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NEUTRON TOTAL CROSS SECTIONS

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ABSTRACT

We have measured total cross sections for neutrons on protons, deuterons, beryllium, carbon, aluminum, iron, copper, cadmium, tungsten, lead and uranium for momenta between 30 and 300 GeV/c. Typical accuracy of the data is 0.5 to 1%. Our results are compared with other measurements and with theoretical predictions. In particular, our results for nuclei seem to be inconsistent with recent predictions by Koplik and Mueller which are based on a Regge model.

The apparatus and techniques used in this measurement have been described in two letters[1,2] and a long article,[3] and need not be discussed here. Rather we shall concentrate on a comparison of the results with theory and other data.

Briefly, the measurements were made with a neutron beam (the M3 beam at Fermilab) and a technique similar to the standard transmission technique. The transmitted neutrons were detected with a calorimeter which provided an energy measurement with a resolution of approx. ±7%. The cross sections were determined directly from the ratio of beam transmitted with target in to that with target out. With this technique it is not necessary to know the absolute neutron flux or the efficiency of the detector.

Corrections to the raw data were made for the finite solid angle subtended by the detector (≈0.3% for small nuclei and up to 7% for large nuclei), for beam contamination (usually <1%), rate effects (usually <1%), and magnetic dipole scattering (<<1%).

Our results for n-p total cross sections are given in Fig. 1 and compared with previous data and with p-p total cross section measurements. Only <u>direct</u> measurements of n-p cross sections are shown. Measurements based on a (pd-pp) subtraction suffer from a rather large uncertainty (~1 mb) because of the uncertainty in the shadowing correction.

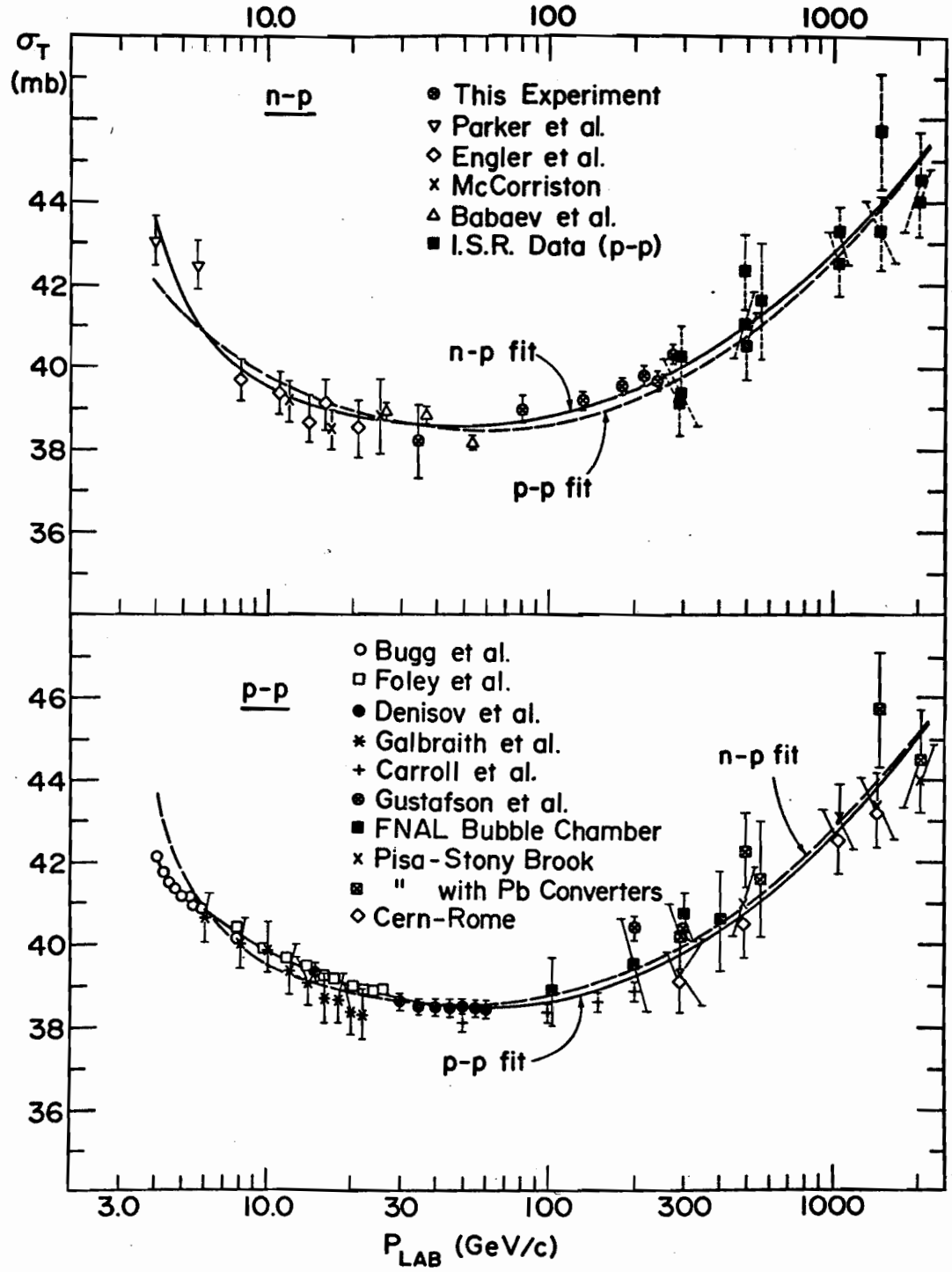

Fig. 1

(a) n-p total cross section from this experiment and previous measurements with neutron beams above 4 GeV/c. Some p-p data are shown with dashed error bars for comparison.

(b) p-p total cross section data above 4 GeV/c

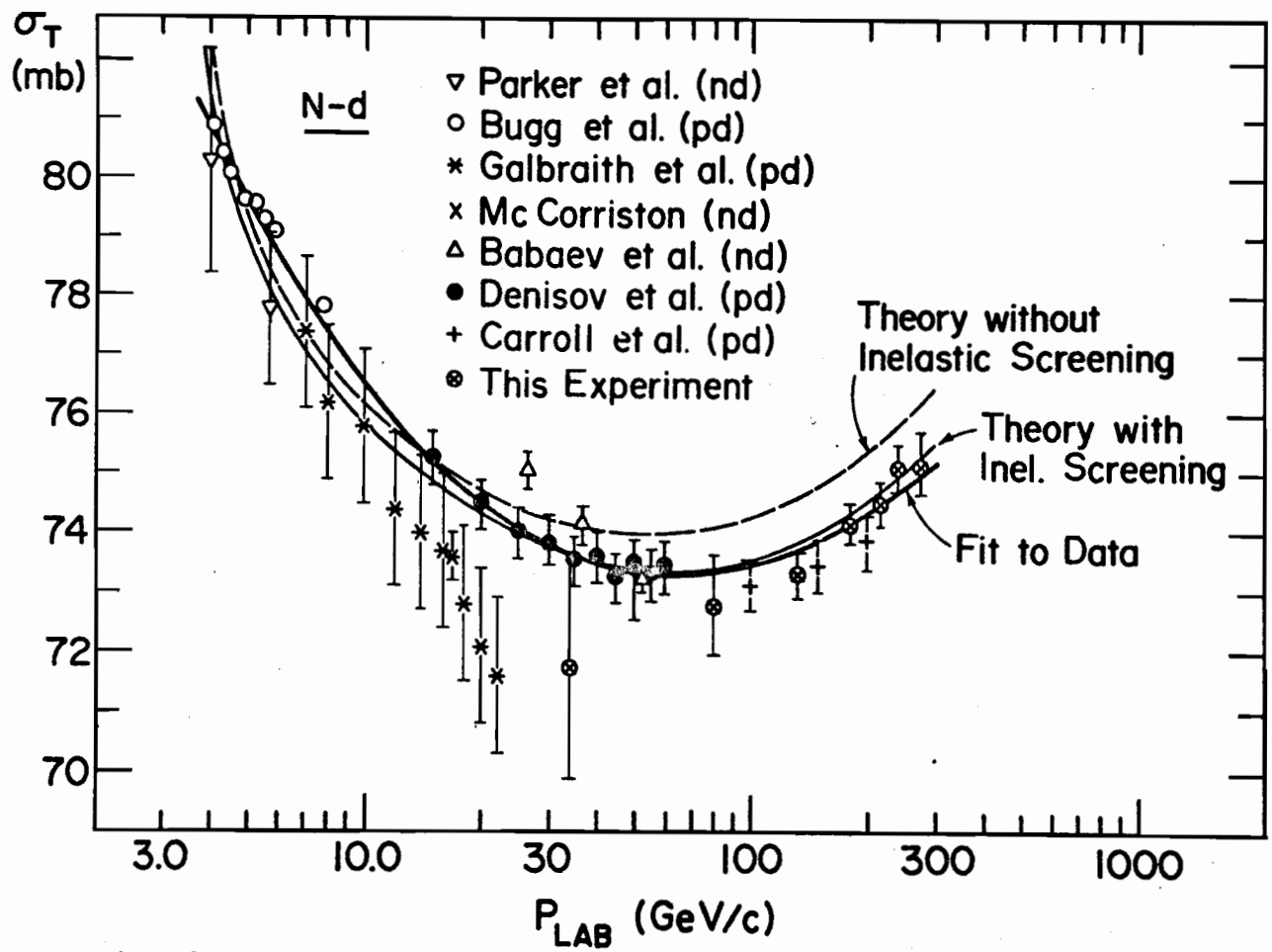

Fig. 2
N-d total cross section data above 4 GeV/c. Total errors including scale errors, are shown on all points. The heavy solid curve is a fit to Eq. (1). The light solid and dashed curves are theoretical cross sections calculated with and without the inelastic screening corrections.

The smooth curves in Fig. 1 are fits of the data to a power series of the form

$$\sigma_T = A_1(\log P_L)^{-2} + A_2(\log P_L)^{-1} + \ldots + A_5(\log P_L)^2 \quad (1)$$

This fit provides a convenient way of smoothing the data and of comparing the np and pp data. The np fit was forced to converge to the pp data for $P_L \geq 1000$ GeV/c but it is clear that the two fits are barely distinguishable above 5 GeV/c.

Figure 2 shows our nd data in comparison with previous nd and pd measurements. Except for the higher energy data of Galbraith et al. and the lowest point of Babaev et al., the various experiments are in excellent agreement. (See Ref. 3 for a complete list of references.) The heavy solid curve is a fit of the data to Eq. 1. The theoretical curves are discussed below.

Our cross sections for several nuclei are shown in Figs. 3 and 4. Our data tie on smoothly to the lower energy data. However, there is some disagreement with the preliminary data of Biel et al.[4] It is surprising that this disagreement is worst for carbon at momenta ~200 GeV/c because corrections to our carbon data in this region were < 1% and we made ≈50 separate measurements on carbon with many different targets with very consistent results.

In order to study how the nuclear transparency varies with energy we have fitted the data for nuclei with $A \geq 9$ to the form.

$$\sigma_T(A) = \sigma_o A^{\nu} \quad (2)$$

Figure 5 shows the variation of ν with lab momentum. To an accuracy of ±0.01, ν appears to be constant above 8 GeV/c. This is in sharp contrast to theoretical predictions that nuclei should become more opaque[5] ($\nu \to 2/3$) or less opaque[6] ($\nu \to 1$) at high energies.

Total cross sections for neutrons on nuclei can be calculated from Glauber theory. There has been considerable debate about whether inelastic screening corrections, due to processes such as that shown in Fig. 6b, are important.

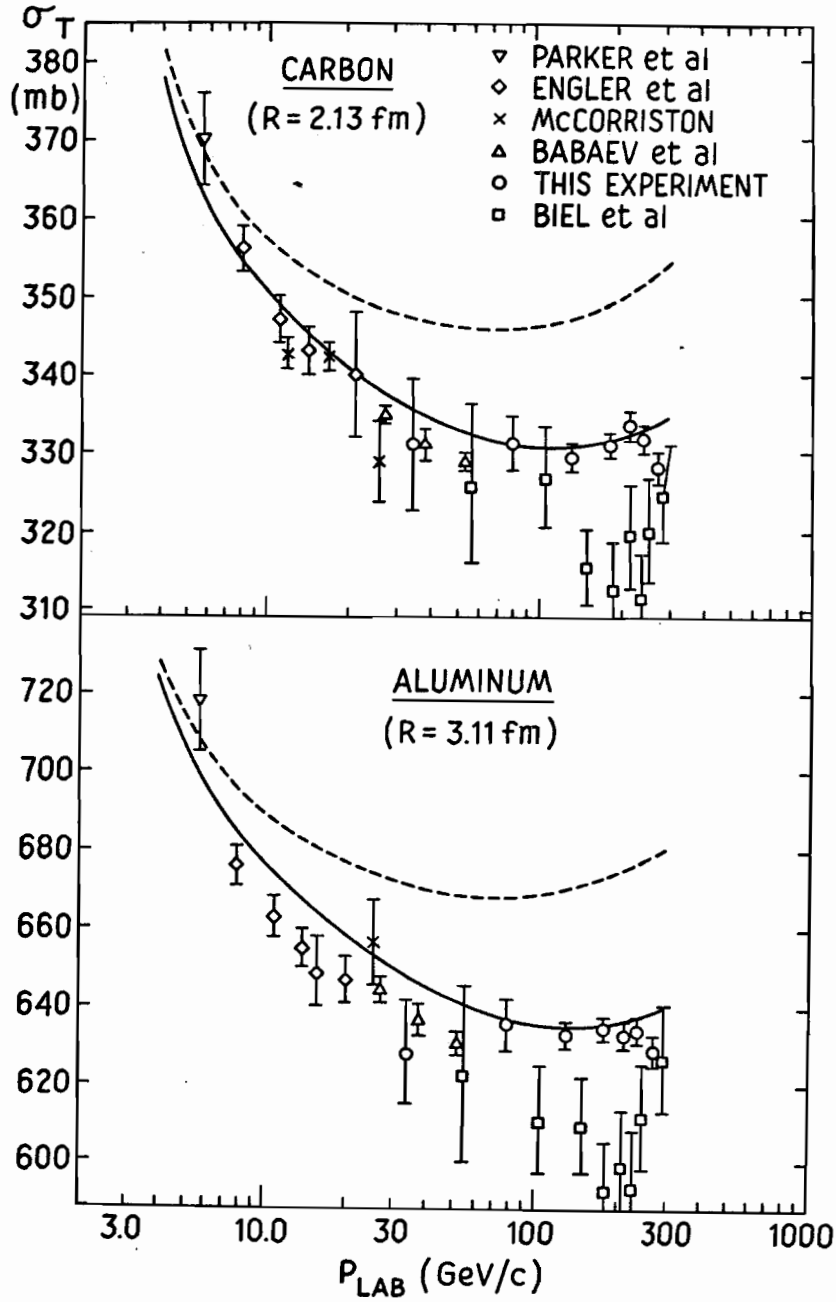

Fig. 3

Total cross sections for neutrons on various nuclei. The solid and dashed curves are theoretical predictions with and without inelastic screening corrections resp.; the nuclear radii were chosen to give the best agreement with the data at low momenta.

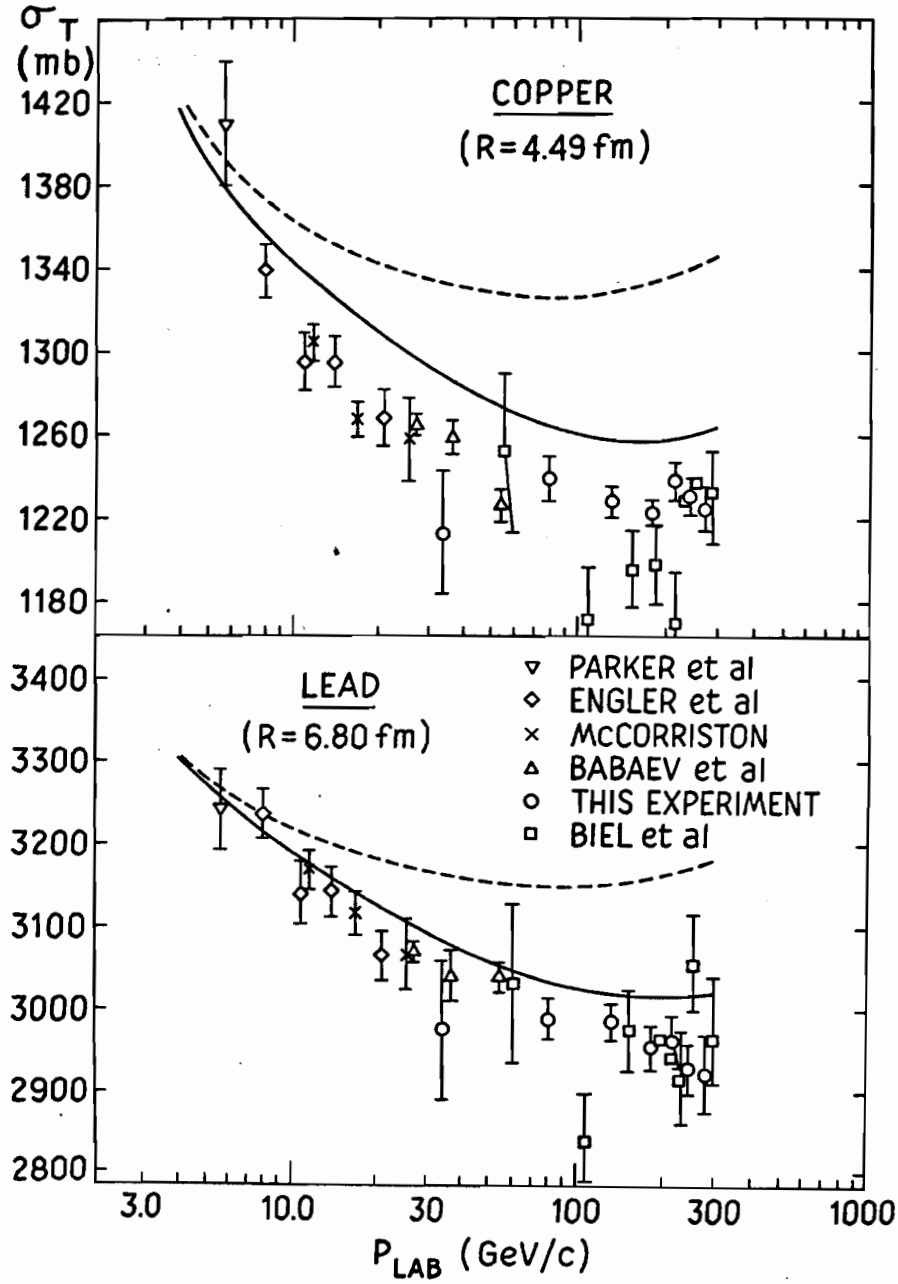

Fig. 4

Total cross sections for neutrons on various nuclei. The solid and dashed curves are theoretical predictions with and without inelastic screening corrections resp.; the nuclear radii were chosen to give the best agreement with the data at low momenta.

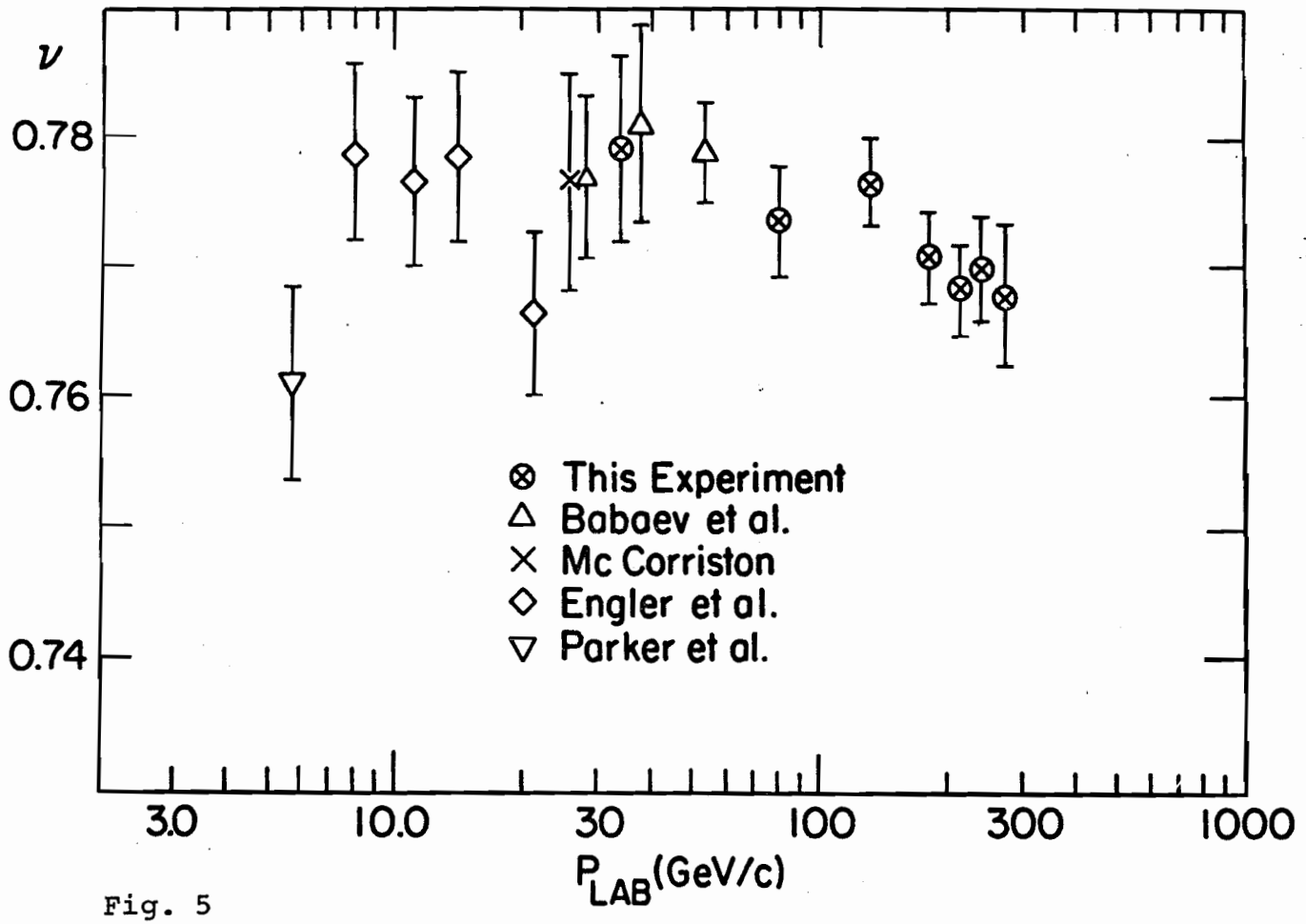

Fig. 5

Values of the exponent ν from fits of the heavy element total cross sections ($A \geq 9$) to $\sigma_T(A) = \sigma_o A^{\nu}$

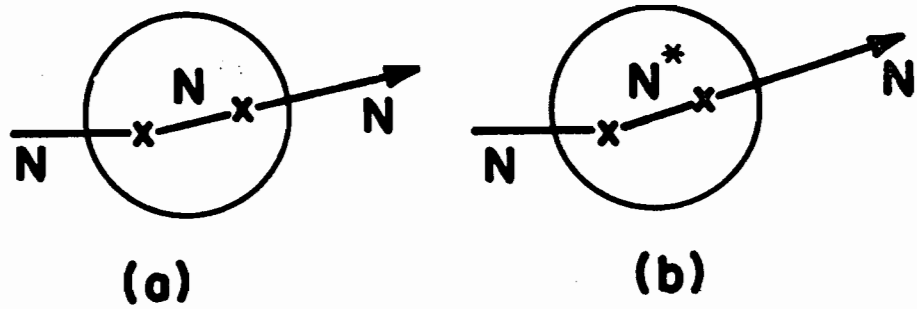

Fig. 6

(a) The double scattering diagram in conventional Glauber theory. The intermediate particle is a nucleon.

(b) Double scattering diagram in which the intermediate particle is an excited state of the nucleon. The contribution from this diagram is the "inelastic screening".

This can be tested experimentally now that precise data at high energies are available.

Total cross sections were calculated from standard Glauber theory[7] with and without inelastic screening corrections. The inelastic screening corrections were evaluated using the expression of Karmanov and Kondratyuk.[8] (See Ref. 3 for more details.)

The following data are required as input to the theory:

- $\sigma_T(pp)$ and $\sigma_T(np)$. These were obtained from the fits to the total cross section data shown in Fig. 1.
- The slope and real part of the forward NN scattering amplitudes. These are reasonably well known and the calculated cross sections are not sensitive to these.
- For deuterium the charge form factor determined from fits to electron scattering data was used. For other nuclei a Woods-Saxon nuclear shape was used. The radius was adjusted to give good fits to the n-nucleus total cross sections at <u>low</u> energies (where inelastic screening is unimportant).

For the inelastic screening corrections, data on $d^2\sigma/dt\, dM_x^2$ for the process $N + N \rightarrow N + X$ are required. Kaidalov and Kondratyuk[9] argue that only the diffractive (i.e. - energy independent) part of $d^2\sigma/dt\, dM_x^2$ should be included in the calculation. Fermilab data[10] show that $d^2\sigma/dt\, dM_x^2$ at small $|t|$ is approx. independent of P_{Lab} for $P_{Lab} > 50$ GeV/c so the Fermilab data was used in the calculation of the inelastic screening at all energies.

Theoretical N-d total cross sections calculated with and without inelastic screening are shown in Fig. 2. The theory with inelastic screening included is in very good agreement with the data if the data of Galbraith et al. are excluded.[11] It is important to note that there are no free parameters in the theory.

The heavy-element data give stronger evidence for the necessity of the inelastic screening corrections. In Figs. 3 and 4 the curves with inelastic screening included are in much better agreement with the energy dependence of the data. The N-N missing mass data that go into the calculation have a normalization uncertainty ~20%. These could easily explain any remaining discrepancy between the data and theory with inelastic screening. (It is important to remember that the theoretical curves have a scale uncertainty due to the uncertainty in nuclear radii. Thus only the momentum dependence should be considered in comparing theory and experiment in Figs. 3 and 4.)

The nuclear radii we obtain by adjusting the theoretical curves to agree with the data are in good agreement with previous electromagnetic and strong-interaction nuclear radii. The theoretical curves are not sensitive to reasonable variations in the N-N cross sections, forward slopes, or the real part.

Recently Koplik and Mueller[12] have questioned the validity of Glauber theory as applied to heavy nuclei. Galuber theory assumes that in a double scattering the projectile and the state interacting at the second scattering are identical, but they argue that at high energies the incident wave does not have sufficient time between the first and second encounter to evolve into its asymptotic state. Therefore, the Glauber theory breaks down.

We have shown, however, that Glauber theory (when patched up a bit to account for intermediate states like those in Fig. 6b) gives an excellent account of the neutron total cross section data between 4 and 300 GeV/c. Thus the Glauber theory can be rather readily modified to correct for the effects which Koplik and Mueller[12] are concerned with.

Koplik and Mueller have taken a different approach. They use a softened field theory of Regge poles and cuts to make predictions about interactions with nuclei. In particular, they predict that instead of the well-known result that for large nuclei $\sigma_T \cong 2\pi R^2$, where R is the nuclear radius, the total cross section should be more like

$$\sigma_T \cong C\ \pi R^2 (p/R)^{\alpha-1} \qquad (3)$$

where C is a constant of $\mathcal{O}(1)$, and α is some effective Regge trajectory. The value of α can be obtained by fitting the energy dependence of n-nucleus total cross section data to the form $\sigma_T(p) \propto p^{\alpha-1}$. The results are shown in the table.

Nucleus	α-1
Be	.023 ± .007
C	.004 ± .003
Al	.001 ± .004
Cu	.000 ± .005
Pb	-.021 ± .006

In the fits, only data with P > 50 GeV/c were used. The resulting values of α are not especially constant, in disagreement with Eq. 3. If we take the Regge mass scale parameter to be ~1 GeV, the term in parentheses in Eq. 3 is ~10. Since experimentally $(\alpha-1) \approx 0.002$, $(p/R)^{\alpha-1} \approx 1.005$. Thus,

$$\sigma_T \approx C\pi R^2 \qquad (4)$$

A comparison of the total cross section data with Eq. 4 shows that reasonable values for the nuclear radii can only be obtained if $C \approx 2$, a value suspiciously close to the conventional $\sigma_T \approx 2\pi R^2$.

In conclusion, the high energy neutron-nucleus total cross section data between 4 and 300 GeV/c are in agreement with Glauber theory (as modified to account for

inelastic screening) at the 1% level. Recent attempts by Koplik and Mueller to give a more rigorous theory seem to be unable to give a quantitative description of the neutron-nucleus total cross section data.

References

1. M.J. Longo et al., Phys. Rev. Letters 33, 725 (1974).
2. L.W. Jones et al., Phys. Rev. Letters 33, 1440 (1974).
3. P.V.R. Murthy et al., Nucl. Phys. B92, 269 (1975).
4. J. Biel et al., "Coherent Dissociation and Total Cross Sections of Neutrons in their Collisions with Nuclear Targets at Fermilab Energies". Paper submitted to 1975 DPF Meeting in Seattle (Presented by P. Slattery).
5. J. Pumplin and M. Ross, Phys. Rev. Letters 21, 1778 (1968).
6. B. Udgaonkar and M. Gell-Mann, Phys. Rev. Letters 8, 346 (1962).
7. V. Franco and R.J. Glauber, Phys. Rev. 142, 1195 (1966).
   V. Franco, Phys. Rev. C6, 748 (1972).
8. V. Karmanov and L. Kondratyuk, JETP Letters (Sov. Phys.) 18, 266 (1973).
9. A. Kaidalov and L. Kondratyuk, Nucl. Phys. B56, 90 (1973).
10. V. Bartenev et al., Phys. Letters 51B, 299 (1974).
    Y. Akimov et al., Fermilab repts. NAL-Conf 74/56 EXP and 74/66 EXP, unpublished.
11. K. Riley [Phys. Rev. D1, 2481 (1970)] attributes the systematic discrepancy between the higher energy data of Galbraith et al. and other data to an underestimate of the correction for the finite solid angle subtended by their detector.
12. J. Koplik and A.H. Mueller, "Hadron-Nucleus Collisions at High Energies", Columbia Univ. Preprint CO-2271-59 (unpublished).