SOME NEW OBSERVATIONS ON HIGH-ENERGY SCATTERING FROM NUCLEI

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1. INTRODUCTION

In this review talk, I will examine some of the theoretical models that have been proposed to describe high-energy processes involving hadron-nucleus scattering.

To define the term "high energy", one has to introduce a scale. In atomic and nuclear physics, the scale is usually defined by level spacing. In elementary-particle physics, the scale can be characterized by the spacing between resonances. In terms of constituent models, the characteristic energies (or the scale) might also be related to the binding of the various pieces. Thus the ratios of binding energies to rest energies for the constituents are typically

for an atom $\frac{\text{a few eV}}{0.51\ \text{MeV}} \sim 10^{-5} << 1,$

for a nucleus $\frac{8\ \text{MeV}}{930\ \text{MeV}} \sim 10^{-2} << 1,$

for a proton $\frac{100\text{'s of MeV}}{100\text{'s of MeV}} \sim 1\ .$

Asymtotic considerations apply when interaction energies are large compared with such characteristic energies. A given system may have several quite distinct characteristic energies corresponding to possible coherent excitations of the whole nucleus, as well as those related to resonant excitations of the individual nucleons of which the nucleus is composed.

2. STANDARD GLAUBER MULTIPLE-SCATTERING THEORY

The basic premise in studying the high-energy propagation of a single hadron or of a nucleus through nuclear matter is the scattering of the various constituents of which the nucleus is composed. Microscopic models that are most frequently used are all extensions or elaborations of the original Glauber multiple-scattering theory[1). The main assumptions of this theory are the following:

a) In combining the effects of multiple scattering, the phases involved are simply added (additivity of phase shifts).

b) Spin effects are neglected.

c) Nucleon binding energy is neglected; nucleons inside a nucleus are uncorrelated.

d) The results of such calculations are valid only for small scattering angles (small-angle approximation).

The amplitude for hadron-nucleus scattering is

$$F_{fi}(\vec{q}) = \frac{ik}{2\pi} \int d^2b e^{i\vec{q}\vec{b}} \langle f|\Gamma(\vec{b})|i\rangle \quad , \tag{2.1}$$

where $\Gamma(\vec{b})$ is the nucleus profile-function operator acting in the space of the nucleus constituents. Define

$$\Gamma(\vec{b}) = 1 - \exp[i \sum_i \chi_i(\vec{b})]$$

$$= \sum_i \Gamma_i(\vec{b}) - \sum_{i<j} \Gamma_i(\vec{b})\Gamma_j(\vec{b}) + \cdots \quad ,$$

$$\rho(1\ldots A) = |\psi_{initial}|^2 = \prod_{i=1}^{A} \rho(i) \quad , \tag{2.2}$$

$$f_a(\vec{q}) = \frac{ik}{2\pi} \int d^2b e^{i\vec{q}\vec{b}} \Gamma_a(\vec{b}) \quad ;$$

then for elastic aA scattering, we find

$$F_{aA}(\vec{q}) = \frac{ik}{2\pi} \int d^2b e^{i\vec{q}\cdot\vec{b}}[1-(1 + \frac{2\pi i}{k}f_a(0)T(\vec{b}))^A] \quad ,$$

$$T(\vec{b}) = \int dz\rho(\vec{b},z) \quad , \tag{2.3}$$

where the projectile particle a moves in the positive z-direction.

The total hadron-nucleus cross section is

$$\sigma_{aA}(tot) = \sum_{i=1}^{A} \sigma_a(i) - \delta\sigma \quad , \tag{2.4}$$

where

$$\sigma_{aA}(tot) = \frac{4\pi}{k} \text{Im } F_{aA}(0) \quad . \tag{2.5}$$

The term $\delta\sigma$ is known as the cross-section defect or the screening contribution. As it is seen from (2.3), the microscopic theoretical description makes use only of the elastic particle-nucleon scattering amplitude (fig. 1).

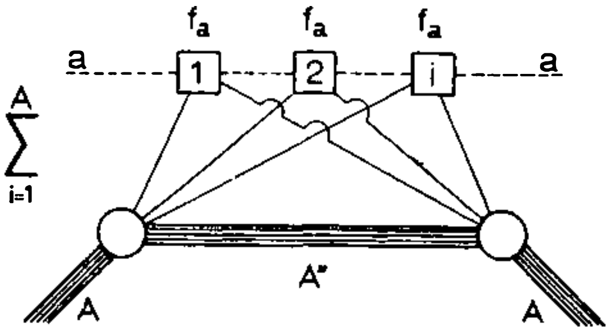

Fig. 1

Diagrammatic representation of elastic intermediate states in elastic particle-nucleus scattering.

Between the two successive interactions, one considers only the propagation of a particle identical to the incident projectile particle.

In the case of πd scattering[2], we find

$$\delta\sigma \sim \sigma_{\pi p}\sigma_{\pi n}\langle r^{-2}\rangle \quad , \tag{2.6}$$

where

$$\langle r^{-2}\rangle_{Glauber} \sim 0.027 \text{ mb} \quad .$$

It is evident from the data (Fig. 2) that $\langle r^{-2}\rangle$ is consistent with the theoretical value computed from the Gartenhaus deuteron wave function at momenta up to 5 GeV/c, but shows a tandency toward increase at higher momenta. The disagreement between theory and experiment is evident at incident momenta higher than 5 GeV/c. A possible way out is the inclusion of inelastic intermediate states (Fig. 3).

3. INELASTIC PRODUCTION PROCESSES FROM NUCLEI

The standard theory allows only one inelastic transition from the initial to the final particle; both particles are allowed to have any number of elastic collisions before and after the production act. This is connected with the fact that

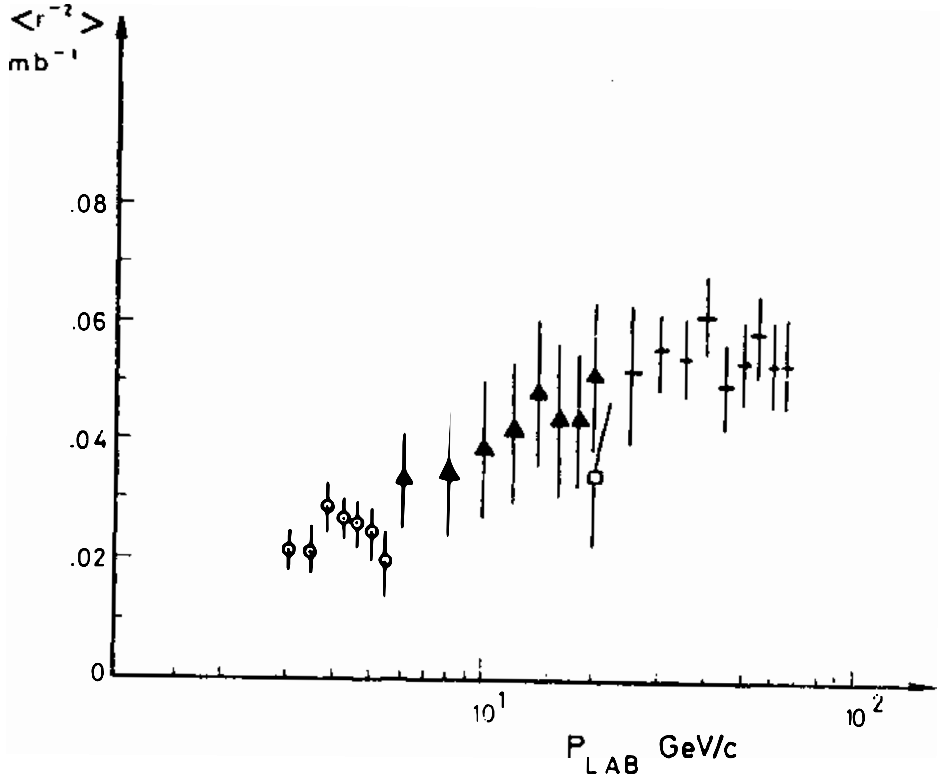

Fig. 2

Experimental values of $<r^{-2}>$ in πd scattering (from ref. 3).

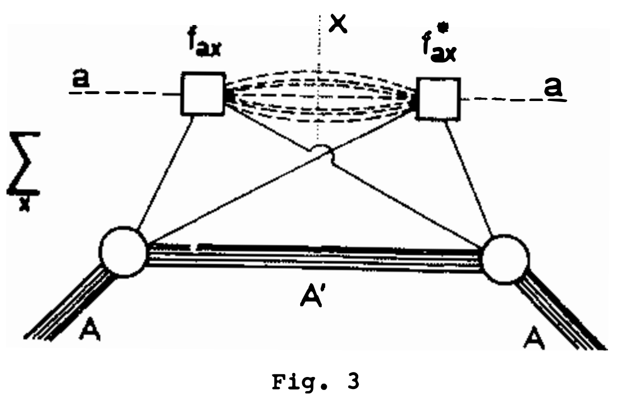

Fig. 3

Inelastic intermediate contributions to double scattering in the energy range considered, the amplitude for every individual inelastic channel is much smaller than the corresponding elastic amplitude. Even if every inelastic channel gives a small contribution, the sum over a large number of channels may become sizable[4].

4. INTERACTION OF HIGH-ENERGY PHOTONS WITH NUCLEI

In terms of the a-nucleon total cross section ($\sigma_a = -i\,\frac{4\pi}{k}\,f_a(0)$) , for a purely imaginary elastic amplitude f_a, the mean free path of an incident particle a through nuclear matter of density

$$\rho_p = \frac{3}{4}\,\frac{m_p}{\pi R_p^3} \sim 4.1\times10^{14}\ \mathrm{g/cm^3}\ , \qquad R_p \sim 1\ \text{fermi} \tag{4.1}$$

is defined by

$$\lambda_a = (\rho_p\sigma_a)^{-1} \quad . \tag{4.2}$$

Two limits are of particular interest:

I) long mean free-path: $\lambda_a >> R$, $\sigma_a \to 0$, where $R = R_o A^{1/3}$ ($R_o \sim 1$ fermi) is the nucleus radius.

$$\sigma_{aA} \simeq A\sigma_a \qquad \text{(a "volume effect")} \tag{4.3}$$

II) short mean free-path: $\lambda_a << R$

$$\sigma_{aA} \simeq 2\pi R^2 \qquad \text{(a "surface effect")} \tag{4.4}$$

At energies higher than 1 GeV , the measured photon-nucleon cross section is of the order of 120 μb. The corresponding mean free path in nuclear matter is $\lambda_\gamma \sim 500$ fermi. Even if we consider a very heavy nucleus, the longest nuclear dimension is only $2R \sim 15$ fermi.

Since $\lambda_\gamma >> 2R$, the chance for a photon to interact twice inside the nucleus is very small; so, one expects

$$\sigma_{\gamma A} \simeq A\sigma_{\gamma N} \quad . \tag{4.5}$$

The experimental data on the ratio $A_{eff}/A = \sigma_{\gamma A}/(A\sigma_{\gamma N})$ (Fig. 4) show agreement with (4.5), that is, with $A_{eff}/A \sim 1$, at lower energies, but the ratio is definitely smaller than 1 at higher energies. This result can be related to the problem of the

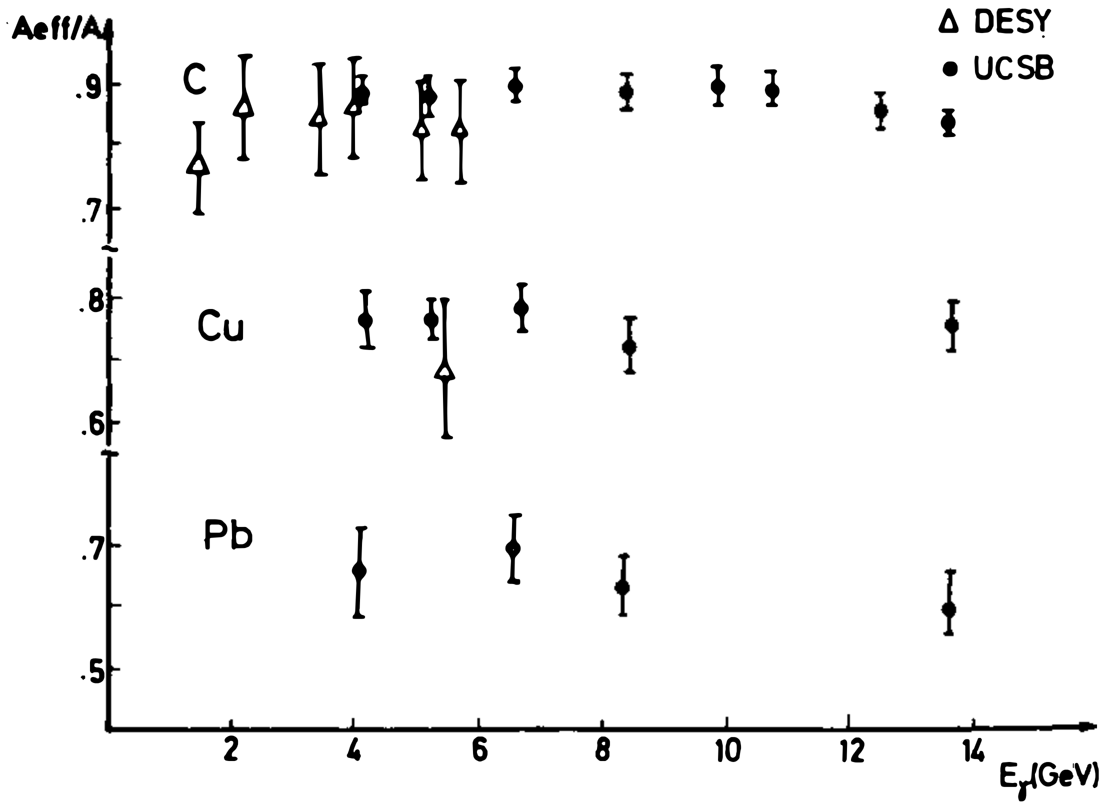

Fig. 4

Experimental results of the DESY and UCSB groups (ref. 5) for total photon-nucleus cross sections on C, Cu and Pb.

"vector-Meson-Dominance" model (VMD), which is a resonable approximation (within probably 20%) to the high-energy photon-hadron interaction.

Since the ρ meson gives the dominant contribution, the statement of VMD is expressed by the relation

$$f_{\gamma a \to b} = c_\rho f_{\gamma\rho \to b} \quad . \qquad (4.6)$$

Hence, we obtain

$$\sigma_{\gamma A} = c_\rho^2 \sigma_{\rho A} \quad . \qquad (4.7)$$

Since the ρ meson is a hadron

$$\sigma_\rho \simeq \text{a few tens of mb}$$

and its mean free path in nuclear matter is short, it follows

$$\sigma_{\rho A} \sim 2\pi R^2 \sim A^{2/3} \qquad (4.8)$$

and

$$\sigma_{\gamma A} \sim c_\rho^2 A^{2/3} \quad . \qquad (4.9)$$

The solution of this obvious paradox[6] is to assume that the photon can interact with hadrons in nuclei both directly and through ρ intermediation. At high energies (E_γ>>5 GeV), both propagation mechanisms are important, but the volume contributions ($\sim$A) cancel out, leaving only the surface contribution to survive.

5. COHERENT PARTICLE PRODUCTION

Great interest has been attracted by a recent experiment of the CERN-ETH Zürich-IC London-Milano collaboration[7] concerning coherent dissociation of pions on nuclei at high energy. It has attracted much theoretical activity to understand the problem of propagation of a dissociated hadronic system (mostly $\pi\rho^0$) through nuclear matter; in particular, the unexpectedly low absorption which is found in this propagation[8]. There is at present no general agreement on the explanation of this very interesting phenomenon. We distinguuish three stages in the physical process $\pi A \to 3\pi + A$: the propagation of the incident pion through nuclear matter, its diffraction dissociation on some nucleon, and the propagation of the dissociated hadronic system through the remaining depth of nuclear matter.

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COHERENT AND CHAOTIC PRODUCTION OF HADRONS

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We give arguments in favour of a statistical approach to production processes similar to the one developed in quantum optics. In particular, we consider an example of pion production in nucleon-nucleon scattering. The "basic equation" for the pion fields is[1)]

$$(\Box + \mu^2)\pi(x) = j(Y,\vec{B};x) \quad ,$$

where j is a c-number random source, Y is the rapidity difference, and $\vec{B}$ is the relative impact parameter of the two incident nucleons. Connection with a two-component picture and the Koba-Nielsen-Olesen scalling is indicated[2)].

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