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THE DETERMINATION OF MATTER DENSITIES IN $^{131}Xe_{54}$ NUCLEUS USING NEGATIVELY CHARGED PIONS

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1. INTRODUCTION

The application of high energy hadrons as probes for the nuclear matter distribution studies has long been a difficult problem [1]. A need for such studies arises in attempts to obtain in a direct way some information about the neutron density distribution in nuclei. We now have a precise knowledge of the shapes and sizes of charge distributions of nuclei throughout the periodic table, as a result of the extremely accurate electron scattering experiments by Hofstadter and collaborators in the mid-fifties [2]. The indications are quite strong that the neutron distribution does not differ markedly from the proton one [3] and does not extend by much beyond it; there is inadequate direct evidence on the neutron distribution inside the nuclei, and what there is, is not conclusive [1,3]. The difficulty in measuring neutron, or nucleon, distributions is, of course, that the electromagnètic interaction provides little information. After considerations, we were led to the conclusion that the only probes of the whole nuclear matter distribution must be strongly interacting [1].

But,many methods which have been used,in studying the nuclear structure by means of the strongly interacting probes necessarily involved some model-dependences of the results obtained. Moreover, the collision of a hadron with a nucleus does not distingush itself by the basic simplicity, similarly as the collision of electrons with nuclei. The hadron-nucleus collision leads, in contrast, to interaction of particles of rather complicated structure - as pion and proton with nucleus, or as a nucleus with a nucleus.

Thus, some model-independent method should be worked out and more experimental investigations are desired using the method which, in a direct way, will tell us as much and more about the neutrons in nuclei.

The aim of this work is: a) to work out a new method for nuclear matter distribution studies using strongly interacting probes; b) to determine, as an example, the nuclear matter distribution in xenon $^{131}Xe_{54}$ nucleus, and to obtain an information about the neutron-proton ratio N_n/N_p in this nucleus; N_n and N_p are the neutron and proton numbers correspondingly.

2. METHOD

Before to present our method, let us introduce some difinitions and units, adequately for the object under study.

Information about inner structure of a nucleus is to be obtained from the analysis of collisions of hadrons with layers of nuclear matter of various thicknesses, the hadrons interacted with. We must determine the ability for a hadron to interact inside nuclear matter layers, therefore, and to characterize the layers as conveniently as possible.

The atomic nucleus for the projectiles falling randomly on it is a spherical piece of nuclear matter and we characterize it as a target by its maximum thickness λ_{max}, mean thickness $<\lambda>$, and the thickness $\lambda(b)$ at a given distance from nuclear center, or at a given inpact parameter b. From the well-known charge distribution in nuclei, under assumption that the neutron density distribution does not differ markedly from the proton distribution (from the Fermi distribution [3], for example), the probability $W[\lambda(b)]$ can be evaluated [6] that hadrons, in colliding with a given target nucleus, fall on the nuclear matter layer thickness $\lambda(b)$. All the thicknesses $\lambda_{max}, <\lambda>$, and $\lambda(b)$ we will express, for natural convenience, in nucl/S - in nucleons per some area $S = \pi D_0^2 \approx 10.3$ fm^2, where D_0 is the nucleon diameter. When such units are used, the probability $W[\lambda(b)] = W[\lambda(b)\cdot S] = W[n_N(b)] = W(n_N)$, where n_N is the number of nucleons contained within the volume λS centered on the hadron course.

For a given target nucleus, characterized by its charge Z and mass A numbers, the lengths can be expressed in proton/S, under assumption that the neutron-proton ratio within the nucleus is the same as the (A-Z)/Z ratio.

A hadron as a projectile we characterize by the mean free path for its total interaction in nuclear matter $<\lambda_t>$, connected with the total hadron-nucleon cross section σ_t in S/nucleon units. In characterizing a hadron in such a way, it should be remembered that it is correct when the nucleons scatter or absorb the hadron wave independently of each other; for the independence condition to hold strictly it is necessary that both the hadron wavelength and the range of the hadron-nucleon interaction be smaller than the average internucleon spacing; the first of conditions is fulfilled at energies higher than about 1 GeV, the second is almost fulfilled and we take it to be so.

In hadron-nucleus collisions nucleons are emitted plentifully, of kinetic energies from about 20 up to about 400 MeV, we call them "fast nucleons" - they are known as the g-track leaving particles if fast protons are identified in emulsions.

Now we can express our method. The underlying principle of it is formed by following experimental findings obtained in studying the hadron passages through nuclear matter during about seven last years by Strugalski and collaborators [4-7]:

1. Any hadron of kinetic energy higher than the pion production threshold causes emission of last nucleons from the target nuclei in passing through nuclear matter layers of thicknesses λ nucl/S in them; the number n_N of the nucleons emitted is [4]:

$$n_N = \lambda S(1 - e^{-\lambda/<\lambda_t>}). \qquad (1)$$

2. The probability $P_{n_N}(n_p)$ to emit n_p fast protons, when a hadron collided with a given nuclear matter layer thickness λ nucl/S and met $n_N = \lambda S$ nucleons within the volume λS centered on its course, is [5,7]:

$$P_{n_N}(n_p) = C_{n_N}^{n_p}\left(\frac{Z}{A}\right)^{n_p}\left(1-\frac{Z}{A}\right)^{n_N-n_p}, \qquad (2)$$

where $C_{n_N}^{n_p} = n_N!/[n_p!(n_N-n_p)!]$.

3. The patricle production process in hadron-nucleus collisions does not influence the nucleon emission process at any projectile energy; due to the loss of a part of the projectile energy used for the particle production, some shortening of the path in nuclear matter at energies smaller than a few GeV should be taken into account [4].

The findings, together with our precise knowledge of the shapes and sizes of the proton, or charge, distributions in nuclei [2], allowed to describe quantitatively the multiplicity n_p distribution $N(n_p)$ of fast protons emitted from a given target nucleus when bombarded by a definite projectile hadron at definite energy [8]:

$$N(n_p) = k \sum_{\substack{n_N=1 \\ n_N \geq n_p}}^{n_N=DS} W(n_N)(1-e^{-n_N/n_t})\, C_{n_N}^{n_p}\left(\frac{Z}{A}\right)^{n_p}\left(1-\frac{Z}{A}\right)^{n_N-n_p}, \qquad (3)$$

where k is the normalization coefficient $k = [\sum_{n_N=1}^{n_N=DS}(1-e^{-n_N/<n_t>})]^{-1}$,

$n_N = DS = \lambda_{max}S$ and D is the nucleus diameter in nucl/S, $<n_t> = <\lambda_t>S$.

This formula holds at hadron energies above a few GeV without limitations - for pions above ~3 GeV, for protons above ~6 GeV; at lower energies the thicknesses λ nucl/S of nuclear matter layers covered by the hadrons are shortened, because of hadron energy loss [4] in nuclear matter.

Predictions on $N(n_p)$ by this formula, when at the known charge Z and mass A numbers for a given nucleus are in fact those which one expects to obtain according to the commonly known indication that the matter distribution in nuclei does not differ by much from the well-known experimentally electric charge distribution. If it is not the case, the predicted $N(n_p)$ distribution should differ evidently from the experimentally obtained one, and we will have corresponding direct evidence that the charge and matter distributions in nuclei are different.

Thus, to obtain an information about nuclear matter distribution in nuclei, relatively to the charge distribution, we should prepare and analyse an accurate proton multiplicity distribution $N(n_p)_{exp}$ from experiment for a sample of collision events of a definite hadron with a definite target nucleus; in this nucleus the nuclear matter density distribution is to be searched. It will be enough to search for the neutron-proton ratio, because the proton distribution is known accurately.

Let us do it for xenon $^{131}Xe_{54}$ nucleus, using our experimental data on pion-xenon nucleus collisions at 3.3 GeV energy [9].

3. THE DETERMINATION OF THE RADIAL DEPENDENCE OF THE NEUTRON-PROTON RATIO N_n/N_p IN $^{131}Xe_{54}$ NUCLEUS

The proton multiplicity n_p distrubution $N(n_p)_{exp}$ for about 20000 fast protons emitted in 6301 pion-xenon nucleus collisions, registered in the 180 litre xenon bubble chamber [10] of the Moscow Institute of Theoretical and Experimental Physics, exposed to 3.3 GeV energy negatively charged pions, is shown in the figure. The distribution $N(n_p)$ expressed by formula (3) is superimposed on the experimental one, in this figure. In formula (3) Z = 54 and A = 131 were used as the charge and mass numbers in the xenon nucleus are.

Both the distributions are similar by much. It means that:

1. The mean neutron-proton ratio in the xenon nucleus is constant and equals $N_n/N_p = (A - Z)/Z$, independently of the distance from the nuclear center. This result agrees well with the commonly existing opinion that indications are quite strong, that the neutron distribution does not differ markedly from the proton one, and does not extend by much beyond it [3]; the opinion is true!

2. The $N_n/N_p = (A - Z)/Z$ is constant in average; nevertheless, the hadron meets along its path in the nucleus the namber of the protons according to formula (2) [5,8].

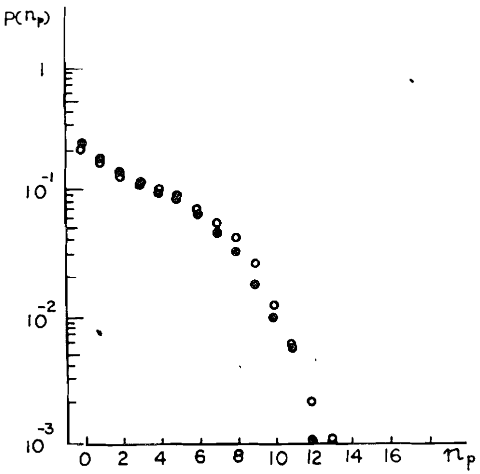

Fig. Fast proton multiplicity n_p *distribution* $P(n_p) = N(n_p)$ *in pion-xenon nucleus collision events at 3.3 GeV energy:* ● *- experiment,* ○ *- prediction by formula (3) when Z = 54 and A = 131 were used. Data are from our previours work* [9].

4. CONCLUSION AND REMARKS

On the basis of the above presented results, it can be concluded that: The matter distribution in atomic nucleus does not differ markedly from the charge distribution and does not extend by much beyond it; the matter distribution is constant but the neutron-proton ratio as seen by hadron probes corresponds to the above-written law (2), in average the proton-neutron ratio is constant and equal to $(A - Z)/Z$.

But, we obtained information about one nucleus, more measurements, for other nuclei are needed.

It should be noted that the nuclear matter density distribution in nuclei can be obtained this way explicitly - from the $N(n_p)_{exp}$ distribution, as well.

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Стругальский З. и др. E1-86-642
Определение плотностей материи в ядре ксенона $^{131}Xe_{54}$ с помощью отрицательно заряженных пионов

Предлагается способ определения плотности ядерной материи с помощью адронов. В качестве примера определено распределение материи в ядре ксенона. Распределение материи не отличается существенно от распределения электрического заряда и не распространяется сильно вне его; распределение материи может быть неизменным, но число протонов, встречаемых адронами при пересекании ядра по данному курсу, меняется определенных образом, хотя в среднем число это соответствует соотношению (A-Z)/Z.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна 1986

Strugalski Z. et al. E1-86-642
The Determination of Matter Densities in $^{131}Xe_{54}$ Nucleus Using Negatively Charged Pions

Method for nuclear matter density distribution determination using strongly interacting probes is proposed. As an example the matter distribution in xenon nucleus is determined. The matter distribution in the nucleus does not differ markedly from the charge distribution and does not extend by mach beyond it; the matter distribution seems to be constant but the number of the protons met by a hadron in traversing nucleus changes in definite manner, on average this number corresponds to the neutron-proton ratio (A-Z)/Z.

The investigation has been performed at the Laboratory of High Energies, JINR.

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