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TOTAL CROSS SECTION OF ULTRA-RELATIVISTIC HEAVY ION REACTIONS

by

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ABSTRACT

A possibility of an increase of the nuclear reaction cross section with incident energy for heavy ion collisions in the ultra-relativistic domain is suggested. At the energy of 200 GeV/A, the total reaction cross section may increase even up to twice the conventional geometrical cross section. Recent experimental results seem to be consistent with this picture.

Key-words: Ultra-relativistic heavy ion reactions; RIO effect; Geometrical cross section.

The main motivation for studying relativistic heavy ion collisions (RHIC) has been the generalized expectation of observing new forms of nuclear matter such as a quark-gluon plasma phase. Besides this primary objective RHIC offer a first chance to study the relativistic dynamics of a comparatively large quantum system in its bound state. A fully satisfactory quantum mechanical description of a relativistic many body bound system is not yet available.

Recent CERN experimental results on RHIC for energies ranging from several tens of GeV up to 200 GeV per nucleon have appeared in the literature[1,2,3]. Although most of the data are reported to be consistent with the existing models[4], there seem to exist some discrepancies which could not be accounted for by these descriptions. In particular, the electromagnetic dissociation (ED) cross sections of S+Ag measured by Hill et al.[2] increase more rapidly than the well known ln γ behavior of theoretical predictions using the virtual photon spectrum method[4], where γ denotes the Lorentz factor. The experimental ED-cross section is obtained by subtracting from the measured total one-neutron emission cross section a nuclear contribution which is estimated based on the limiting fragmentation hypothesis. The limiting fragmentation assumption[5] is a geometrical concept, and gives a nuclear cross section essentially independent of the incident energy. However, there is no obvious reason to believe that the nuclear cross section should stay constant for very high energies.

Nearly three decades ago, it was believed that the total nucleon-nucleon interaction cross-section would remain at a constant value ≅ 40mb at very high energies. This value, in fact, corresponds to the geometrical size of a nucleon, of the order of the Compton wavelength of the pion.

In 1961 Froissart[6] demonstrated that the unitarity of the S-matrix and the microcausality of the local interaction imply that reaction cross sections cannot increase more rapidly than $\ln^2 s$ for very large s, where s refers to the square of the total CM energy. Subsequently, high energy experiments, including cosmic ray results, showed that the nucleon-nucleon cross section does increase as a function of the incident energy. At an energy $\sqrt{s} \cong 1$TeV, it reaches a value roughly twice the one quoted above. The data can be fitted by the Froissart $\ln^2 s$ dependence although the absolute value is far from the saturation value[7].

From a phenomenological point of view, it can be shown using a simple geometrical argument that a $\ln^2 s$ behaviour is followed by any system which has an exponential tail in the probability density distribution[6,8], although from a field theoretical point of view it is not apparent how to manage such a geometrical concept in the description of the nucleon-nucleon scattering amplitude. Anyhow, the surface diffuseness of the mass distribution should be relevant for very high energies.

In nucleus-nucleus collision processes, W. Myers proposed a phenomenological model which allowed for the inclusion of nuclear surface diffuseness effects[9]. Its application to the production of heavy fragments was discussed by Oliveira et al.[10]. They concluded that the model overstimates the reaction cross section and this characteristic was traced back to the exponential dependence of the mass distribution in the tail region. In this model the nucleon distribution is regarded as an actual classical continuous medium carrying mass and energy, so that no matter how low the density is, the mass in the tail region can always acquire a large energy and momentum according to the incident energy, leading to the nuclear excitation of the colliding nucleus. As the model takes the energy threshold to be the nucleon separation energy ($\cong$ 8 MeV), the calculated reaction cross section has an undesirable increase with the incident energy in the Bevalac energy range[10).

It should be reminded that the surface diffuseness represents the probability of finding a nucleon in that region. Therefore, in this energy region, it is not reasonable to suppose that the nucleon distribution behaves as a continuous medium to provide the dynamical properties of matter for very low density. For such low density part, a Glauber type approach would be more adequate and in this case, the expected nuclear cross section does not depend on the incident energy, giving the usual geometrical value.

On the other hand, at very high collision energies, the virtual meson field associated to the nucleon distribution could give rise to a variety of processes such as pair production. At such energies, it could be possible to associate the classical matter behaviour to the tail of the probability density due to the many degrees of freedom which then come into play. In fact, this is the argument to understand the observed increase of nucleon--nucleon cross section at very high energies[11).

According to the above idea, we propose the following model for nucleus-nucleus collisions at very high energies, namely, $\gamma \gg 1$. Let us consider the collision process of two nuclei with impact parameter b (see Fig. 1). Similar to the firestreak model[9], we divide the target nucleus into thin tubes parallel to the beam direction (z-axis). As the projectile nucleus passes through the target nucleus, each of such tubes receives the impact of the tube in the projectile at the same (x,y) position. The amout of energy per unit transversal area of the target tube is

$$E_T(x,y) = \int dz\, \mathcal{E}_T(x,y,z) \,, \tag{1}$$

whereas the projectile tube has the rest mass energy per unit area

$$E_P(x,y;b) = \int dz\, \mathcal{E}_P(x,b-y,z) \,, \tag{2}$$

where $\varepsilon_{T(P)}(\vec{r})$ denotes the energy density of the target (projectile) nucleus.

We suppose that the inelastic process takes place whenever a sufficient energy, say greater than some threshold value E* per unit area is deposited in the CM system of these two colliding tubes. Let k be the inelasticity. Our condition for the occurrence of the reaction is that, for a given impact parameter b, there exists at least one tube such that

$$k\, T_{CM}(x,y;b) \geq E^* \,, \tag{3}$$

where T_{CM} denotes the kinetic energy per area. We have

$$T_{CM}(x,y;b) = \frac{2(\gamma-1)E_P E_T}{\sqrt{2(\gamma-1)E_P E_T} + E_P + E_T} \,, \tag{4}$$

so that we may calculate the total cross for the target excitation as

$$\sigma = \pi b_{max}^2(\gamma) , \qquad (5)$$

where

$$b_{max} = \underset{(x,y)}{Max}\ b(x,y;\gamma), \qquad (6)$$

$b(x,y;\gamma)$ is calculated from the equation

$$E_P(x,y;b) = \frac{\xi\,[\,\xi + 2E_T(x,y)]}{2\,[\,(\gamma-1)E_T(x,y) - \xi\,]} , \qquad (7)$$

with $\xi = E^*/k$.

For simplicity, let us approximate the nuclear energy density $\varepsilon(\vec{r})$ as

$$\varepsilon(\vec{r}) = \begin{cases} \varepsilon_0 , & 0 \le r \le R-\Delta , \\ \varepsilon_0 \exp\left\{\frac{R-\Delta-r}{\Delta'}\right\}, & r > R-\Delta . \end{cases} \qquad (8)$$

where ε_0 is the central density, R is the half-density radius of the nucleus, and $\Delta' = \Delta/\ln 2$ is half the surface thickness. Furthermore, it is easy to see that the maximum of b in Eq. (6) is attained for x = 0, so that we only need to calculate $b(x,y;\gamma)$ for x = 0. Using Eq. (8) for the energy density, we have for $b > R_T+R_P$, $y < R_T$,

$$E_T(0,y) \cong 2\varepsilon_0\sqrt{R_T^2-y^2} + \varepsilon_0\sqrt{2\pi\Delta' y}\ e^{\frac{R_T-\Delta-y}{\Delta'}} , \qquad (9)$$

and

$$E_P(0,y;b) \cong \varepsilon_0\sqrt{2\pi\Delta'(b-y)}\ e^{\frac{R_P-\Delta}{\Delta'}}\ e^{\frac{b-y}{\Delta'}} . \qquad (10)$$

Taking $\varepsilon_0 \cong 1\ \text{GeV}/(\frac{4\pi r_0^2}{3})$, with $r_0 = 1.2$fm, and Δ'

$\cong$ 0.7fm, we plotted in Fig. 2 the ratio of the calculated reaction cross section of S+Pb to that of the geometrical cross section $\pi(R_T+R_P)^2$ as functions of γ for several values of ξ. These values of ξ were chosen assuming that the inelastic processes require an amount of deposited energy of the order of one GeV within the correlation area for the particle production. As we can see from this figure, the calculated cross section increases quite significantly, achieving more than twice the geometrical value at the energy region of 1 TeV/nucleon. On the other hand, in the Bevalac energy region the geometric value is dominant. We refer to this effect as Relativistic Ion Overgrowth, (RIO - effect).

We also note that the maximum value of b in Eq. (6) is attained in the peripheral region of the target nucleus. This suggests that the mechanism of cross section increase is mainly related to processes of diffractive nature in the nucleus-nucleus collision, similar to those found in the nucleon-nucleon case[11)].

Very recently, two groups[1,3)] have analysed the fragmentation cross sections of O and S at 200 GeV/A using various targets, ranging from C to Pb. The measured total fragmentation cross sections are suprisingly large. Both groups subtract the usual geometrical contribution from the measured values and attribute the large remaining difference entirely to electromagnetic processes.

One of the main contributions to the electromagnetic excitation mechanism comes from the giant resonance of the target nucleus. This part is relatively well studied[4,12)], and is known to be insufficient to explain the large observed difference[1,2,3)].

The other electromagnetic contributions such as mesonic or baryon resonances which are expected to explain the rest of the difference in Refs. 1 and 3 are not so well established. This leaves room for the existence of the kind of nuclear mechanisms suggested in this work. We consider particularly suggestive that the observed dependence of the cross section on the target atomic number is considerably slower than that expected from the pure Coulomb like interaction[1)].

In our model, we found that the cross section as a function of target mass A_T depends rather sensibly on the form of the tail of the distribution. In Fig. 3, we show the calculated nuclear contribution to the cross section as a function of A_T for $\xi = 0.5\ \mathrm{GeV/fm^2}$ using Eq. (8) for the nuclear energy density distribution. The slope of this curve is much smaller than that of a Coulomb Z^2-dependence. Although the form of nuclear distribution used here is not very realistic, we can conclude that the RIO effect suggested here could be distinguished from the Coulomb contribution by the A_T-dependence of the total cross section. This would be an interesting point to investigate in future experiments.

Finally, remembering the peripheral nature of the mechanism proposed here, we expect that one-nucleon emission proceses can become more important at very high energies. This could help to explain the data of Hill et al.. Work along this line is in progress.

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FIGURE CAPTIONS

FIG. 1. Geometrical description of the colliding system. The spherical nuclei of radii R_T and R_F (shown deformed because of Lorentz contraction) collide with an impact parameter b. The energy contained in the tubes defined by their axis coordenates (x,y) can give rise to inelastic processes.

FIG. 2. Ratio of the nuclear cross sections calculated in our model to the conventional geometrical values (σ_G = $(R_T+R_F-b)^{1)}$, plotted as functions of incident energy. The numbers indicated are the values of ξ (see text for details).

FIG. 3. Target mass dependence of the excess ovcer σ_G of the projectile break-up inclusive cross section. In the case of Coulomb Excitation process, it rizes as Z_T^2 (dashed curve). The effect proposed here (solid line) has a weaker A_T-dependence. The experimental data of Price et al. (black squares) are also indicated. Theoretical curves are normalized to the ^{12}C data point in order to facilitate the comparison.

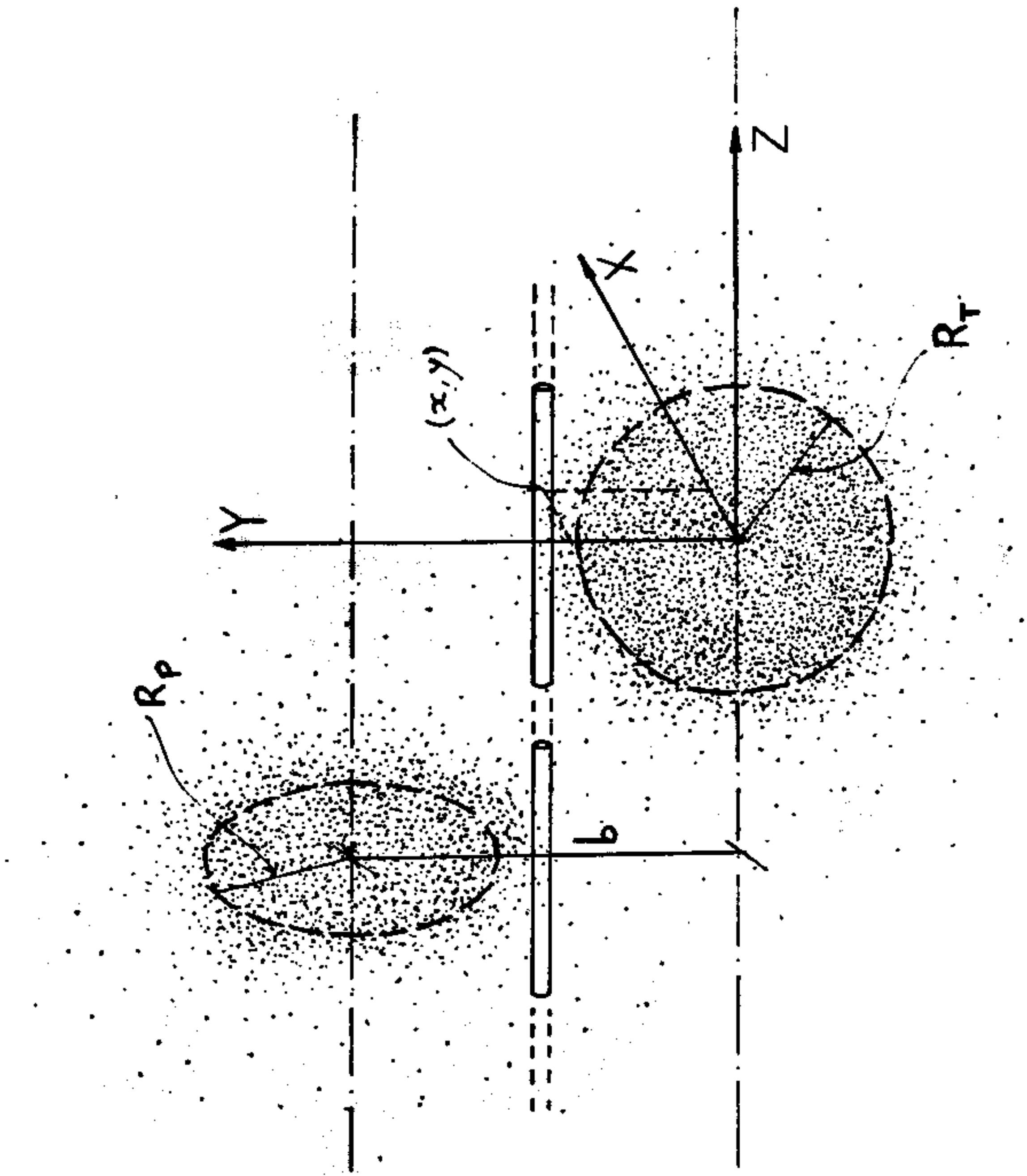

Fig. 1

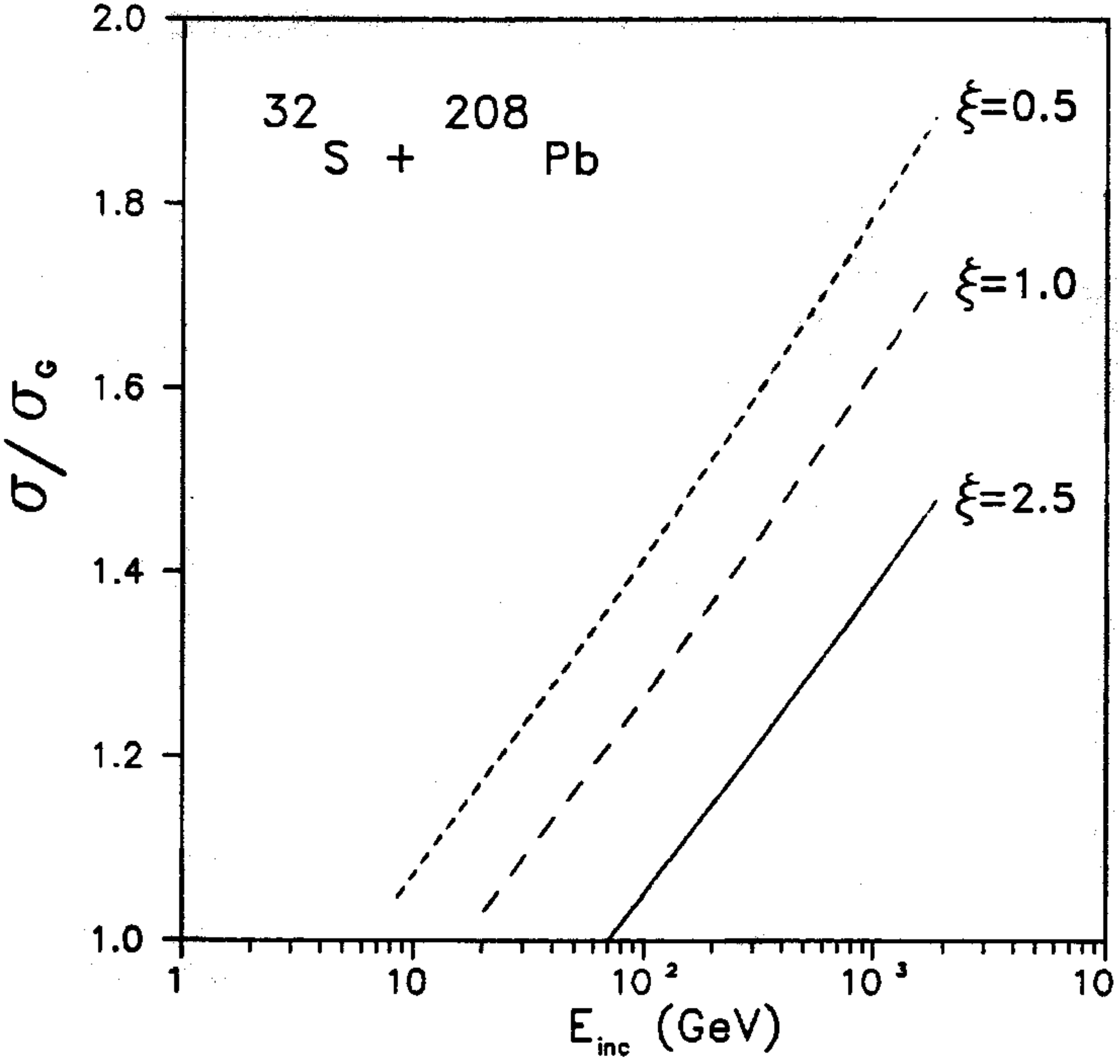
2.0
1.8
1.6
1.4
1.2
1.0
σ/σ_G
$^{32}S + ^{208}Pb$
ξ=0.5
ξ=1.0
ξ=2.5
1
10
10 ²
10 ³
10
E_{inc} (GeV)

Fig. 2

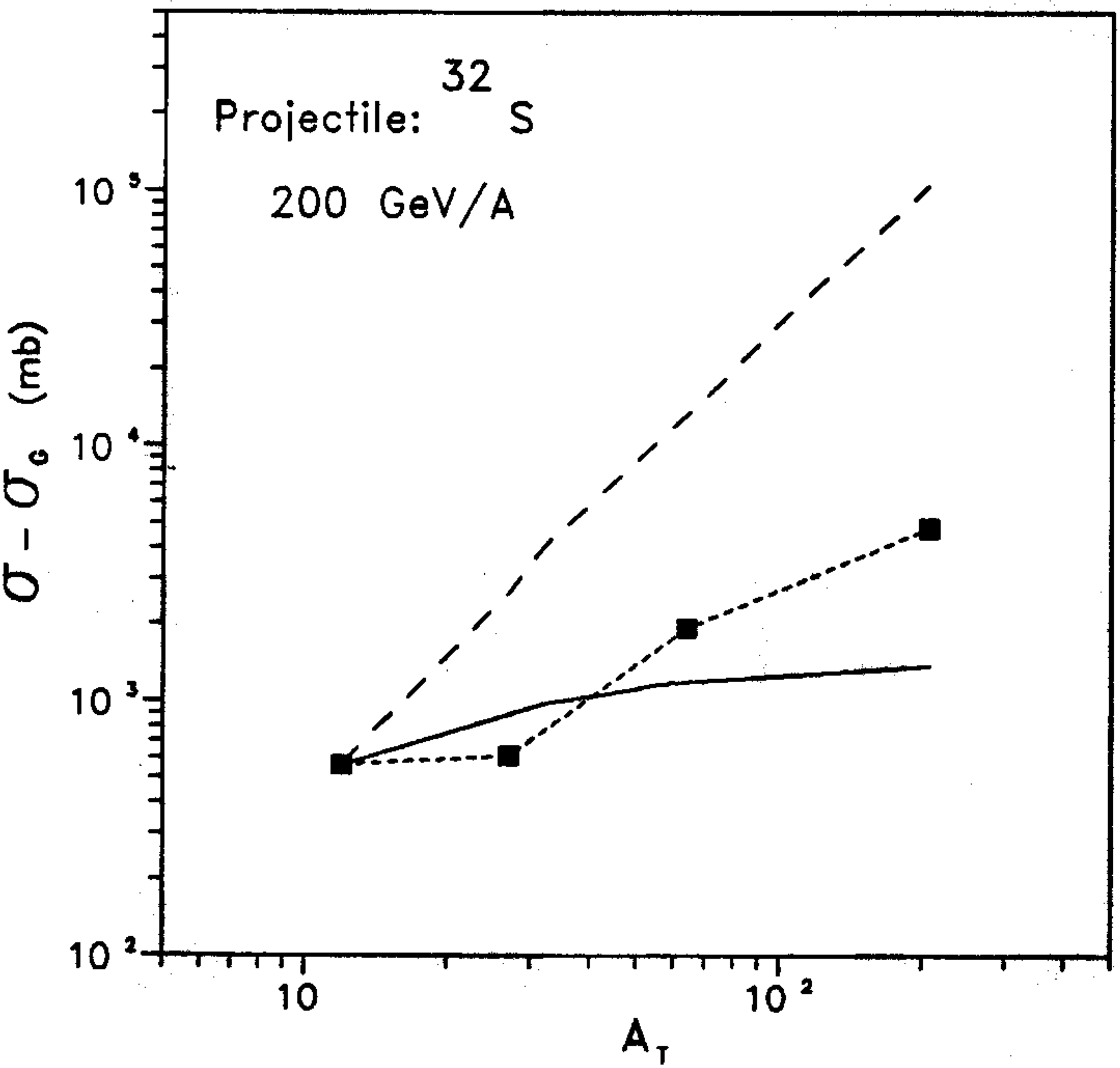

Fig. 3

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