Measurements of the A Dependence of Deep-Inelastic Electron Scattering from Nuclei

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The deep-inelastic electron-scattering cross sections per nucleon σ_A for D, He, Be, C, Al, Ca, Fe, Ag, and Au were measured in the kinematic range $0.09 \leq x \leq 0.9$ and $2 \leq Q^2 \leq 15$ $(\text{GeV}/c)^2$ with use of electrons with energies ranging from 8 to 24.5 GeV. The ratio σ_A/σ_D is consistent with unity in the range $0.1 < x < 0.3$. For $0.3 < x < 0.8$, the ratio decreases logarithmically with atomic weight A, or linearly with average nuclear density. No Q^2 dependence in the ratio was observed over the kinematic range of the data.

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Significant differences in the inelastic structure functions of Fe, Al, and deuterium nuclei have recently been observed in muon-[1] and electron-scattering[2] experiments. This has been interpreted as a distortion of the quark momentum distributions in bound nucleons. To study the A dependence of this effect, we have measured differential cross sections for the inelastic scattering of electrons from deuterium, He, Be, C, Al, Ca, Fe, Ag, and Au over a large kinematic range [x values between 0.09 and 0.9 and Q^2 values of 2, 5, 10, and 15 $(\text{GeV}/c)^2$]. The Stanford Linear Accelerator Center (SLAC) provided electrons with incident energies (E) ranging from 8 to 24.5 GeV. The SLAC 8-GeV/c spectrometer was used at 23 kinematic settings to detect electrons with energies (E') from 3.1 to 8.4 GeV scattered at angles (θ) between 11° and 23°. A nitrogen-filled threshold Čerenkov counter and a 20-radiation-length (r.l.) segmented lead-glass shower counter were used to identify electrons, whose trajectories were defined by ten planes of proportional wire chambers. The electron contributions from background processes such as π^0 decay and

pair production were determined by reversing the spectrometer polarity and measuring the charge-symmetric positron cross sections.

The target assembly consisted of a 15-cm-long (2% r.l.) cylindrical target of recirculating liquid deuterium, a 25-cm-long (2% r.l.) cylindrical target of recirculating pressurized (25-atm) helium, empty target cells, and >99.9% pure solid targets with natural isotopic abundances. The D and He targets were cooled to 21 K. Data were usually[3] taken with 2% r.l. Be, C, and Fe in order to minimize radiative correction differences, with thicker (6% r.l.) Al, Ca, Fe, Ag, and Au targets being used to maintain reasonable counting rates. Both the 2% and 6% r.l. Fe targets were used at each setting to check radiative corrections. Various thicknesses of C, Al, Fe, and Au were used at selected settings as a further check. Measurements with the different targets were interspersed frequently to minimize systematic errors.

To monitor the D and He target densities, the SLAC 1.6-GeV/c spectrometer was used as a relative luminosity monitor for all data taking. Data at each kinematic setting were taken with at

least two beam repetition rates. In addition, high-statistics calibration data were taken at several beam intensities and repetition rates at each beam energy. The density changes were reproducible and well parametrized as a linear function of average beam current. By comparing the corrections (up to 1% for D and 7% for He) as determined by several different methods, we conclude that the uncertainties in the relative densities are less 0.5% for D and 1.4% for He.

The measured cross sections were radiatively corrected with the method of Mo and Tsai[4] in a manner similar to that described by Stein et al.[5] The Z-dependent correction for the nuclear Coulomb field was not applied, but has been calculated[6] to be less than 1.5% for Au over our kinematic range. The radiative correction factors were nearly identical for different targets having the same thickness (in r.l.), except for the D and He targets, where geometrical effects introduced differences of up to 3%. The radiatively corrected cross sections for targets of the same material but different radiation lengths were consistent within statistics.

The cross sections were adjusted to compensate for neutron excess, such that σ_A represents the cross section per nucleon of a hypothetical nucleus with an equal number $(A/2)$ of protons and neutrons. With use of the approximation $\sigma_n = \sigma_p(1 - 0.8x)$, corrections as large as 10% for Au were obtained at $x = 0.8$.

The deuterium cross sections extracted from the data are in excellent agreement ($\pm 2\%$) with a fit to previous data[7] in the same kinematic region. Systematic uncertainties (Δ) in the ratios σ_A/σ_D due to radiative corrections ($\pm 0.6\%$), spectrometer acceptance ($\pm 0.3\%$), electronics dead time ($\pm 0.3\%$), beam intensity monitoring ($\pm 0.1\%$), pion backgrounds ($\pm 0.5\%$), neutron excess (up to $\pm 0.7\%$), and pair-symmetric electron backgrounds (up to $\pm 0.5\%$ except $\pm 2\%$ at $x = 0.09$) were, when added in quadrature, comparable to the uncertainties in the target thicknesses, estimated to be $\pm 1.2\%$ for deuterium and $\pm 0.5\%$ to 1.5% for the other targets.

Within the quark-parton model, the variable $x = Q^2/2M_p\nu$ is related to the momenta of the quarks in a nucleon, where $Q^2 = 4EE'\sin^2(\theta/2)$, $\nu = E - E'$,
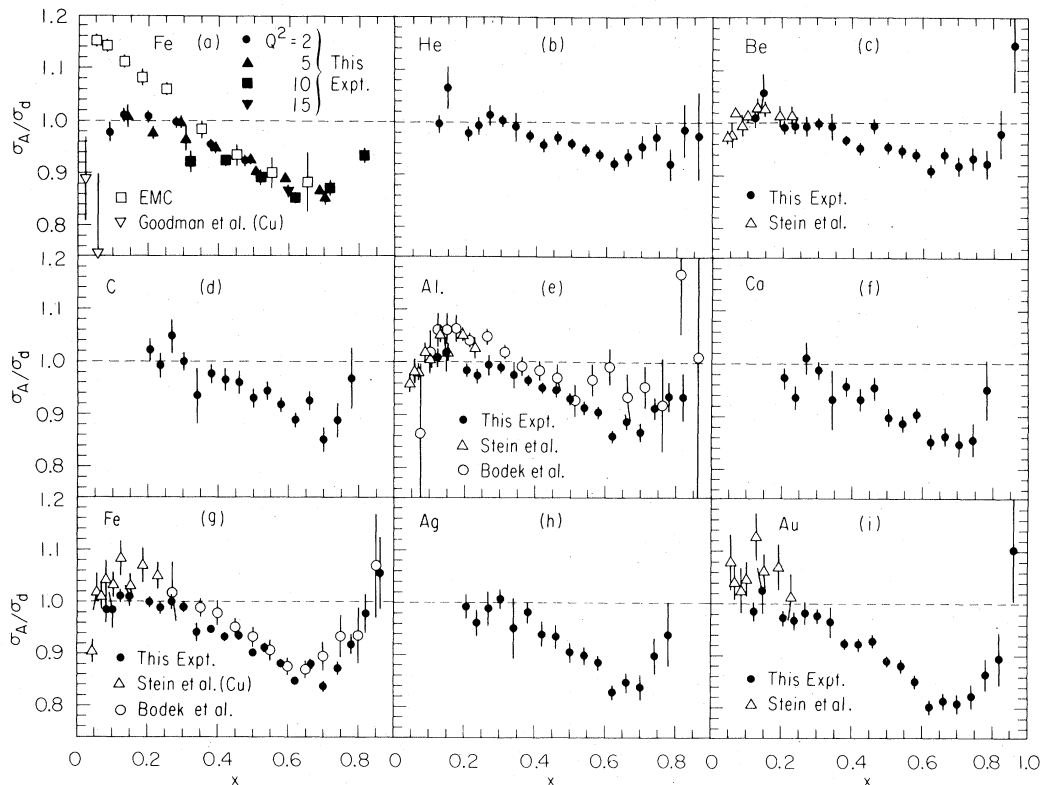

FIG. 1. (a) σ_{Fe}/σ_D as a function of x for various values of Q^2, as well as higher-energy muon data from Refs. 1 and 9. (b)–(i) σ_A/σ_D averaged over Q^2 as a function of x for various nuclei, as well as electron data from Refs. 2 and 5. The errors shown are statistical only.
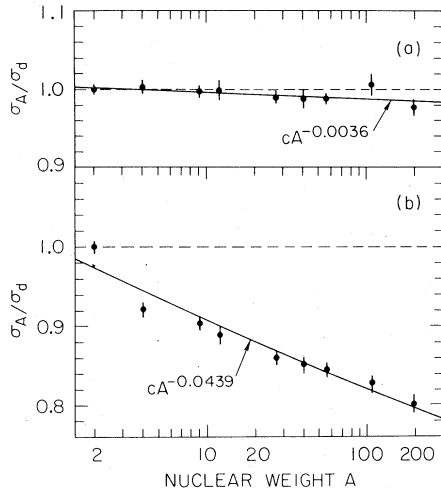
FIG. 2. Q^2-averaged ratios σ_A/σ_D vs A at fixed x. (a) $x = 0.3$, (b) $x = 0.62$. The solid line is a fit of the form $\sigma_A/\sigma_D = cA^\alpha$. The errors shown are statistical only.

FIG. 3. Values as a function of x of parameters in fits to Q^2-averaged ratios σ_A/σ_D. (a) Nuclear-density fit, (b) power-law fit.

and M_p is the proton mass. The structure functions $W_1{}^A$ and $W_2{}^A$ per nucleon are related to the differential cross section per nucleon by

$$\sigma_A = \sigma_M [W_2{}^A(x, Q^2) + 2W_1{}^A(x, Q^2)\tan^2(\theta/2)],$$

where $\sigma_M = 4\alpha^2 E'^2 \cos^2(\theta/2)Q^4$. The ratio

$$W_2{}^A/W_1{}^A = (1 + R)/(1 + Q^2/4M_p{}^2 x^2)$$

is determined by $R = \sigma_L/\sigma_T$, the ratio of the cross sections for absorption of longitudinal and transverse virtual photons. To study the possible A dependence of R, measurements were made at $Q^2 = 5$ (GeV/c)^2 and $x = 0.3$, 0.5, and 0.7 using two different angles θ for each x value. The resulting x-averaged values for R are 0.112 ± 0.048 for d, 0.127 ± 0.174 for He, 0.195 ± 0.112 for Al, 0.299 ± 0.079 for Fe, and 0.382 ± 0.197 for Au. The errors are statistical only. The results are consistent with the average value for deuterium ($R = 0.24 \pm 0.1$) from previous measurements[8] in our kinematic region, but do not exclude an increase with A that would significantly change the extracted structure functions. Therefore we do not make the assumption that $W_2{}^A/W_2{}^D = \sigma_A/\sigma_D$ in this paper.

Figure 1(a) shows our data for the ratio σ_{Fe}/σ_D [taken at Q^2 values of 2, 5, 10 and 15 (GeV/c)^2], along with data from higher-energy muon experiments.[1,9] While our data alone show no significant Q^2 dependence, comparison with the higher-Q^2 muon data[1] ($\Delta \approx \pm 6\%$) indicate a Q^2 dependence for $x < 0.3$ consistent in direction with that ex-
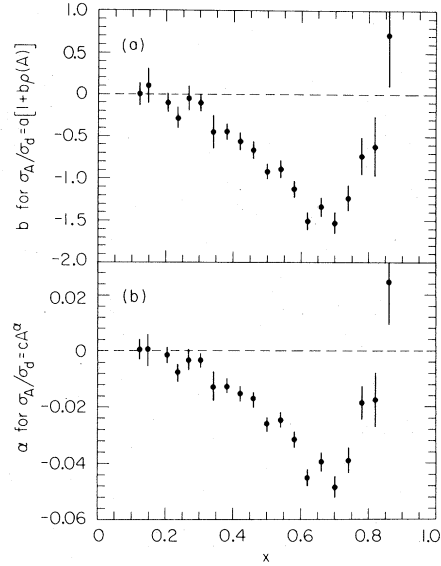
pected from nuclear shadowing.

Because we see no significant Q^2 dependence in our data, Figs. 1(b)–1(i) show Q^2-averaged ratios for each target in finer x bins than in Fig. 1(a). Also shown are data from Stein et al.[5] for Be ($\Delta = \pm 3.2\%$), Al ($\Delta = \pm 3.2\%$), Cu ($\Delta = \pm 4.2\%$), and Au ($\Delta = \pm 10\%$) and from Bodek et al.[2] for Al ($\Delta = \pm 2.3\%$) and Fe ($\Delta = \pm 1.1\%$). Systematic differences between our results and the earlier data are within quoted systematic errors. The data for all the targets display a similar trend. The deviation from unity is largest for x near 0.6 and is larger for the heavier elements. Except for $x > 0.8$, the trend of the data is opposite to that expected from Fermi-motion effects.[2,10]

Figure 2 shows Q^2-averaged ratios σ_A/σ_D as a function of atomic weight A for two selected values of x. The data may be equally well described by two-parameter fits of the form $\sigma_A/\sigma_D = cA^\alpha$ or $\sigma_A/\sigma_D = a[1 + b\rho(A)]$, where $\rho(A)$ is the average nuclear density.[11] Values of α and b from fits to our data are shown in Fig. 3. The systematic uncertainties in the target thicknesses were included in the fits, resulting in χ^2 per degree of freedom of ≈ 1.2 for either type of fit.

The data do not directly correlate with binding energy per nucleon, which peaks around Fe, since the observed ratios continue to decrease for A above Fe. The anomalous binding energies and nuclear densities for D and He make them of

particular interest. For $x > 0.4$, where $|\alpha|$ and $|b|$ are large, the x-averaged ratio σ_A/σ_D for D (He) differs from the power-law fit by $1.3 \pm 0.3\%$ ($-1.9 \pm 0.4\%$), and from the nuclear-density fit by $0.3 \pm 0.3\%$ ($2.0 \pm 0.4\%$). These differences are only slightly greater than the systematic uncertainties in the D and He normalizations.

Theoretical mechanisms[12] for the distortions of structure functions of bound nucleons include ideas such as multiquark bags, a larger confining radius for bound-nucleon bags, delta resonances in nuclei, and an enhancement of the abundance of pions or quark-antiquark pairs in large nuclei. Our data on the atomic-weight dependence of nuclear cross sections will provide a test for such models.

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[1]J. J. Aubert et al., Phys. Lett. 123B, 275 (1983).

[2]A. Bodek et al., Phys. Rev. Lett. 50, 1431 (1983), and 51, 534 (1983).

[3]All the targets were used for $Q^2 = 5$ $(\text{GeV}/c)^2$, $x = 0.22, 0.3, 0.4, 0.5, 0.6,$ and 0.7, whereas all targets except C, Ca, and Ag were used for $Q^2 = 2$ $(\text{GeV}/c)^2$, $x = 0.13, 0.22, 0.3, 0.4, 0.5$; $Q^2 = 10$ $(\text{GeV}/c)^2$, $x = 0.4, 0.5, 0.6, 0.7, 0.8$; and $Q^2 = 15$ $(\text{GeV}/c)^2$ at $x = 0.6$. Only D and Fe were used for $Q^2 = 2$ $(\text{GeV}/c)^2$ at $x = 0.089$, $Q^2 = 5$ $(\text{GeV}/c)^2$ at $x = 0.14$, and $Q^2 = 10$ $(\text{GeV}/c)^2$ at $x = 0.3$.

[4]L. W. Mo and Y. S. Tsai, Rev. Mod. Phys. 41, 205 (1969); Y. S. Tsai, SLAC Report No. SLAC-PUB-848, 1971 (unpublished).

[5]S. Stein et al., Phys. Rev. D 12, 1884 (1975). See also W. R. Ditzler et al., Phys. Lett. 57B, 201 (1975).

[6]S. Brodsky and M. Soldate, private communication. See also E. Calva-Tellez and D. R. Yennie, Phys. Rev. D 20, 105 (1979).

[7]A. Bodek et al., Phys. Rev. D 20, 1471 (1979).

[8]M. D. Mestayer et al., Phys. Rev. D 27, 285 (1983), and references therein.

[9]M. S. Goodman et al., Phys. Rev. Lett. 47, 293 (1981)

[10]A. Bodek and J. L. Ritchie, Phys. Rev. D 23, 1070 (1981), and 24, 1400 (1981).

[11]We used $\rho(A) = 3A/4\pi R_e^3$, where $R_e^2 = 5\langle r^2 \rangle/3$, and $\langle r^2 \rangle$ is the electron-scattering rms radius of the nucleus taken from C. W. DeJager, H. De Vries, and C. De Vries, At. Data Nucl. Data Tables 14, 479 (1974). Values of ρ (in units of nucleons/fm^3) used in the fits were 0.024 for D, 0.089 for He, 0.062 for Be, 0.089 for C, 0.106 for Al, 0.105 for Ca, 0.117 for Fe, 0.126 for Ag, and 0.147 for Au.

[12]For reviews and theoretical references see C. H. Llewellyn-Smith, Oxford University Report No. OXFORD-TP-37/83 (to be published); K. Rith, Universität Freiberg Report No. TH-EP-83/5, in Proceedings of the International Europhysics Conference on High Energy Physics, Brighton, England, July 1983 (to be published); R. L. Jaffe, Massachusetts Institute of Technology Report No. MIT-CTP-1120, 1983 (to be published); A. Bodek, University of Rochester Report No. UR858, 1983, in Proceedings of the Sixth High Energy Heavy Ion Study in Berkeley, June, 1983 (to be published).