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HADRON NUCLEUS INELASTIC COLLISIONS AND FORMATION ZONE OF FAST HADRONS

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A method of determining the formation zone by measurement of absorption of the medium-energy hadrons created in nuclear matter is outlined. It is applied to recent data on the process $\pi^- A \to \bar{p} + X$ and used to estimate the formation zone of p at ~ 16 GeV/*c*.

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It is now well established that heavy nuclei are rather transparent to high energy hadrons [1]. The transparency can be attributed to a large time necessary for a high--energy hadron to be produced [2–5]. This formation time, sometimes called "formation zone" increases linearly with increasing hadron energy (Lorentz factor) and therefore may reach very large values at sufficiently high energies. Thus at high energies hadrons are produced mostly far beyond the target nucleus and consequently are not disturbed by final state interaction with nuclear matter.

Since the details of time dependence of hadron production are not known, the actual value of the formation time cannot be, at present, calculated from theory. Nevertheless, it represents an interesting parameter of hadron physics. Recently, we proposed a method of measuring this parameter in lepton-nucleus interactions [6, 7]. The purpose of the present note is to extend this argument to hadron-nucleus collisions. We also discuss the recent data [8] and extract from them a rough estimate of formation time $\bar{p}$ at 16 GeV/*c*.

To present our argument let us consider the additive quark model of high-energy hadron-nucleus collisions [9–11]. We are studying the inclusive process

$$h + A \to h' + \text{anything}, \tag{1}$$

where the hadron h′ takes at least half of the energy of the incident hadron h (to minimize additional complications due to coherent scattering it is useful to consider $h \neq h'$). In the additive quark model, the non-diffractive meson-nucleus interaction[1] can proceed

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[1] In the following we restrict the discussion to incident mesons. Generalization to incident baryons is straightforward.

by one of the three possibilities: one may have an inelastic interaction of either the quark or antiquark or both. This is illustrated in Fig. 1. The quark (antiquark) which interacted inelastically emits particles in the central region of rapidities and therefore loses a large fraction of its energy. Consequently, its contribution to the projectile fragmentation region is expected to be small and is in fact neglected in the model [11–13]. Thus the projectile fragmentation region (which we are discussing here) is populated mostly by fragments of the spectator quark or antiquark (Figs 1(a) and 1(b)).

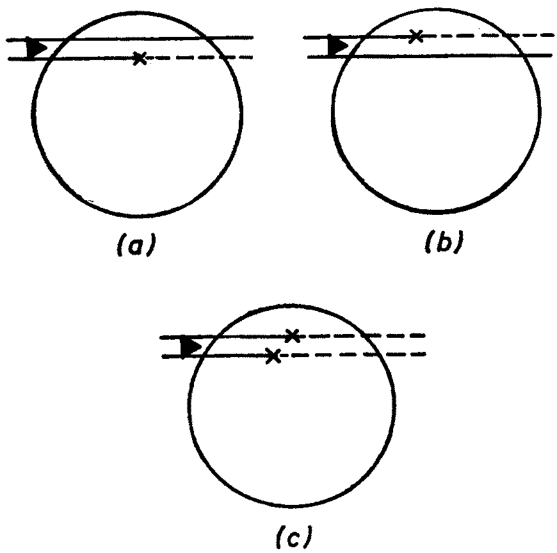

Fig. 1. Meson-nucleus inelastic collision in the additive quark model

At very high energies the formation zone for producing such fragments is large so they are produced way out from the nucleus and are thus unperturbed by nuclear matter. However, at intermediate energies the formation zone is finite and it is necessary to take into account absorption of the final hadron h′ inside the nucleus. By comparison to the data the effects of absorption can be measured and thus the magnitude of formation time deduced by the method described below.

To estimate the yield of the final hadrons in the reaction (1) we have to calculate the cross section for the following process:

(a) the quark interacts at point $(\vec{b}, z)$ inside the nucleus,

(b) the antiquark does not interact,

(c) the antiquark fragment h′ also does not interact,

plus the contribution from a similar process with the roles of the quark and of the antiquark interchanged.

This can be done in the following way (the argument is a straightforward generalization of that presented in Refs [6] and [7]). We assume that after, say, the quark interacted non-diffractively at the point $(\vec{b}, z)$, the antiquark continues along the z direction and fragments into the hadron h′. The probability of finding the antiquark at any point (b, z'), $z' \geqq z$ is

$$P_{\bar{q}}(z'-z) = \exp\,[(z-z')/\tau], \tag{2}$$

where τ is the fragmentation time in the laboratory frame. Consequently, the probability of having a hadron at the point $(\vec{b}, z)$ is

$$P_h(z'-z) = 1-P_{\bar{q}}(z'-z). \tag{3}$$

With this notation, the probability that either the antiquark or the hadron h′ interacts inelastically with one given nucleon at any point $z' \geqq z$ inside the nucleus is

$$P_f(\vec{b}, z) = \int_z^{\infty} \{\sigma_{\bar{q}} P_{\bar{q}}(z'-z)+\sigma_{h'} P_h(z'-z)\}\varrho(\vec{b}, z')dz', \tag{4}$$

where ϱ is the nuclear density normalized to unity. Similarly, the probability that a quark or antiquark interacted with a nucleon at any point $z' < z$ is

$$P_i(\vec{b}, z) = \int_{-\infty}^{z} \sigma_h \varrho(\vec{b}, z')dz'. \tag{5}$$

Here $\sigma_{\bar{q}}$, σ_h, and $\sigma_{h'}$ are non-diffractive cross sections of the corresponding particles from nucleons.

We thus see that the probability that there should be no interaction for $z' \leqq z$ and no interaction of $\bar{q}$ or h′ for $z' \geqq z$ on any of the $A - 1$ nucleons inside the target nucleus is

$$\{1-P_i(\vec{b}, z)-P_f(\vec{b}, z)\}^{A-1}. \tag{6}$$

Thus the cross section for the process (1) is given by

$$d\sigma_A = d\sigma_N A \int d^2b dz \varrho(\vec{b}, z)\,\{1-P_i(\vec{b}, z)-P_f(b, z)\}^{A-1} \tag{7}$$

+ an analogous contribution with q and $\bar{q}$ interchanged. Here $d\sigma_N$ is the cross section for the relevant process on a nucleon target.

Formula (7) generalizes the result of Ref. (7) to the case of hadron-nucleus collisions[2]. It contains only one unknown parameter, namely the formation time τ (other parameters, i.e. inelastic cross sections can be estimated from the measured hadronic cross sections). Comparison of Eq. (7) with experimental data may thus be used for the determination of τ.

The data of Ref. [8] give production of baryons and antibaryons off several nuclei by incident 30 GeV pion beams. The process

$$\pi^- A \rightarrow \bar{p} + \text{anything} \tag{8}$$

is particularly convenient for the analysis we describe here. First, it selects the contribution

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[2] It might be worth mentioning that, although our argument is formulated in terms of the additive quark model, it is actually more general and can easily be extended to other models of hadron-nucleus interactions. In such a general formulation the intermediate state after the first collision is not necessarily the spectator antiquark (quark) but may be a more complicated system. The formula (7) applies also to this more general case, but the cross section of the intermediate state ($\sigma_{\bar{q}}$ in the Eq. (7)) is no longer the cross section of the single antiquark (and must be specified by a given model or remains a free parameter). Also. the sum over all intermediate states (which may have different cross sections) must be taken.

from antiquark fragmentation (recombination)[3] — it is unlikely that the antiprotons come from quark fragmentation. Secondly, the elementary process

$$\pi^- N \to \bar{p} + \text{anything} \tag{9}$$

is expected to be well described by the additive quark model [4][4].

In Fig. 2 the calculated ratio $d\sigma_{Pb}/d\sigma_C$ is plotted[5] versus τ. One observes a fairly strong dependence on τ in the region from 1 to about 100 fermi, thus one may hope for a reasonably accurate measurement of τ in this region[6]. The data of Ref. [8] are also indicated in Fig. 2. It is seen that they give the value of $\tau \simeq 15 \pm 5$ f. We have also checked that this value is consistent with measurements for other nuclei [8].

A more precise analysis was not attempted because the data are still preliminary. However, we feel that our results suggest that such an analysis should be possible, once

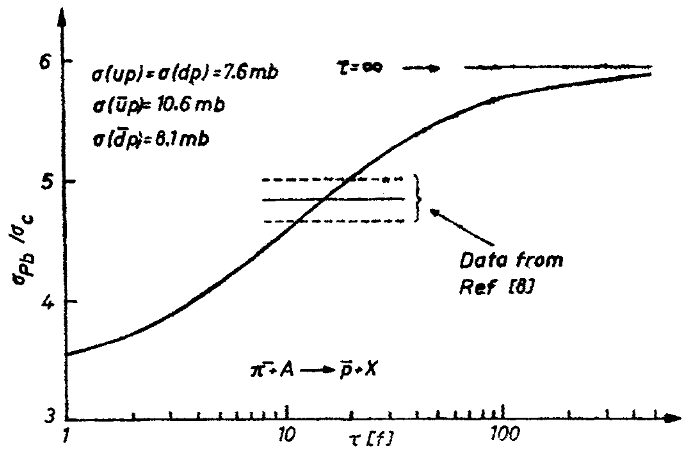

Fig. 2. The ratio $d\sigma_{Pb}/d\sigma_C$ for the process (8) calculated according to the formula (7). The data are from Ref. [8] and correspond to the interval $0.47 \leqq x \leqq 0.51$

[3] For our purpose it is inessential whether one adopts recombination or fragmentation [14] picture.

[4] This would not be the case for e.g. the process $\pi p \to p + X$ where the contribution from the capture of a (target) diquark by the (projectile) spectator quark must be taken into account. This affects the magnitude and perhaps also the A-dependence of the cross section. The analysis is thus more complicated and may require introduction of other unknown parameters.

[5] The nuclear density $\varrho(r)$ was taken in the form $\varrho = \varrho_0\{1+\exp[(r-R)/a]\}^{-1}$ with $a = 0.5$ f, $R = (0.978+0.03\,A^{1/3})$ [10]. We used the following values of non-diffractive cross sections: $\sigma(\pi^- p) = 18.2$ mb, $\sigma(\pi^+ p) = 15.7$ mb, $\sigma(pp) = \sigma(np) = 22.8$ mb. Using additivity, this gives $\sigma(up) = \sigma(dp) = 7.6$ mb, $\sigma(\bar{u}p) = 10.6$ mb, $\sigma(\bar{d}p) = 8.1$ mb. The cross section $\sigma_{\bar{q}}$ in the formula (7) was then calculated as $\sigma_{\bar{q}} = \{z\sigma(\bar{u}p)+(A-Z)\sigma(\bar{d}p)\}/A$ to take into account the Z/A ratio in different nuclei. Consequently, for σ_π in (7) the value $\sigma_\pi = \sigma_q + \sigma_{\bar{q}}$ was used. Finally $\sigma_{\bar{q}}$ was taken to be 32 mb. In Ref. [8] the yield from a hydrogen target was not given, therefore the data cannot be compared directly with the ratio $d\sigma_{Pb}/d\sigma_H$.

[6] The theoretical ratio $d\sigma_{Pb}/d\sigma_C$ depends also on the adopted value of $\sigma_{\bar{q}}$. We checked that with the present experimental accuracy this is not the dominant source of error, provided we believe the determination of $\sigma_{\bar{q}}$ up to ± 0.5 mb. Furthermore, this problem can be removed by performing measurements at several energies (τ depends linearly on energy, whereas the energy dependence of inelastic cross sections is known to be rather weak). See also Ref. [7] for a discussion of this problem which is much more severe for lepton-induced processes.

the final version of the data is obtained. Thus a better estimate of the formation time of antibaryons may be available in the not-too-distant future.

We would like to end this note with the following comments:

(a) If the picture described here is a correct one, the effects of absorption should disappear (in a calculable way) at higher energies. As seen from Fig. 2, this is expected to happen at $\tau \gtrsim 100$ f, i.e. at energies $\gtrsim 150$ GeV.

(b) To obtain more reliable results it might be helpful to perform measurements of absorption at slightly higher values of x where the x-dependence flattens out.

(c) The value of τ obtained from Fig. 2 indicates that $\tau \sim 1$ fm in the rest frame of the final antiproton. It would be of course very interesting to compare this value with measurements for mesons [11] and with the values obtained from lepton-nucleus experiments, once they are available.

(d) Interpretation of the formation time remains still somewhat obscure [7] and we feel that the measurements of the type we advocate here may help in understanding its physical significance. E.g., the universality of formation times of different hadrons, if observed experimentally, would suggest an interpretation of τ as the lifetime of quasi-free quark.

In conclusion, we proposed a method of measurement of the hadronic formation time in medium-energy hadron-nucleus reactions. The method represents a simple generalization of the additive quark model to the intermediate energy range. Comparison with a recent experiment indicates that the formalism can indeed serve as a useful tool for extracting information on strong interaction parameters.

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