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Nuclear and partonic dynamics in high energy elastic nucleus-nucleus scattering

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A hybrid description of diffraction which combines a geometrical modeling of multiple scattering with many-channel effects resulting from intrinsic dynamics on the nuclear and subnuclear level is presented. The application to ^{4}He-^{4}He elastic scattering is satisfactory. Our analysis suggests that, at large momentum transfers, the parton constituents of nucleons immersed in nuclei are deconfined.

Recently, a theory of diffractive processes, including elastic scattering, was developed [1–3]. The term "diffraction" refers to a specific class of transitions between states which are "close" to each other, that is, having dominant internal quantum numbers of the initial state. Closeness of states can be defined more precisely in mathematical terms as an equivalence relation with respect to an operator. The formal definition was given in Ref. [1] and it has been applied to elastic scattering and inelastic diffraction of high-energy hadrons in Refs. [1–3]. Our approach to diffraction allows us readily to describe the many-channel dynamics of the scattering process. The diffraction is built as a chain of intermediate transitions inside the set of close states. The wealth of this set reflects on compositeness of the particles involved in the collision. In this paper we study elastic nucleus-nucleus scattering as an interesting generalization of our method to the case of two-level compositeness occurring in nuclei. We show how the two kinds of diffractiveness (nuclear and nucleonic) can be accounted for and investigate their role in building the elastic cross section on the example of ^{4}He-^{4}He scattering at the c.m. energy $\sqrt{s}=9.3$ GeV [4].

The scattering operator T can always be presented in the form [1,3]

$$T=T_0-\Lambda T_0-T_0\Lambda^\dagger+\Lambda T_0\Lambda^\dagger \tag{1}$$

where T_0 is a unitary transform of T, and Λ is a normal operator. Transformation (1) will be specified by requiring that the dominant part of scattering is contained in the operator T_0 while the operator Λ is responsible for corrections. We assume that T_0 is given and the effect of the remaining part will be evaluated by assuming suitable properties of the "soft" operator Λ in a subspace of physical states. The states which are close with respect to the operator Λ by definition satisfy the following equivalence relation:

$$\frac{\Lambda|j\rangle}{\phi_j}=\frac{\Lambda|k\rangle}{\phi_k}=\frac{\Lambda|l\rangle}{\phi_l}=\cdots \tag{2}$$

where $\phi_j, \phi_k, \phi_l, \ldots$ are complex functions which turn out to be wave functions of the eigenstate of Λ in the basis of the physical states $|j\rangle, |k\rangle, |l\rangle, \ldots$.

The theory of diffraction [1,3] based on Eqs. (1) and (2) leads to the following expression for the amplitude of elastic scattering in the initial state $|i\rangle$:

$$T_{\rm el}\equiv\langle i|T|i\rangle=t_i+\Delta t\,, \tag{3}$$

where

$$t_i\equiv\langle i|T_0|i\rangle \tag{4}$$

is the initial-state diagonal matrix element of T_0 and

$$\Delta t=\lim_{B_j} G\cdot(t_{\rm av}-t_i) \tag{5}$$

is a diffractive correction to this value, $t_{\rm av}$ being an average value (over an infinite set of equivalent states) of diagonal matrix elements of T_0 which are weighted with the squares of wave functions ϕ_j of the states

$$t_{\rm av}=\sum_{|j\rangle}|\phi_j|^2 t_j\,. \tag{6}$$

Correction (5) has to be considered in the Bjorken-type limit with the coupling constant $G\to\infty$ and $t_{\rm av}-t_i\to 0$ such that Δt remains finite. This simple correction is achieved as a result of considerable reductions in the evaluation of diffractive amplitude [3].

We construct the states equivalent to the initial state of two colliding hadrons as built of the two-hadron core and a number of quanta responsible for the soft interaction. Thus the density of an equivalent state in the impact parameter representation becomes

$$|\phi_j|^2\to P_m\prod_{k=1}^{m}|\Psi(b_k)|^2\,, \tag{7}$$

where $|\Psi(b)|^2$ describes a spatial distribution of quanta (with respect to the two-hadron core) and P_m is a probability of their number ($m=1,2,\ldots$).

The diagonal elements of T_0 are assumed to be purely absorptive and expressed in terms of the real profile functions:

$$\begin{aligned} &t_i(b)\equiv i\Gamma_0(b)\,,\\ &t_j(b)\to t_i+i(1-\Gamma_0)\sum_{k=1}^{m}\gamma(\mathbf{b}-\mathbf{b}_k)\,, \end{aligned} \tag{8}$$

with γ describing the soft interaction with a single quantum.

With the *Ansätze* (7) and (8) the elastic profile (i.e., the elastic scattering amplitude in the impact parameter space) resulting from Eq. (3) is [2,3]

$$\begin{aligned}\Gamma_{\rm el}(b)&=\Gamma_0+(1-\Gamma_0)\Gamma_1(b)\\ &=1-(1-\Gamma_0)(1-\Gamma_1)\,,\end{aligned} \tag{9}$$

where

$$\Gamma_1(b)=G\bar{m}\int d^2s|\psi(s)|^2\gamma(\mathbf{b}-\mathbf{s}), \qquad (10)$$

$\bar{m}$ being the mean number of soft quanta. Assuming, for illustration, the Gaussian density

$$|\Psi(s)|^2=\exp(-s^2/2R_1^2)/2\pi R_1^2 \qquad (11)$$

and

$$\gamma(b)=\tfrac{1}{2}\sigma_\epsilon\delta^{(2)}(b),\ \ \sigma_\epsilon\to 0,$$

one obtains

$$\Gamma_1(b)=\sigma_1\exp(-b^2/2R_1^2)/4\pi R_1^2, \qquad (12)$$

where

$$\sigma_1\equiv\lim_{G\to\infty,\sigma_\epsilon\to 0} G\bar{m}\sigma_\epsilon .$$

Equation (9) readily combines the two sources of diffraction which manifest themselves through the profiles Γ_0 and Γ_1. The natural way of picturing Γ_0, which is supposed to describe a dominant but very complicated part of scattering, is a *geometrical* model of scattering on a black disk, "blackness" referring both to our ignorance and to the absorptive character of the interaction. By contrast, the profile Γ_1 represents the *dynamical* correction corresponding to a definite mechanism of intermediate transitions between close states. It is thus a multichannel effect implied by unitarity, which should not be confused with eventual multiple-scattering corrections to the black disk picture, resulting from a geometrical distribution of scattering centers.

In nucleus-nucleus collisions there are two sources of dynamical diffractiveness, related to the two levels of compositeness of nuclei. At the nuclear level the equivalent states correspond to various configurations of nucleons. At the subnuclear level the wealth of the set of equivalent states reflects on the partonic compositeness of nucleons. In the language of Eq. (1) this two-level structure can be written formally as follows:

$$T=T_N+T_n,$$

where

$$T_N=T_0-\Lambda_N T_0-T_0\Lambda_N^\dagger+\Lambda_N T_0\Lambda_N^\dagger$$

and

$$T_n=-\Lambda_n T_N-T_N\Lambda_n^\dagger+\Lambda_n T_N\Lambda_n^\dagger \qquad (13)$$

with the subscripts N and n referring to the nuclear and nucleon structure, respectively.

This gives rise to the following extension of formula (9) for the profile of elastic scattering:

$$\begin{aligned}\Gamma_{\mathrm{el}}(b)&=\Gamma_0+(1-\Gamma_0)\Gamma_N+[1-\Gamma_0-(1-\Gamma_0)\Gamma_N]\Gamma_n\\&=1-(1-\Gamma_0)(1-\Gamma_N)(1-\Gamma_n),\end{aligned} \qquad (14)$$

where $\Gamma_N(b)$ and $\Gamma_n(b)$ are defined analogously to $\Gamma_1(b)$ in Eq. (10) with suitable distinction between nuclear (N) and nucleonic (n) diffractiveness.

The choice of the profile $\Gamma_0(b)$ requires a moment's reflection. The *Ansatz* of Glauber [5] for scattering of two nuclei A and B

$$\begin{aligned}\Gamma_{AB}(b)&\\&=1-\langle 0_A 0_B|\prod_{l=1}^{A}\prod_{k=1}^{B}[1-\gamma_{jk}(\mathbf{b}+\mathbf{s}_{jA}-\mathbf{s}_{kB})]|0_A 0_B\rangle,\end{aligned} \qquad (15)$$

where $|0_A\rangle$ and $|0_B\rangle$ are the nuclear ground states and γ_{jk} is the nucleon-nucleon profile, admits the possibility of excitation and deexcitation of the nuclei during collision. However, one can easily extract from (15) a term which is not affected by the virtual excitations [6]:

$$\begin{aligned}\Gamma_0(b)&=1-\prod_{j=1}^{A}\prod_{k=1}^{B}[1-\langle 0_A 0_B|\gamma_{jk}(\mathbf{b}+\mathbf{s}_{jA}-\mathbf{s}_{kB})|0_A 0_B\rangle]\\&\equiv 1-[1-\gamma_{AB}(b)]^{AB}.\end{aligned} \qquad (16)$$

Equation (16) corresponds to multiple scattering on nucleons which are frozen in the nuclear ground states. It is usually referred to as the optical limit of the Glauber model [5]. This choice of Γ_0 allows for a separation between multiple-scattering effects which are of geometrical nature and the dynamical many-channel contributions arising from unitarity and present in the profiles Γ_N and Γ_n. [In other words, choice (16) helps us to avoid double counting when introducing the three components of the elastic profile together.] By contrast, in the standard Glauber model the many-channel effects are only simulated through the geometry of multiple scattering. Therefore, that model may be an approximation to the nuclear part T_N of the scattering operator (13), but will be rather inadequate where dynamical diffractive contributions are important.

In the application of Eq. (16) we assume the Gaussian shape of nuclear densities and treat nucleons as pointlike objects. Then the basic ingredient of the geometrical profile Γ_0 is

$$\gamma_{AB}(b)=(\sigma/4\pi R_{AB}^2)\exp[-(b^2/2R_{AB}^2)]$$

with

$$R_{AB}^2=\frac{1}{2}\left(\frac{A-1}{A}R_A^2+\frac{B-1}{B}R_B^2\right), \qquad (17)$$

σ being the total nucleon-nucleon cross section and R_A,R_B the radii of the two colliding nuclei. In our analysis of the ^{4}He-^{4}He elastic scattering we take the following values: $A=B=4$, $R_A=R_B=1.37$ fm, $\sigma=47.3$ mb [4].

If the density distribution of soft quanta describing nuclear and nucleon compositeness is also Gaussian, Eq. (12) allows us to write the two dynamical profiles in the form

$$\begin{aligned}\Gamma_N&=\sigma_N\exp(-b^2/2R_N^2)/4\pi R_N^2,\\ \Gamma_n&=\sigma_n\exp(-b^2/2R_n^2)/4\pi R_n^2.\end{aligned} \qquad (18)$$

The radii R_N,R_n and the cross sections σ_N,σ_n are to be determined from fitting the elastic differential cross section based on the profile (14) to experimental data. The two dynamical profiles (18), entering Eq. (14) in a sym-

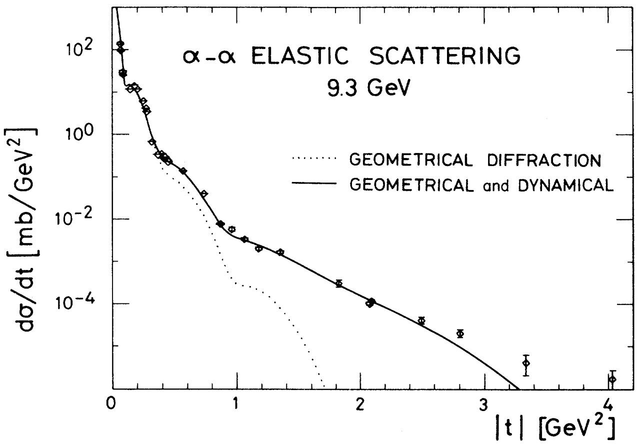

FIG. 1. The ^{4}He-^{4}He elastic cross section in the function of the squared momentum transfer. The experimental data [4] are compared with the results of our model [Eq. (14)] including the dynamical contributions to diffraction Γ_N and Γ_n (solid curve). The dotted curve represents the geometrical contribution Γ_0 only.

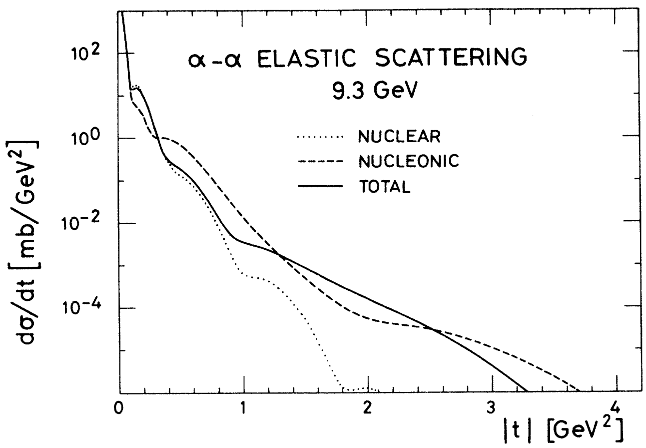

FIG. 2. The ^{4}He-^{4}He elastic cross section in the function of the squared momentum transfer. The dynamical contributions to diffraction Γ_N and Γ_n are presented jointly (solid curve) and separately ($\Gamma_n = 0$, dotted curve; $\Gamma_N = 0$, dashed curve). In all cases, the geometrical contribution Γ_0 is included.

metric way, will be identified through the condition $R_N > R_n$. From our experience gained in the analysis of p-p data [1,2] we expect $R_n \simeq 0.4$ fm. The radius corresponding to nuclear diffractiveness should be close to the nucleon size, $R_N \geq 0.8$ fm.

The profiles occurring in Eqs. (14)–(18) are real and correspond to the imaginary part of the scattering amplitude. The real part, though small, should not be completely neglected. Since an exact procedure is lacking we introduce the real amplitude using the simple approximate recipe of Martin [7]. (We prefer this method to the complexification of the nucleon elastic slope [8]. We also do not like the approach [9] which treats the real part as the dominant unitarity correction at large momentum transfers.) Thus the imaginary part of the elastic-scattering amplitude composed, as in our case, of a number of Gaussians (in momentum transfer q)

$$\mathrm{Im}T_{\mathrm{el}}(q) = \frac{1}{4\pi}\sum_j \sigma_j \exp(-\tfrac{1}{2}R_j^2 q^2) \tag{19}$$

has the following real part corresponding to it:

$$\mathrm{Re}T_{\mathrm{el}}(q) = \frac{\rho}{4\pi}\sum_j \sigma_j (1-\tfrac{1}{2}R_j^2 q^2)\exp(-\tfrac{1}{2}R_j^2 q^2)\,, \tag{20}$$

ρ being the Re/Im ratio in the forward direction.

In Fig. 1 we present our best fit to the ^{4}He-^{4}He elastic scattering data at 9.3 GeV [4]. The parameters used are $R_N = 0.95$ fm, $\sigma_N = 96.1$ mb, $R_n = 0.35$ fm, $\sigma_n = 778$ mb, $\rho = -0.23$. The comparison with the contribution of the Γ_0 profile alone, which describes geometrical diffraction, shows that the dynamical terms Γ_N and Γ_n become very important at $q^2 > 1.0$ GeV^2. The pattern of their interference turns out to be quite involved. As shown in Fig. 2, in the interval 0.1–0.6 GeV^2, the two dynamical contributions nearly cancel each other. At larger momentum transfers the partonic compositeness of the nucleon prevails over nucleon structure effects though some interference effects still persist.

Our analysis points to the existence of three characteristic interaction radii in nucleus-nucleus scattering. The external radius R_{AB} determined by nuclear sizes, characterizes classical diffraction on a black disk with suitable modifications due to multiple scattering on constituent nucleons. The larger intrinsic radius R_N, which is close to the value of nucleon size, characterizes the intranuclear dynamics of an assembly of interacting nucleons. Finally the smaller intrinsic radius R_n may be interpreted as the size characterizing clustering of partonic constituents inside the nucleons. However, the very large value of the cross section $\sigma_n \gg \sigma_N$ can signal the transition of the hadronic interaction to the quark-gluon level in the whole nuclear interior. Indeed, with increasing momentum transfer the effective color coupling between quarks and gluons becomes small so they are no longer confined to nucleons. Moreover, the increased spatial resolution reveals that the quark is itself surrounded by a cloud of partons. The unexpectedly large value of the cross section σ_n which characterizes the intensity of interaction at subnuclear level may thus be interpreted as due to an enhanced population of partons.

The deconfinement mechanism was used to explain the EMC (the European Muon Collaboration) effect in deep inelastic lepton scattering [10] and the cumulative effect in multiple-particle production [11] on nuclear targets. Our analysis shows that hadron elastic scattering at large momentum transfers may also be strongly affected by the deconfinement of parton constituents of nucleons. Reaching this conclusion has been possible owing to the unitarity inspired approach to scattering that allows us to disentangle the many-channel dynamics from the vagueness of a black disk diffraction.

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