditions.

The hadronic projectile as the probe is characterized by some its properties which manifest themselves in exploring the target nucleus:

1) Only definite, relatively small part of the target nucleus is involved in the hadron-nucleus collision — the cylindrical volume of the radius R_h centered on the hadron course.

2) The collision mean free path l_c is given by relation $l_c = 1/(\rho\sigma_c)$ which is path travelled, on the average, in intranuclear matter by the probe before being involved into a collision:

$$l_c\ [\mathrm{fm}]\,\rho\ [\frac{\mathrm{nucleons}}{\mathrm{fm}^3}] = l_c\ [\mathrm{nucleons/fm}^2] = \frac{1}{\sigma}, \qquad (1)$$

where l_c [nucleons/fm^2] is the mean free path expressed in units convenient in use when the intranuclear matter density ρ [nucleons/fm^3] varies markedly, as it is in fact when intranuclear matter sheets at various distance from the nucleus center are in use [3—6].

It is naturally convenient to use the unit [nucleons/S] for distances in nuclei, where $S = \pi R_h^2 \approx \pi D_o^2 = 10.292$ [fm^2] ≈ 10 [fm^2] and R_h is the strong interactios range as large approximately as the nucleon diameter $D_o \approx R_h$ is [24].

3) The hadronic projectile in its passage through atomic nucleus, leaves observable [8,9,21—23] «track» — the projectile causes the emission from the target-nucleus «fast» nucleons with kinetic energy from about 20 up about 500 MeV [21].

4) The laws of the fast nucleon emission and nuclear fragment evaporation from nuclei bombarded by high energy hadrons were discovered [21]:

I. Any hadron with kinetic energy higher than the pion production threshold causes fast nucleon emission from the target nuclei in traversing them along a path l [fm]; the number n_N of emitted nucleons equals the number of nucleons contained within the cylindrical volume $v = \pi D_o^2 l$ [fm^3] centered on l in the target nucleus:

$$n_N = \pi D_o^2 l \langle \rho \rangle\ [\mathrm{nucleons/fm}^2]\,. \qquad (2)$$

where D_o is the diameter of the nucleon, $D_o = R_h$ [fm] and $\langle \rho \rangle$ in [nucleons/fm^3] is the mean density of nucleons inside the volume v.

Relation (2) can be expressed simply and more conventiently for applications

$$n_N = lS\ [\mathrm{nucleons}/S] \qquad (2')$$

when l is expressed in [nucleons/S] units, where $S = \pi R_h^2 \approx \pi D_o^2$. Relation (2') allows one to conclude additionally that the nucleon emission proceeds fluently along l [nucleons/S].

II. In passing through nuclear matter, any hadron of kinetic energy larger than the pion production threshold loses fluently its kinetic energy; the energy ΔE_n [MeV] of the hadron lost on the path length Δl [nucleons/S] equals

$$\Delta E_n = \varepsilon_n \Delta l, \qquad (3)$$

where ε_n [MeV/(nucleons/S)] depends on the hadron identity. From exepriments [10,25]: for the pions $\varepsilon_\pi = 180$ [MeV/(nucleons/S)] and for the protons $\varepsilon_p = 360$ [MeV/(nucleons/S)].

III. Energy and momentum spectra and angular distrubutions of nucleons appeared in the fluent nucleon emission process are independent of the projectile energy and identity, in the target nucleus system of reference and of the number n_N of emitted nucleons and of the number n_π of produced pions in hadron-nucleus collisions.

IV. Any hadron of kinetic energy larger than the pion production threshold causes nucleon emission from the target nucleus in any-type collision with it; the emission goes on in any case fluently along the hadron course through the thickness l [nucleons/S] of intranuclear matter layer the hadron interacted with and its intensity is characterized by

$$n_N = lS\ [\mathrm{nucleons}] \qquad (4)$$

and

$$\langle n_N \rangle = \langle l \rangle S, \qquad (5)$$

where $\langle l \rangle$ is the mean thickness of the intranuclear matter layer involved.

V. The relations between the mean multiplicity $\langle n_b \rangle$ of evaporated charged fragments of the damaged target nucleus and the multiplicity n_p of the emitted protons exist:

$$\langle n_b \rangle 1.25 \left(lS + \frac{A-Z}{Z} \right) \tag{6}$$

and

$$\langle n_b \rangle / (\langle n_b \rangle + \langle n_p \rangle) = \langle n_b \rangle / \langle n_h \rangle = 0.4, \tag{7}$$

where $lS = n_p$ and l is the thickness of the intranuclear matter layer involved in the hadron-nucleus collision, measured in [proton/S] units. Short argumentation for the laws formulated above is given in our publication, for example in [21]. The hadronic probe mean free path in intranuclear matter for the particle creating collision is the measurable quantity [12,24].

So high energy hadrons can be used as nuclear probes for exploration of atomic nuclei within the spatial region of about 10^{-13} up to about 10^{-12} [cm]. The method is model-independent.

5. CONCLUSION AND REMARKS

The method of the atomic nuclei exploration by hadronic probes was tested experimentally successfully in studying the mechanism of the hadron-nucleus collision process, for example [13—15,17] and of the matter density distributions in atomic nuclei, for example [11].

It may be concluded that high energy hadrons in passing through layers of intranuclear matter leave something like the «tracks» which might be treated as an analogy of the tracks of electrically charged particles in layers of materials. But, the tracks in materials are «macroscopic», that tracks in intranuclear matter are in a «subnuclear» scale in the spatial regions of diameters as large as about $10^{-13} \div 10^{-12}$ cm.

Some parts of this work were prepared by one of the authors (A.Wojciechowski) for his PhD Thesis.

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Received by Publishing Department
on April 8, 1996.