CONF-75-145 E
E-0004

CONF-75-145-E E-4

UM HE 75-14

NEUTRON-NUCLEUS TOTAL CROSS SECTION, 30-270 GeV*

*Submitted to Fourteenth International Cosmic Ray Conference, Munich, W. Germany

CONF-75-145-E

HE 2-9

NEUTRON-NUCLEUS TOTAL CROSS SECTION, 30-270 GeV

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In an experiment at FNAL, n-p, n-d and n-nucleus total cross sections have been measured to an accuracy of $\leq 1\%$. While cross sections in hydrogen and light nuclei show the now-familiar rise above 100 GeV, cross sections in heavy nuclei are nearly constant or very slowly falling at high energies. The cross sections for $A \geq 9$ may be fitted at high energy by $\sigma \propto A^{0.77\pm.01}$. These data clearly demonstrate the existence of the inelastic screening (Gribov-Ross-Pumplin) effect in addition to the familiar Glauber screening.

1. Introduction. The dramatic rise in the nucleon-nucleon total cross sections above 100 GeV is now firmly established. Only recently, however, have total cross sections on heavier nuclei been made. Besides interest in basic physics, nuclear cross sections are of practical interest in cosmic ray studies. We present below measurements on total cross sections from 30 to 270 GeV of neutrons on nuclei from hydrogen to uranium.[1] Neutrons provide the means for particularly clean cross sections on heavy nuclei due to the absence of coulomb scattering.

2. Experiment. A tightly-collimated neutron beam at the Fermi National Accelerator Laboratory with angular divergence $<10^{-5}$ rads was directed onto various targets and transmitted neutrons were detected with the ionization calorimeter described in paper T3-2. Neutrons were converted in a 20g cm^{-2} Fe plate ahead of the calorimeter and the resulting shower detected in a series of disc counters centered on the beam, so that both the energy and scattering angle of each detected neutron were recorded. The smallest counter subtended $\theta \sim 10^{-4}$ rad from the target. With the neutron beam monitored continuously, the cross sections for each of 7 energy and 6 angle intervals were determined by alternating the target into and out of the beam. Data were collected at various beam rates so that corrections for various rate-dependent effects could be made. Cross sections were extrapolated to zero solid angle and corrected for kaon flux in the beam.

3. Results. Neutron cross sections are presented in Table I for each nucleus studied and for each of the energy intervals. Figures 1,2 and 3 present neutron cross sections on H^1, H^2, and five representative complex nuclei, respectively. The errors include statistical errors as well as many possible systematic uncertainties. The larger errors in the lower energy bins reflect the uncertainties in the kaon flux corrections. Note that, in essentially all energy bins above 50 GeV and for $9 \leq A \leq 238$, $\sigma \propto A^{0.77}$. While $\sigma(np)$ and $\sigma(nd)$ both show a clear rise over $100 < E < 300$ GeV, much less rise is seen in $\sigma(nBe)$ and $\sigma(nC)$ and cross sections on heavier elements appear to either remain constant or perhaps even fall slightly above 100 GeV.

Table I

Nucleus	Mean Momentum (GeV/c) 34	80	131	180	215	240	273
H	38.2 ±0.9	38.98 ±0.33	39.17 ±0.19	39.52 ±0.18	39.79 ±0.24	39.66 ±0.24	40.32 ±0.23
D	71.7 ±1.9	72.78 ±0.83	73.30 ±0.39	74.16 ±0.34	74.48 ±0.36	75.08 ±0.38	75.18 ±0.55
Be	263.9 ± 5.7	269.7 ± 2.8	266.5 ± 1.3	271.1 ±1.1	273.5 ±1.3	270.8 ±1.3	273.8 ±1.6
C	331.1 ±8.6	331.4 ±3.4	329.5 ±1.7	331.1 ±1.5	333.5 ±1.8	331.9 ±1.8	328.2 ±2.1
Al	628.5 ±13.5	636.0 ±6.1	633.3 ±3.0	634.8 ±2.8	633.3 ±3.4	634.4 ±3.5	629.5 ±3.7
Fe	1100 ±29	1122 ±11	1110 ±7	1110 ±8	1112 ±8	1113 ±8	1107 ±10
Cu	1213 ±30	1239 ±11	1228 ±7	1223 ±6	1238 ±9	1231 ±9	1225 ±11
Cd	1884 ±46	1912 ±16	1890 ±11	1885 ±12	1887 ±16	1873 ±16	1882 ±18
W	2840 ±72	2804 ±28	2786 ±23	2751 ±24	2746 ±35	2748 ±34	2720 ±36
Pb	2973 ±85	2986 ±25	2981 ±21	2951 ±28	2959 ±32	2926 ±32	2919 ±48
U	3402 ±113	3410 ±29	3399 ±26	3361 ±32	3353 ±39	3365 ±46	3297 ±60

4. Discussion. There is no agreed-upon understanding of the rise of NN total cross sections at energies above 100 GeV. This experiment further confirms that rise as well as demonstrating the substantial equivalence (within experimental errors) of $\sigma(np)$ and $\sigma(pp)$ over the entire energy range where both have been measured.

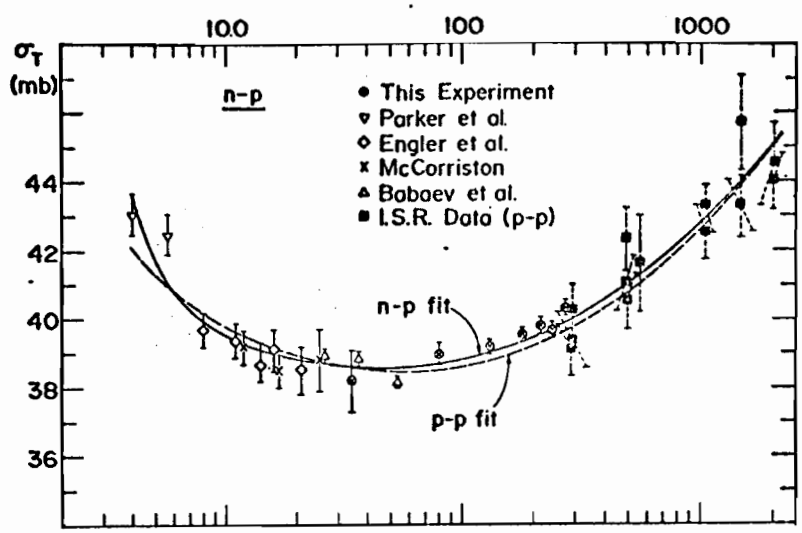


Fig. 1. Neutron-proton total cross sections from this experiment and previous measurements with neutron beams above 4 GeV. Some p-p data are shown with dashed error bars for comparison.

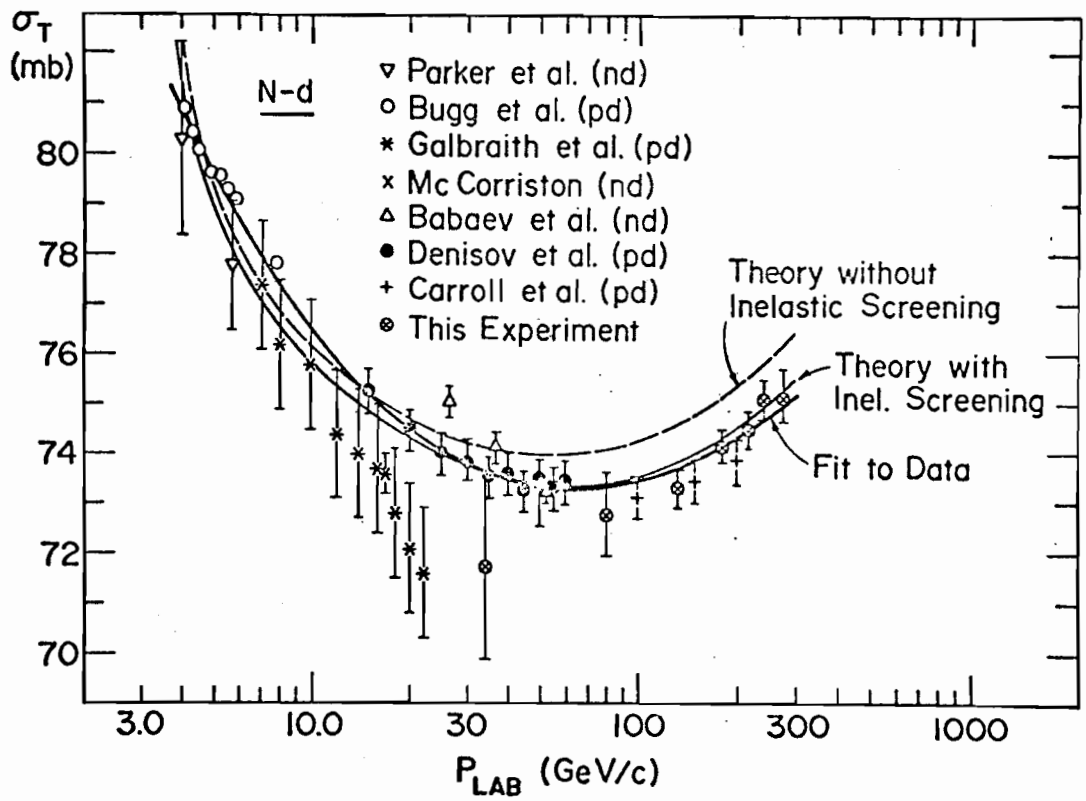
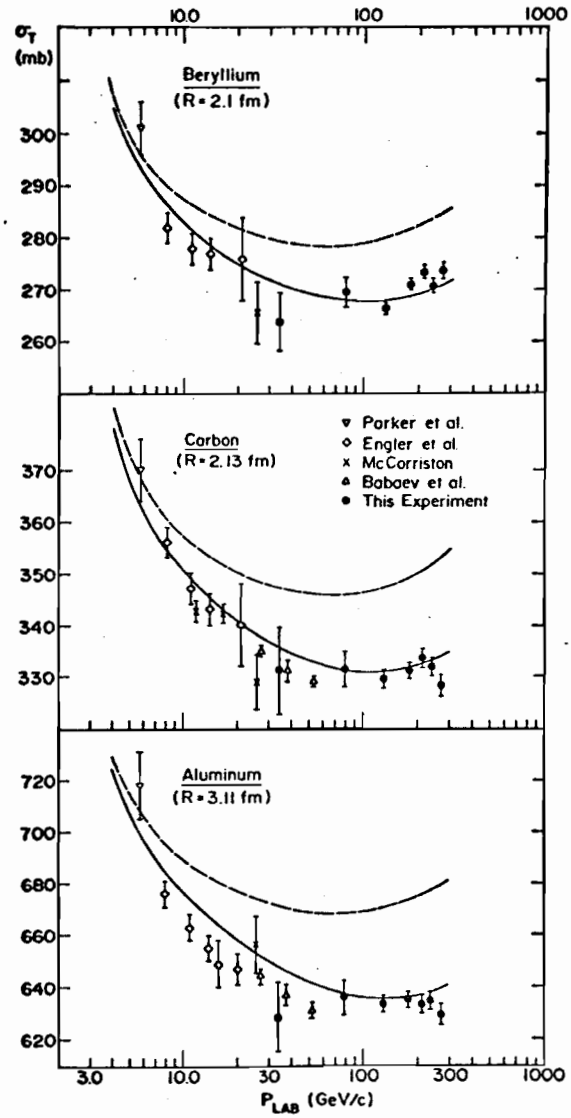


Fig. 2. Neutron-deuteron total cross section data above 4 GeV/c. Total errors, including scale errors, are shown on all points. The heavy solid curve is a fit to the data. The light solid and dashed curves are theoretical curves calculated with and without inelastic screening corrections.



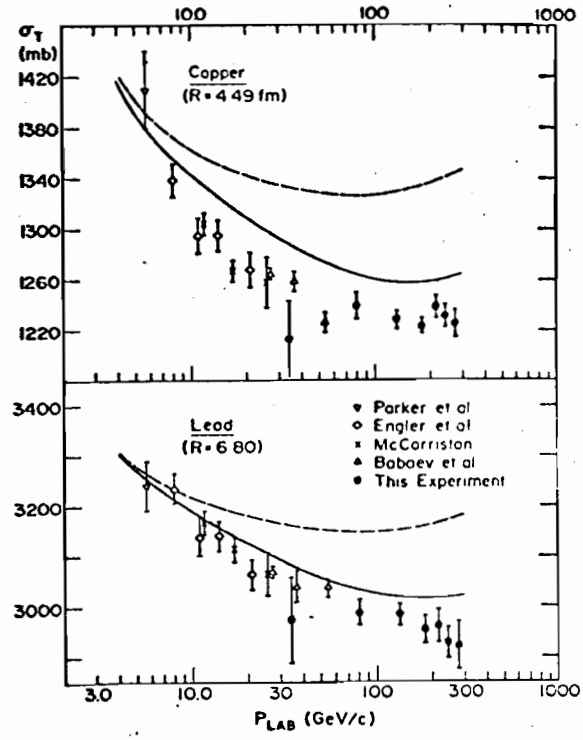


Fig. 3. Total cross sections for neutrons on Be, C, Al, Cu, and Pb. The solid and dashed curves are theoretical predictions with and without inelastic screening corrections. The nuclear radii were chosen to give the best agreement with the data at low momenta.

Cross sections on complex nuclei involve three different phenomena: (a) the free NN cross section, (b) nuclear optical phenomena, and (c) an inelastic screening correction. From the free NN cross section and a nucleon density distribution, it should be possible in principle to calculate cross sections on complex nuclei. A formal procedure, originally developed by Glauber[2] for the deuteron problem, has been applied to the nuclear problem by Franco with good results at energies below 30 GeV.[3] The cross section on a large nucleus shows less energy dependence than free nucleon cross sections when the nuclear diameter exceeds the nucleon mean free path in nuclear matter.

At higher energies, cross sections fall below these predictions as a result of an effect first discussed by Pumplin and Ross[4] and calculated in detail by Karmanov and Kordratyuk.[5] This effect is the diffraction inelastic scattering of the incident nucleon on a nucleon in the target nucleus and the subsequent rescattering of the excited nucleon state on a second target nucleon (in the same nucleus). Just as the Glauber screening calculation includes the shadowing of one nucleon by another in terms of double scattering, the Pumplin-Ross effect is a double scattering with an inelastic intermediate state, and produces a cross section reduction by increasing the effective screening of nucleons in a nucleus. This sets in only at higher energies, in view of the relationship between the mass of the intermediate state M, the scattering four-momentum transfer t , and the nucleon-nucleon c.m. energy squared s.

The data in Figures 2 and 3 are presented along with calculations both excluding (dashed line) and including (solid line) the Pumplin-Ross effect. The calculations are normalized to the data below 10 GeV using a Woods-Saxon nuclear model with a skin thickness fixed at 2.3 fm. It is seen that the inelastic screening correction is necessary for reasonable agreement with the data. Independent determinations of nuclear radii from these data agree well with values from electron scattering and photo-rho production. While total cross sections below 20 GeV now appear the weakest components of the data sets and normalization at higher energies would improve the apparent agreement between data and calculation, it is clear that the inelastic screening correction is essential for reasonable agreement with the data over the full energy range explored.

The most significant data for cosmic ray phenomenology are not the total cross sections but the inelastic cross sections. These have not been measured well at high energy,[6] and clean experiments are sorely needed for better interpretation of air shower data, attenuation of cosmic ray primaries, etc. The techniques developed here with neutrons may be directly applied to this problem as well.

5. Acknowledgements. This work was supported by the U.S. National Science Foundation and would not have been possible without the dedicated cooperation of the staff of the Fermi National Accelerator Laboratory.

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