Partial transparency of nuclei and universal properties of proton spectra in collisions of relativistic protons and nuclei with nuclei

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Universal properties of inclusive proton spectra in proton-nucleus and nucleus-nucleus collisions are interpreted on the basis of a model with an incomplete dissipation of the initial relative momentum of the nucleons of the incident particle and the target. Comparison with experimental data reveals a completely definite picture of the stopping power of nuclear matter.

Man'ko and Nagamiya's kinematic analysis[1] of the experimental inclusive spectra of protons and composite fragments in high-energy nucleus-nucleus collisions revealed that these spectra can be described as a superposition of components from three quasi-Maxwellian sources: a "slow" source in the target-fragmentation region, a "fast"

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source in the fragmentation region of the incident nucleus, and an "intermediate" source in the region of the effective fireball. Adyasevich *et al.*[2] studied the properties of this slow proton source in more detail. They found that in the target-fragmentation region (i.e., at longitudinal rapidities y of the secondary protons close to the initial rapidity of the target and at comparatively low transverse momenta $x = p_\perp / m_N < 1$, where m_N is the mass of the nucleon) the inclusive proton spectra exhibit certain universal properties, primarily an independence of the effective temperature of the slow source ($T \cong 55$ MeV) from the collision energy and from the particular combination of colliding nuclei. Similar properties of the inclusive proton spectra in proton-nucleus collisions were observed a long time ago and were generalized as a "nuclear scaling."[3]

In the present letter we show that these empirical properties of inclusive proton spectra[1-3] can be explained in a natural way on the basis of the hypothesis of a partial transparency of nuclei. Furthermore, these properties indicate a completely definite stopping law for a fast nucleon in nuclear matter.

We begin with the model of partial transparency, set forth in Ref. 4. This model uses the assumption of a tubular collision geometry, for which the invariant inclusive cross section for the yield of nucleons is written in the form[5]

$$\sigma_{\text{inv}}(\mathbf{p}) \equiv E \frac{d^3 \sigma}{d^3 p} = \sigma^* \sum_{N_p = 1}^{A_p} \sum_{N_t = 1}^{A_t} W_p(N_p) W_t(N_t) \varphi(\mathbf{p}, N_p, N_t), \tag{1}$$

where the factors $W_\alpha(N_\alpha)$ are the effective numbers of tubes in nucleus[1)] α which contain N_α nucleons, and σ^* is the cross section of the tube (a parameter of the model). The function $\varphi(p, N_p, N_t)$ characterizes the momentum distribution of the nucleons of two colliding tubes after their interaction. The partial transparency model does not assume that the matter of the colliding tubes is completely stopped in the center-of-mass frame of the tubes. On the contrary, we assume that as a result of the incomplete stopping of the tubes, especially short tubes, the nuclear matter becomes spatially resolved into two blobs whose relative velocity (V_{rel}) and whose internal energies per baryon (ϵ_α) are found from time-evolution equations.[4] An important parameter of the model is the stopping length $\lambda_T(V_{\text{rel}})$, which appears in these equations and which determines the stopping effectiveness. The functions $\varphi(\mathbf{p}, N_p, N_t)$ are written as superpositions of two Maxwellian distributions whose parameters are determined by the average velocities and excitation energies ($\epsilon_\alpha - m_N$) of the tubes after their interaction.

The transparency was introduced in the simplest possible way, $\lambda_T(V_{\text{rel}}) = \text{const}$, in Ref. 4, but λ_T had to be increased with increasing energy of the incident particle, E_{lab}, in order to reproduce the experimental data. In the present letter we show that all the inclusive proton data available from proton-nucleus[6,7] and nucleus-nucleus[2,7,8] reactions in the energy range $E_{\text{lab}} = 0.5$–5 GeV/nucleon can be reproduced in a common way under the assumption that the effective stopping length is proportional to the kinetic energy of the relative motion:

$$\lambda_T(V_{\text{rel}}) = \lambda_0 [(1 - V_{\text{rel}}^2)^{-1/2} - 1]. \tag{2}$$

This functional dependence $\lambda_T(V_{\rm rel})$, furthermore, makes it possible to explain in a natural way the qualitative experimental behavior which has been observed in inclusive proton spectra.[2,3] This point can be demonstrated most simply in the particular case of the interaction of an incident nucleus with a thin nuclear target (such as ^{20}Ne), for which the effective tube lengths $l_t = N_t/\sigma^* n_0$ (n_0 is the normal nuclear density) are small in comparison with λ_0.

We begin with proton-nucleus collisions [$W_p(1) = 1$, $A_p = 1$]. With $\lambda_T(V_{\rm rel})$ in the form in (2), the partial transparency model yields the following results for the rapidity of the entrainment of the target tube, y_t, and its excitation energy $(\epsilon_t - m_N)$ in first order in l_t/λ_0:

$$\epsilon_t - m_N \cong m_N/\kappa, \qquad y_t \cong \frac{1}{\kappa} \coth y_0/2, \tag{3}$$

where $\kappa = n_0\sigma^*\lambda_0$, and y_0 is the initial rapidity of the incident particle. At $y_0 \gtrsim 1$ the contribution of the leading proton to $\sigma_{\rm inv}$ is concentrated at high rapidities, $y \sim y_0$, and can thus be ignored in the target-fragmentation region. Consequently, the only N_t dependence in $\varphi(\mathbf{p}, 1, N_t)$ comes from the normalization factor, which is proportional to N_t. Using the relation $\Sigma_{N_t=1}^{A_t} N_t W_t(N_t) = A_t$, in (1), and ignoring for the moment the excitation of Δ resonances and the production of π mesons, we can write the following expression for the inclusive proton spectrum in the target-fragmentation region:

$$\sigma_{\rm inv}(\mathbf{p}) \propto A_t \sigma^* E_t(\mathbf{p}) \exp\{-E_t(\mathbf{p})/T_t\}, \tag{4}$$

where $E_t(\mathbf{p}) = m_N\sqrt{1+x^2}\cosh(y - y_t)$ is the energy of the secondary proton in a frame of reference moving at the rapidity y_t, and $T_t \cong (2/3)(\epsilon_t - m_N)$ is the effective temperature. We thus find, in agreement with the experimental data, that the inclusive proton spectra in the target-fragmentation region have a universal Maxwellian shape with a temperature that is independent of $E_{\rm lab}$. The rapidity of the slow source, y_t, decreases with increasing $E_{\rm lab}$, gradually approaching the asymptotic form $y_t \cong \kappa^{-1}$. This behavior of the parameters of the slow source is observed experimentally. The asymptotic approach to the regime of complete nuclear scaling[3] is explained in our approach on the basis of the asymptotic behavior $y_t \to \kappa^{-1}$.

For high-energy nucleus-nucleus collisions $\sigma_{\rm inv}$ in the target-fragmentation region is basically determined by collisions of peripheral tubes of the incident particle, containing a single nucleon, with denser parts of the target. This situation is the result of several geometric and kinematic factors. In the first place, a direct calculation[2)] shows that the geometric factors $W(N)$ reach maxima at $N = 1$, even for the heaviest nuclei. The reason for this behavior is the large contribution from the diffuse tails of the nuclear density distributions. Furthermore, the entrainment rapidity of the target tube increases with increasing N_p, so that the functions $\varphi(\mathbf{p}, N_p, N_t)$ are centered near higher rapidities at $N_p \geqslant 2$ than at $N_p = 1$. The net result is that in the target-fragmentation region $\sigma_{\rm inv}$ is determined primarily by the term in (1) proportional to $W_p(1)$:

$$\sigma_{\rm inv}(\mathbf{p}) \approx \sigma^{*} W_p(1) \sum_{N_t=1}^{A_t} W_t(N_t)\,\varphi(\mathbf{p},\, 1,\, N_t), \tag{5}$$

to which everything we have said about proton-nucleus reactions applies. The universal properties of the cross sections for nucleus-nucleus collisions are thus explained in our model on the basis of the universal nature of the contributions of the corresponding nucleon-nucleus collisions.

We have calculated inclusive proton spectra for the proton-nucleus reactions $p + \mathrm{C}$, $p + \mathrm{Cu}$, and $p + \mathrm{Pb}$ for $E_{\rm lab} = 0.43$–5.1 GeV and also for nucleus-nucleus reactions at $E_{\rm lab} = 0.4$, 0.8, 2.1, and 3.6 GeV/nucleon, for which experimental data are available on the inclusive proton spectra. In these calculations, as in Ref. 4, we take

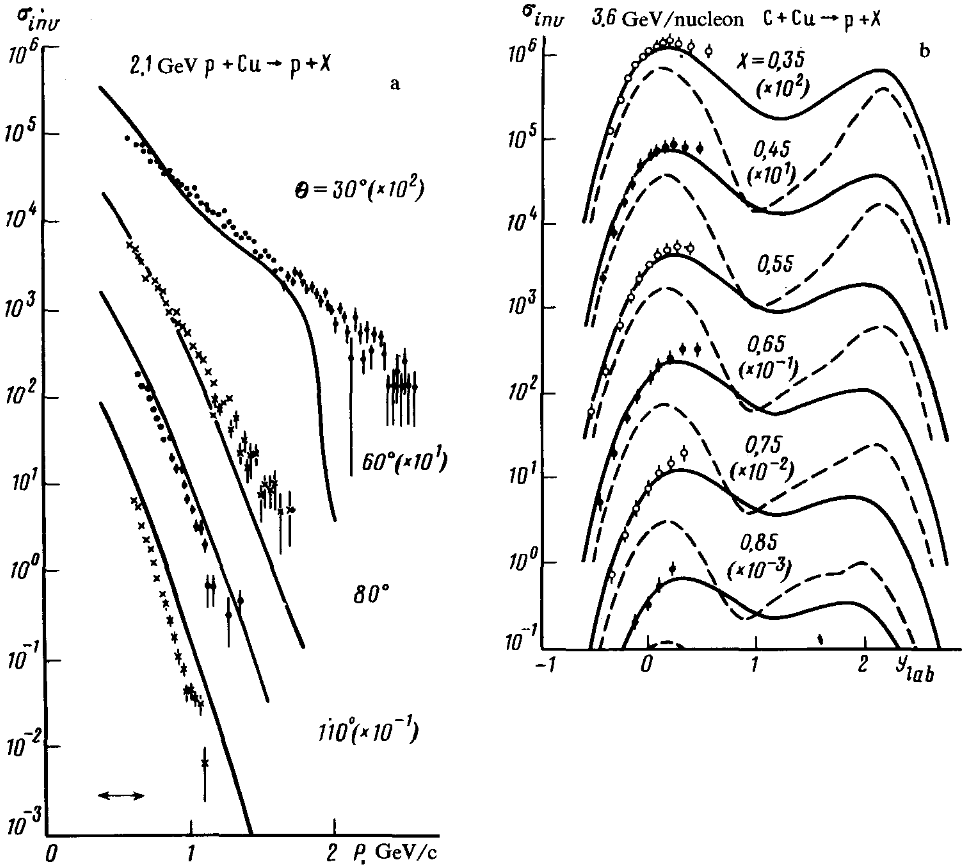

FIG. 1. Invariant cross sections for the proton yield (in millibarns · cubic seconds per square GeV) in two reactions: a—$p + {}^{64}\mathrm{Cu}$, $E_{\rm lab} = 2.1$ GeV (P is the proton's momentum in the laboratory frame); b—${}^{12}\mathrm{C} + {}^{64}\mathrm{Cu}$, $E_{\rm lab} = 3.6$ GeV/nucleon. Solid curves—Inclusive cross section; dashed curves—contribution of events with N_p or $N_t = 1$; points—experimental data.[2,7]

into account the production of Δ isobars and π mesons and also corrections for the finite phase space of the final states of the secondary protons and the emission of composite fragments. We find that the inclusive proton spectra for all these reactions are reproduced best with $\lambda_0 = 13$ fm. The success in producing the experimental data can be judged from Fig. 1, which shows some typical results.

The equations of the partial transparency model lead to the following results on the stopping of a fast nucleon in a nuclear medium:

$$\frac{dE_p}{dz} = -\frac{E_p}{\lambda_T(V_{rel})}, \quad \frac{d(\epsilon_p - m_N)}{dz} = \frac{m_N}{\lambda_0} - \frac{\epsilon_p - m_N}{\lambda_T(V_{rel})}, \tag{6}$$

where z is the distance traveled by the incident particle in the proper frame of the medium, $E_p = \epsilon_p \cosh y_p - m_N$ is the total energy of the incident particle (without its rest energy), ϵ_p includes the transverse mass and internal excitation energy (in the Δ-isobar state), and $V_{\rm rel} = \tanh y_p$. In the initial stage of the stopping ($z \ll \lambda_0$), we have $\epsilon_p \cong m_N$, so that the loss of energy by the incident particle per unit length along its path is essentially constant: $dE_p/dz \cong -m_N/\lambda_0$. At $z \sim \lambda_0$, there is a significant increase in ϵ_p, and this increase is accompanied by an increase in the energy loss.

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[1)]Here $\alpha = p, t$ specifies whether the tube initially belongs to the incident nucleus or to the target, respectively.
[2)]In the calculation of $W(N)$ we used experimental nuclear distributions of the charge density.

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