MULTIPLE PRODUCTION ON NUCLEI

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The evidence for the unexpectedly high transparency of nuclei to newly produced particles, and the theoretical interpretations of this phenomenon are reviewed.

The formulae used to describe scattering on nuclei are usually more complicated then the corresponding formulae for scattering on protons. In this paper we review the indications that besides these technical difficulties there is a more fundamental one: that in order to understand scattering on nuclei a new idea is necessary. We begin by giving a map of this field of physics.

1. Systematics and the problem

In scattering on nuclei, just like in scattering on protons, one observes elastic processes and processes with production of high energy particles. Since, however, the target is loosely bound, various things may happen to it. One distinguishes coherent processes, where the target nucleus remains in its ground state, and incoherent processes, where it is excited or broken. Often the nucleus is left in a highly excited unstable state, where it "evaporates" nucleons, or nuclear fragments. These nuclear processes are characterized by a much lower energy scale. Typical energies of evaporated particles are of the order of 10 MeV per nucleon. In this paper we consider only the high energy part of the process, leaving out of considerations the low energy nuclear part.

The main ununderstood problem is:
Why the nucleus is so transparent for newly produced particles? Stressing that the particles are newly produced may seem an unnecessary precaution. The transparency of the nucleus is related to the cross-section for scattering of the particle on nucleons constituting the nucleus. The cross-sections are usually supposed not to depend on whether the particle was produced five minutes before, or ten minutes before. In nuclei, however, something strange happens and the fact that particles scatter about 10^{-23} seconds after

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being produced might yield a valuable clue. In order to show that the nucleus is more transparent than expected, it is necessary to formulate some expectations. The simplest picture of scattering on nuclei is the cascade picture.

2. *Cascade picture*

According to the cascade picture the incident particle hits one nucleon in the nucleus. This first scattering process yields one or more particles, which propagate through the nucleus hitting other nucleons, or just leaving the nucleus. At every collision further particles can be produced, these in turn can collide with further nucleons. The process ends when all the particles sufficiently energetic to leave the nucleus have left. In the standard version of the model (*cf. e. g.* [1]) each collision is supposed to proceed as if the particles were free.

An estimate of the dimensions involved may be illuminating. The radius of the nucleus R is related to the mass number A by the formula

$$R = 1.12\, A^{1/3}\ \text{fm}. \tag{1}$$

Thus a nucleus with $A = 125$ has a diameter of about 10 fm. The mean free path for particles in nuclear matter is of the same order but smaller. It is about 4.5 fm for pions and about 2.7 fm for nucleons. Thus in the cascade picture we may expect two or three generations of particles.

We will show now by a crude estimate that the total multiplicity of produced charged particles—as predicted by the cascade model—is much higher than that observed experimentally. The calculations are admittedly very crude, but we tried to choose the approximations so as to obtain an estimate from below. Much more complex calculations with Monte Carlo techniques give qualitatively the same result [1]. The result is a manifestation of the effect mentioned in the preceding Section: for some reason the nucleus is more transparent than expected and there are less secondary and higher order collisions than our estimate would indicate.

We estimate the average number of produced charged particles for 200 GeV protons incident on heavy nuclei in nuclear emulsion. This example is choosen, because the result can be directly compared with available experimental data. Let us assume that two complete new generations of particles are produced in the nucleus. In the first collision the incident 200 GeV proton will produce on the average 10 particles, since the average multiplicity of charged particles produced in pp collisions at 200 GeV is 7.6 ± 0.2 [2]. Thus on the average each produced particle will have an energy of 20 GeV. At 20 GeV the average multiplicity of charged particles produced in pp collisions is 4.0 ± 0.1 [2]; for πN collisions this multiplicity is even higher. Thus the expected number of charged particles produced in the whole process is about 40. One could object that the leading particle effect has not been taken into account. This is easy to include. Suppose that in the first generation of produced particles one particle has an energy of 100 GeV and the nine others 11 GeV each. The average multiplicities of charged particles at 100 and 11 GeV are 6.3 ± 0.2 and 3.3 ± 0.1

respectively [2]. Thus the predicted final multiplicity would be about 36 in good agreement with the preceding estimate.

Experimentally [3] only 5% of events have multiplicities exceeding 30. Since in the scattering on emulsion about 75% of the cross-section comes from collisions with the heavy nuclei, our estimate is indeed too high: The nucleus is more transparent than expected.[1] We will show now that qualitatively the same effect is observed in the much simpler coherent processes. We choose as illustration the coherent production of (3π) systems on heavy nuclei, though most of the discussion applies to all coherent production processes.

3. Eikonal picture

Coherent production on nuclei is usually described in terms of the eikonal picture. In this picture the incident pion propagates through the nucleus along a straight line like a light ray in geometrical optics. At some point — we will denote it z_0—the pion dissociates into the (3π) system, which continues to propagate along the same straight line until it leaves the nucleus.

Thus in order to describe the coherent production process it is necessary to find descriptions for its four stages.

a) Propagation of the pion
b) Transition process $\pi N \to (3\pi)N$
c) Propagation of the (3π) system in nuclear matter
d) Propagation of the (3π) system in free space from the target nucleus to the detectors.

Out of these stages a, b and d are well understood. Stage c is the controversial one.

The propagation of the pion in nuclear matter can be described by the equation

$$\frac{dc(z)}{dz} = -\lambda_1 c(z), \qquad c(0) = 1, \tag{2}$$

hwere c is the amplitude for finding the pion, z the distance along the pion path from the point where the pion entered the nucleus, and the absorption coefficient λ_1 is proportional to the total cross-section for πN scattering. The proportionality coefficient is well known. For light nuclei formula (2) should be replaced by a more complicated formula following from Glauber's theory. For our discussion, however, formula (2) is sufficient. Since it gives a correct description of elastic scattering on nuclei [5] it probably can be trusted.

Information about the process $\pi N \to (3\pi)N$ can in principle be obtained directly from the scattering on protons. In practice it is difficult to extract from the proton data the diffractive part, which is the only one contributing to coherent scattering on nuclei. It was checked, however, that the amplitudes for the production of the (3π) system of mass m

$$c_m(z_0) = w_m, \tag{3}$$

[1] This has been being pointed out for a long time by cosmic ray physicists [4].

which give a good fit to the data on nuclei, are also consistent with the data from scattering on protons [6].

In order to describe the propagation of the (3π) system in nuclear matter it is natural to use an extension of Eq. (2):

$$\frac{dc_m(z)}{dz} = -\lambda_3 c_m(z) \tag{4}$$

with the initial condition (3). z_0 is by assumption the point, in which the transition $\pi \to (3\pi)$ took place. The absorption coefficient λ_3 could be made to depend on the mass m of the (3π) system, this however was found unnecessary [6]. Equation (4) was found to give very good agreement with experiment, provided one puts

$$\lambda_3 = \lambda_1 . \tag{5}$$

This result is difficult to understand for the following reasons.

4. *How to evaluate the absorption coefficient λ_3*

The (3π) system is known to be mainly $(\varrho\pi)$. Since the ϱN total cross-section is known to be equal to the πN total cross-section, one would expect that the total cross-section for the scattering of the $(\varrho\pi)$ system on a nucleon, should be about twice as big as that for πN scattering. Consequently there should be

$$\lambda_3 \approx 2\lambda_1 . \tag{6}$$

A more refined discussion was given in Ref. [7], where the corrections due to the possible shadowing of one of the particles in the $(\varrho\pi)$ system by the other were taken into account. It was found that even putting the particles exactly one behind the other, which gives maximum shadowing, one reduces λ_3 only to $1.85\,\lambda_1$. Thus for any wave function of the $(\varrho\pi)$ system we should have

$$1.85\,\lambda_1 \leqslant \lambda_3 \leqslant 2\lambda_1 \tag{7}$$

n contradition with (5). Again the nucleus proves to be more transparent than expected.

Looking for some analogy one can notice that the absorption for ϱ in nuclear matter is equal to that for the pion, in spite of the fact that the ϱ ends as a (2π) system. This is explained by pointing out that the ϱ is a quark-antiquark systems, just like the pion and that it is consequently very natural to expect that it has the same absorption coefficient. The same argument can be used for the $(\varrho\pi)$ system [8, 9]. If the production is a two stage process

$$\pi \to \pi^* \to (3\pi) \tag{8}$$

with the second stage occuring outside the nucleus, then perhaps one should not be surprised that π^* — some excited system — has absorption similar to that of the pion. The π^* however, would have to be a very complicated object with a superposition of various masses and angular momenta: something much more coemplicated than the old 1^+ resonance A_1. This is certainly one possibility, pointed out already in Ref. [4].

5. *Non diagonal absorption*

Equation system (4) can be generalized to [10, 11, 12]

$$\frac{dc_m(z)}{dz} = -\sum_{m'} \lambda_{mm'} c_{m'}(z); \tag{9}$$

there the absorption coefficient λ_3 has been replaced by an absorption matrix $\lambda_{mm'}$. In the framework of Glauber's model one would expect now instead of (6)

$$\lambda_{mm} \approx 2\lambda_1 \tag{10}$$

but that is consistent with small absorption, because the nondiagonal terms could partly cancel the term proportional to λ_{mm} [13]. This can be seen from the following example.

Let us consider in Glauber's approximation the scattering of a $(\varrho\pi)$ system on a nucleon. The scattering amplitude will depend on the wave function of the $(\varrho\pi)$. We choose a harmonic oscillator wave function. Since the longitudinal $(\varrho\pi)$ distribution does not affect the result, it is enough to consider a wave function depending on the transverse two-dimensional vector $\boldsymbol{x}_\pi - \boldsymbol{x}_\varrho$. Further it is assumed that the force constant of the oscillator is small, so that most of the time the ϱ and the π are far apart. Then the shadow effect is negligible, and the total cross-section is just the sum of the ϱN and πN total cross-sections. Thus from the relation between the total cross-section and the diagonal element of the absorption matrix

$$\lambda_{mm} \approx 2\lambda_1, \tag{11}$$

where m denotes any state ψ_m of the two-dimensional harmonic oscillator. On the other hand consider the function

$$\Phi(\boldsymbol{x}_\pi - \boldsymbol{x}_\varrho) = \sum_m \psi_m(0)\psi_m(\boldsymbol{x}_\pi - \boldsymbol{x}_\varrho) = \delta^2(\boldsymbol{x}_\pi - \boldsymbol{x}_\varrho). \tag{12}$$

Here the summation extends over all the states of the two-dimensional harmonic oscillator. Wave function (12) corresponds to the two particles shadowing each other as much as possible, and consequently for this particular state the effective absorption coefficient (*cf.* [7]) is:

$$\lambda_3 = 1.85\, \lambda_1. \tag{13}$$

This is smaller than the diagonal absorption coefficient (10), which would be the effective absorption coefficient, if we had neglected the nondiagonal terms. Consequently, including the nondiagonal terms partly cancels the diagonal term and reduces absorption. In the present example this reduction is too weak, because after all we are just using the standard Glauber theory. The reduction is due to shadowing and this is not enough. In order to obtain sufficient reduction it would be necessary to discover the reason why a certain superposition of $(\varrho\pi)$ states has an absorption coefficient equal λ_1 or smaller. Once this problem is solved, nondiagonal absorption can be used to write down elegantly the correct equations. Nondiagonal absorption is however only a formalism, and by itself cannot solve the problem.

In concluding let us note the possibility of making some assumption contradicting (10). Then it is easy to obtain small absorption [11]. In order to justify the result, however, it will be necessary to develop a theory, which could replace Glauber's.

6. Conclusions

Nuclei appear to be unexpectedly transparent to newly produced particles. This effect is quite general, observed both in coherent and in noncoherent processes. Explanations can be grouped into two classes.

1) The incident particle goes over into some excited state (not a resonance!) and this excited state decays into the multiparticle channels only after having left the nucleus. If this is the case, scattering on nuclei offers a unique opportunity to study these excited states.

2) Multiple production takes place inside the nucleus, but the newly made particles scatter differently than what we are used to. Also this would open a new broad field for research.

Whichever is the case, the formalism of nondiagonal absorption is likely to be useful, but being only a formalism it does not solve the problem.

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