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Large–Transverse-Energy Production in High-Energy Proton-Nucleus Collisions.

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Abstract. – We investigate the CERN-SPS preliminary data and the Fermilab data of large–transverse-energy production in proton-nucleus collisions using the wounded nucleon model (WNM) and the additive quark model (AQM). The CERN-SPS data favour the WNM, while the Fermilab data favour the AQM.

Preliminary data [1] of the large–transverse-energy (E_T) production in the proton-Pb collisions at $p_{lab} = 200$ GeV/c were obtained by the HELIOS Collaboration at the CERN-SPS. The E_T distribution is observed till $E_T = 50$ GeV far beyond the kinematical limit ($= 19.4$ GeV) of the proton-nucleon (p$\mathcal{N}$) collision. In the previous two Fermilab experiments [2, 3] of proton-nucleus (pA) collisions at $p_{lab} = 400$ GeV/c, such large-E_T region was not measured. It is believed that the large-E_T tail of the distribution in the nuclear collision reflects the higher-order multiple $\mathcal{N}\mathcal{N}$ collisions and the consequent high-energy density state. Pisutova, Lichard and Pisut [4] investigated the CERN-SPS data using a simple model. They pointed out that the experimental E_T distribution can be reproduced by the simple model.

In this paper, we examine the preliminary data of the CERN-SPS experiment [1] along with the data of the Fermilab experiment [3] using the wounded nucleon model (WNM) [5] and the additive quark model (AQM) [6]. We find that the CERN-SPS data favour the WNM, while the Fermilab data favour the AQM.

In the WNM, the E_T distribution in the pA collisions depends on the number of the wounded nucleons, and is written as [7]

$$\frac{d\sigma^{pA}}{dE_T} = \sigma_{in}^{pA} \sum_{w=2}^{A+1} a(w-1) f_w(E_T). \tag{1}$$

Here, the inelastic cross-section of the pA collisions is given by

$$\sigma_{in}^{pA} = \int d^2 \boldsymbol{b} \, [1 - \{1 - \sigma_{in}^{\mathcal{N}\mathcal{N}} t_A(\boldsymbol{b})\}^A], \tag{2}$$

where $\sigma_{in}^{\mathcal{N}}$ is the $\mathcal{N}\mathcal{N}$ inelastic cross-section. The nuclear thickness is defined by

$$t_A(\boldsymbol{b}) = \int dz\, \rho_A(r), \tag{3}$$

where $\rho_A(r)$ is the nuclear density normalized to unity. We use the Woods-Saxon nuclear density

$$\rho_A(r) = \rho_0/[1 + \exp[(r - R_A)/d]], \tag{4}$$

where $R_A = 1.19A^{1/3} - 1.61A^{-1/3}$ fm and $d = 0.54$ fm [8].

The probability $a(w)$ that w nucleons in the nucleus get wounded is written as

$$a(w) = \int d^2\boldsymbol{b} \binom{A}{w} [\sigma_{in}^{\mathcal{N}\mathcal{N}} t_A(\boldsymbol{b})]^w [1 - \sigma_{in}^{\mathcal{N}\mathcal{N}} t_A(\boldsymbol{b})]^{A-w} / \sigma_{in}^{pA}. \tag{5}$$

The E_T distribution $f_w(E_T)$ is the convolution of the E_T distributions by the w-wounded nucleons:

$$f_w(E_T) = \int dE_T^1 \ldots dE_T^w f_1(E_T^1 \ldots f_1(E_T^w)\, \delta(E_T - E_T^1 \ldots - E_T^w), \tag{6}$$

where $f_1(E_T)$ is the E_T distribution by one wounded nucleon. In the pp collision two protons get wounded, so the normalized E_T distribution is

$$\frac{1}{\sigma^{pp}} \frac{d\sigma^{pp}}{dE_T} = f_2(E_T) = \int dE_T^1\, dE_T^2 f_1(E_T^1) f_1(E_T^2)\, \delta(E_T - E_T^1 - E_T^2). \tag{7}$$

For the E_T distribution in the pp collisions, we assume the simple form [9, 10]

$$f_2(E_T) = \alpha^{\beta+1}/\Gamma(\beta + 1) \cdot \exp[-\alpha E_T] E_T^{\beta}. \tag{8}$$

Several experimental data [9-11] can be fitted with this gamma distribution. From (7) and (8), the E_T distribution by one wounded nucleon is obtained as

$$f_1(E_T) = \alpha^{((\beta+1)/2)}/\Gamma((\beta + 1)/2) \cdot \exp[-\alpha E_T] \cdot E_T^{((\beta-1)/2)}. \tag{9}$$

Then, the E_T distribution by w wounded nucleons is [9]

$$f_w(E_T) = \alpha^{(w(\beta+1)/2)}/\Gamma(w(\beta + 1)/2) \cdot \exp[-\alpha E_T] \cdot E_T^{(w(\beta+1)/2-1)}, \tag{10}$$

which is also normalized to unity.

Next, we give the E_T distribution by the AQM. In the pp collision, a quark in the incident proton collides with a quark in the target proton. Then a coloured string spans between them. Fragmentation of the coloured string gives rise to the particle production in the central rapidity region. In the pA collision, several quark-quark interactions occur and several coloured strings span between them. However, coloured strings connected to the same quark in the incident proton interact and coalesce into a string. So the number of the coloured strings is the same as that of the wounded quarks in the incident proton. We consider that the number of quarks in the proton is three [6].

Therefore, in the AQM, the E_T distribution in the pA collisions is written as [7]

$$\frac{d\sigma^{pA}}{dE_T} = \sigma^{pA} \sum_{w=1}^{3} b(w) \cdot g_w(E_T), \tag{11}$$

where the inelastic cross-section of the pA collisions is given by

$$\sigma^{pA} = \int d^2\boldsymbol{b}[1 - \{1 - \sigma_{qq} t_A(\boldsymbol{b})\}^{3A \cdot 3}]. \tag{12}$$

The probability $b(w)$ that w quarks in the incident proton get wounded is given by [8]

$$b(w) = \int d^2\boldsymbol{b} \binom{3}{w} [1 - \{1 - \sigma_{qq} t_A(\boldsymbol{b})\}^{3A}]^w \cdot [\{1 - \sigma_{qq} t_A(\boldsymbol{b})\}^{3A}]^{3-w} / \sigma^{pA}, \tag{13}$$

where the quark-quark cross-section is given [6] by $\sigma_{qq} = (1/9)\,\sigma_{in}^{\mathcal{N}\mathcal{N}}$. In the derivation of (12) and (13), we neglected the size of the incident proton.

The E_T distribution $g_w(E_T)$ in (11) is the convolution of the E_T distribution of the w coloured strings. Since the E_T distribution in the pp collisions is due to one coloured string,

$$g_w(E_T) = f_{2w}(E_T) . \tag{14}$$

In the first place, we compare the calculations of the WNM and the AQM with the CERN-SPS data [1]. The experimental E_T distribution in the p-Pb collisions at $p_{lab} = 200$ GeV/c is measured for the laboratory pseudorapidity range of $0.6 < \eta_{lab} < 2.4$.

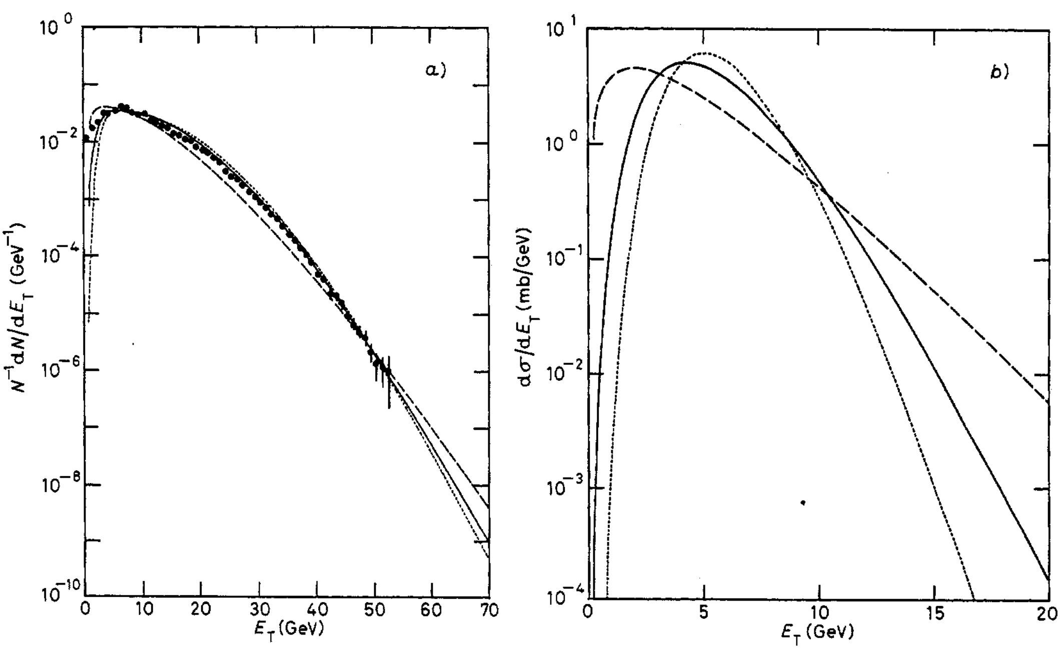

Fig. 1. – *a*) The E_T distributions in the p-Pb collisions. Comparison of the WNM with the CERN-SPS data [1]. Solid line: $\alpha = 1.15$ and $\beta = 5.0$, dotted line: $\alpha = 1.97$ and $\beta = 10.0$ and dashed line: $\alpha = 0.50$ and $\beta = 1.0$. In the three cases, we take $\sigma_{in}^{\mathcal{N}\mathcal{N}} = 25$ mb. *b*) The E_T distributions in the pp collisions corresponding to the three parameter sets of *a*).

Since the experimental E_T distribution in the pp collisions is not present in [1], we take α, β and $\sigma_{in}^{\mathcal{NN}}$ as the free parameters. For the $\mathcal{NN}$ inelastic cross-section, we take $\sigma_{in}^{\mathcal{NN}} = 25$ mb [2, 10]. We show the calculations of the E_T distributions of three sets of the parameters α and β for the WNM in fig. 1*a*) and the AQM in fig. 2*a*), respectively. The case of $\alpha = 1.15$ and $\beta = 5.0$ for the WNM and that of $\alpha = 0.52$ and $\beta = 2.0$ for the AQM are the best fits. The corresponding E_T distributions in the pp collisions are shown in fig. 1*b*) and fig. 2*b*), respectively. For the WNM, comparing fig. 1*a*) with fig. 1*b*), we find that the region of $E_T \leqslant 50$ GeV in the p-Pb collisions roughly corresponds to that of $E_T \leqslant 10$ GeV in the pp collisions. Therefore, the WNM can reproduce the CERN-SPS data if the E_T distribution in the pp collisions is realistic in the region of $E_T \leqslant 10$ GeV.

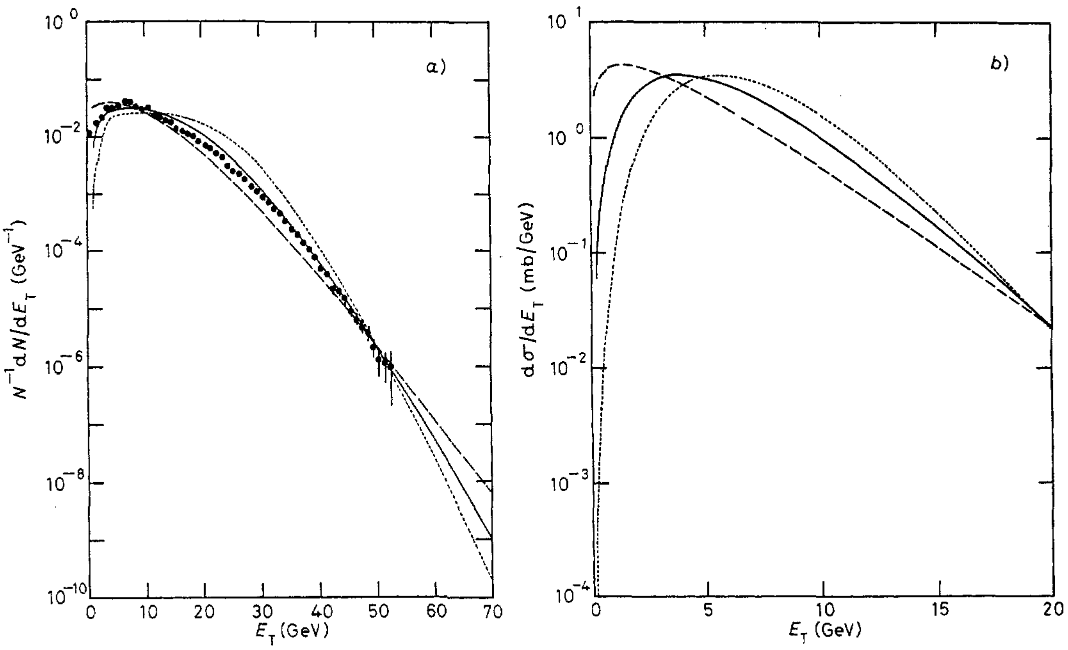

Fig. 2. – *a*) The E_T distributions in the p-Pb collisions. Comparison of the AQM with the CERN-SPS data [1]. Solid line: $\alpha = 0.52$ and $\beta = 2.0$, dotted line: $\alpha = 0.71$ and $\beta = 4.0$ and dashed line: $\alpha = 0.35$ and $\beta = 0.5$. In the three cases, we take $\sigma_{in}^{\mathcal{NN}} = 25$ mb. *b*) The E_T distributions in the pp collisions corresponding to the three parameter sets of *a*).

On the other hand, comparing fig. 2*a*) with fig. 2*b*), we find that in the case of the AQM even the region at about the kinematical limit (= 19.4 GeV) of the E_T distribution in the pp collisions contributes to the E_T distribution of the region of $E_T \leqslant 50$ GeV in the p-Pb collisions. The calculated E_T cross-sections of the pp collisions in fig. 2*b*) are unreasonably large at the kinematical limit. So it is difficult for the AQM to reproduce the CERN-SPS data with a reasonable E_T distribution in the pp collisions, if we stick to the gamma distribution of (8). The main reason of the difference between the calculations of the two models is that the maximum number of the coloured strings is three, while that of the wounded nucleons is $A + 1$. If we use the same parameters for the two models, the E_T distribution of the WNM is more extending than that of the AQM.

Next, we compare the E_T distributions of the WNM and the AQM with the Fermilab data [3] at $p_{lab} = 400$ GeV/c. The data are taken for the full azimuth and the polar angle $30° < \theta_{c.m.s.} < 125°$ in the p$\mathcal{N}$ centre-of-mass system, which corresponds to the rapidity range of $-0.65 < \eta_{c.m.s.} < 1.32$. Though the experimental E_T distribution in the pp collisions is present in [3], the measured E_T region is limited. Therefore, the values of the parameters α, β and $\sigma_{in}^{\mathcal{NN}}$ cannot be determined uniquely. We show in fig. 3*a*) the E_T distributions (solid lines) of the WNM with $\sigma_{in}^{\mathcal{NN}} = 25$ mb, $\alpha = 0.73$ and $\beta = 0.75$ and in fig. 3*b*) those of the AQM with $\sigma_{in}^{\mathcal{NN}} = 25$ mb, $\alpha = 0.85$ and $\beta = 1.2$. Contrary to the case of the comparison with the CERN-SPS data, the AQM can fit better than the WNM. From the comparison between the two experimental data, we notice that the E_T distribution in the p-Pb collisions of the CERN-SPS data is more extending than that of the Fermilab data. The E_T distributions of the two models deviate from data points for the large-E_T region.

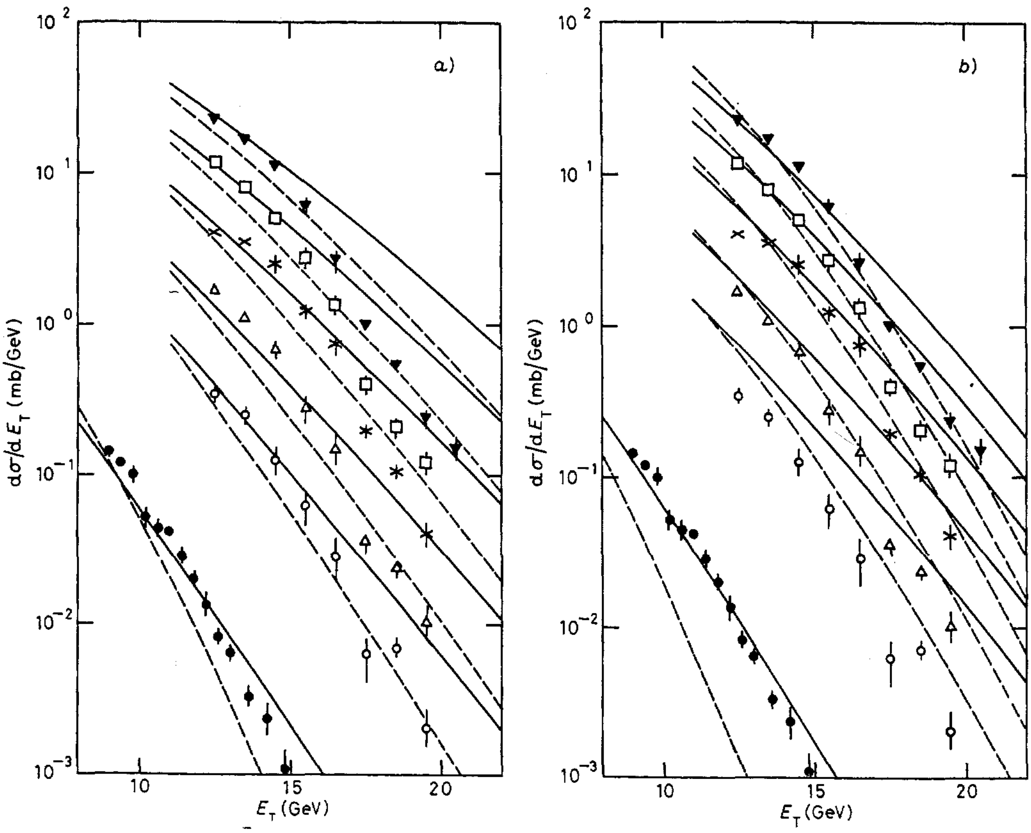

Fig. 3. – The E_T distributions in the pA collisions. Comparison of *a*) the WNM and *b*) the AQM with the Fermilab data [3]. *a*) Solid lines: $\sigma_{in}^{\mathcal{NN}} = 25$ mb, $\alpha = 0.73$ and $\beta = 0.75$, dashed lines: $\sigma_{in}^{\mathcal{NN}} = 10$ mb, $\alpha = 1.4$ and $\beta = 5.0$. *b*) Solid lines: $\sigma_{in}^{\mathcal{NN}} = 25$ mb, $\alpha = 0.82$ and $\beta = 1.2$, dashed lines: $\sigma_{in}^{\mathcal{NN}} = 25$ mb, $\alpha = 1.35$ and $\beta = 3.0$. Both in *a*) and *b*): ▼ Pb, □ Sn, × Cu, △ Al, ○ C, ● H.

As we saw in the case of the comparison with the CERN-SPS data, the E_T region in the pp collisions contributing to the E_T distribution in the pA collisions is smaller than the corresponding E_T region in the pA collisions. Consequently, there is not much need to fit with the pp data in the case of the Fermilab data. If we do not fit with the pp data, the E_T distribution of the AQM can be fitted with the pA data as shown in fig. 3*b*) (dashed lines) with the parameters $\sigma_{in}^{\mathcal{NN}} = 25$ mb, $\alpha = 1.35$ and $\beta = 3.0$, especially for large nuclei. In the case of the WNM, we cannot precisely fit with the experimental E_T distribution of all nuclei at the same time, even if we do not fit with the pp data. However, if we take a small value for the $\mathcal{NN}$ inelastic cross-section, we can better fit with the experimental data. For example, we show the case of $\sigma_{in}^{\mathcal{NN}} = 10$ mb, $\alpha = 1.4$ and $\beta = 5.0$ in fig. 3*a*) (dashed lines). If we take account of the effect of the energy degradation of the incident proton while propagating in the nucleus, by making the $\mathcal{NN}$ inelastic cross-section small, the value of 10 mb is not unreasonable.

We have calculated the large-E_T cross-sections in the pA collisions using the WNM and the AQM, and compared the models with the CERN-SPS data and the Fermilab data. The WNM can reproduce the CERN-SPS data, if the E_T distributions in the pp collisions given by the parameters used here are realistic, while the AQM is difficult to reproduce the data if we stick to the gamma distribution of (8) for the E_T distribution in the pp collisions. On the other hand, the AQM can reproduce the Fermilab data better than the WNM. In the CERN-SPS experiment, the E_T distribution in the pp collisions was not measured. Though in the Fermilab experiment the E_T distribution in the pp collisions was measured, the measured E_T range is narrow. Therefore, we cannot draw the decisive conclusion as to whether the models succeed in reproducing the experimental data, except the case of the comparison of the AQM with the CERN-SPS data. We hope that in the future experiments the E_T distribution in the pp collisions along with that in the nuclear collisions is measured for a wide E_T range.

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