

**MEASUREMENTS OF THE A-DEPENDENCE OF DEEP-INELASTIC  
ELECTRON SCATTERING FROM NUCLEI\***

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**ABSTRACT**

The deep inelastic electron scattering cross sections per nucleon  $\sigma_A$  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  $2 \leq Q^2 \leq 15$  (GeV/c)<sup>2</sup> using electrons with energies ranging from 8 to 24.5 GeV. The ratio  $\sigma_A/\sigma_d$  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. This has been interpreted as evidence for a change in the quark momentum distribution in the nucleus due to the presence of 6 quark clusters or a larger nucleon bag size.

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Significant differences in the inelastic structure functions of Fe, Al, and deuterium nuclei have recently been observed in muon<sup>1</sup> and electron<sup>2</sup> scattering 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 (GeV/c)<sup>2</sup>). 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 ( $\theta$ ) 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  $\pi^0$  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<sup>3</sup> 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 using the method of Mo and Tsai<sup>4</sup> in a manner similar to that described in Stein *et al.*<sup>5</sup> The Z-dependent correction for the nuclear Coulomb field was not applied, but has been calculated<sup>6</sup> 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  $\sigma_A$  represents the cross section per nucleon of a hypothetical nucleus with an equal number ( $A/2$ ) of protons and neutrons. Using 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<sup>7</sup> in the same kinematic region. Systematic uncertainties ( $\Delta$ ) in the ratios  $\sigma_A/\sigma_d$  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  $\pm 1.5\%$  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  $Q^2 = 4EE' \sin^2(\theta/2)$ ,  $\nu = E - E'$ , 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

$$\begin{aligned}\sigma_A &= \sigma_M \left[ W_2^A(x, Q^2) + 2W_1^A(x, Q^2) \tan^2(\theta/2) \right] \\ &= \sigma_M / \epsilon \cdot W_2^A (1 + \epsilon R^A) / (1 + R^A)\end{aligned}\tag{1}$$

where  $\sigma_M = 4\alpha^2 E'^2 \cos^2(\theta/2)/Q^4$  and  $\epsilon$  is the photon polarization. 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 extract  $W_2^A/W_2^d = F_2^A/F_2^d$  from the cross section it necessary to measure the  $A$  dependence of  $R$ . To study this measurements were made at  $Q^2 = 5 \text{ (GeV/c)}^2$  and  $x = 0.3, 0.5, \text{ and } 0.7$  using two different angles  $\theta$  for each  $x$  value. The resulting  $x$ -averaged values for  $R$  are  $0.112 \pm 0.048$  for d,  $0.127 \pm 0.174$  for He,  $0.195 \pm 0.112$  for Al,  $0.299 \pm 0.079$  for Fe, and  $0.382 \pm 0.197$  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<sup>8</sup> in our kinematic region. However, as described below, in the best fit to our data  $R$  has an  $A$  dependence that would give a large difference between  $\sigma^A/\sigma^d$  and  $F_2^A/F_2^d$ . Therefore, we show the ratio of cross sections in this paper.

Figure 1(a) shows our data for the ratio  $\sigma_{Fe}/\sigma_d$  (taken at  $Q^2$  values of 2, 5, 10 and 15  $(\text{GeV/c})^2$ ), along with data from higher energy muon experiments<sup>1,9</sup>. While our data alone show no significant  $Q^2$  dependence, comparison with the higher  $Q^2$  muon data<sup>1</sup> ( $\Delta \approx \pm 6\%$ ) indicate a  $Q^2$  or  $R$  dependence for  $x < 0.3$ .

data from Stein *et al.*<sup>5</sup> 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.*<sup>2</sup> 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.<sup>10,2</sup>

In order to compare with the results of Ref. 1, we have extracted the structure function  $F_2$  using our measurements of  $R$ . Guided by equation 1 we have analyzed  $\sigma_{Fe}/\sigma_d$  versus  $\epsilon$ . The best linear fit gives  $d(\sigma^A/\sigma^d)/d\epsilon = 0.15 \pm 0.11$ . There are large errors associated with the small range of  $\epsilon$  covered in this experiment. Fig. 2 shows  $F_2^{Fe}/F_2^d$  obtained by extrapolating the fit to  $\epsilon = 1$  at different values of  $Q^2$ . The inner error bars show the errors on the cross section while the outer errors fold in the statistical uncertainty of the  $R$  measurement (which are common to all the data points). Systematic errors are still under investigation, but are expected to be smaller than the statistical errors. Our results for  $F_2^{Fe}/F_2^d$  are consistent with the muon data for all values of  $x$  but with very large errors.

Figure 3 shows  $Q^2$ -averaged ratios  $\sigma_A/\sigma_d$  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<sup>11</sup>. Values of  $\alpha$  and  $b$  from fits to our data are shown in Fig. 4. The systematic uncertainties in the target thicknesses were included in the fits, resulting in  $\chi^2$  per degree of freedom of  $\approx 1.2$  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  $\sigma_A/\sigma_d$  for d (He) differs from the power 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<sup>12</sup> for the distortions of structure functions of bound nucleons include ideas such as multi-quark 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. The predictions of a model<sup>13</sup> with a larger confining radius for the nucleon bag is shown in Fig. 3. Our data on the atomic weight dependence of nuclear cross sections will provide a test for such models.

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## FIGURE CAPTIONS

1. (a)  $\sigma_{Fe}/\sigma_d$  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)  $\sigma_A/\sigma_d$  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.
2.  $F_2^{Fe}/F_2^d$  as a function of  $x$  for various values of  $Q^2$ , as well as higher energy muon data from Ref. 1. The outer error bars include the statistical errors in the  $R$  measurement.
3.  $Q^2$ -averaged ratios  $\sigma_A/\sigma_d$  versus  $A$  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. The predictions of Ref. 13 are also shown.
4. Values as a function of  $x$  of parameters in fits to  $Q^2$ -averaged ratios  $\sigma_A/\sigma_d$ . (a) nuclear density fit and (b) power law fit.

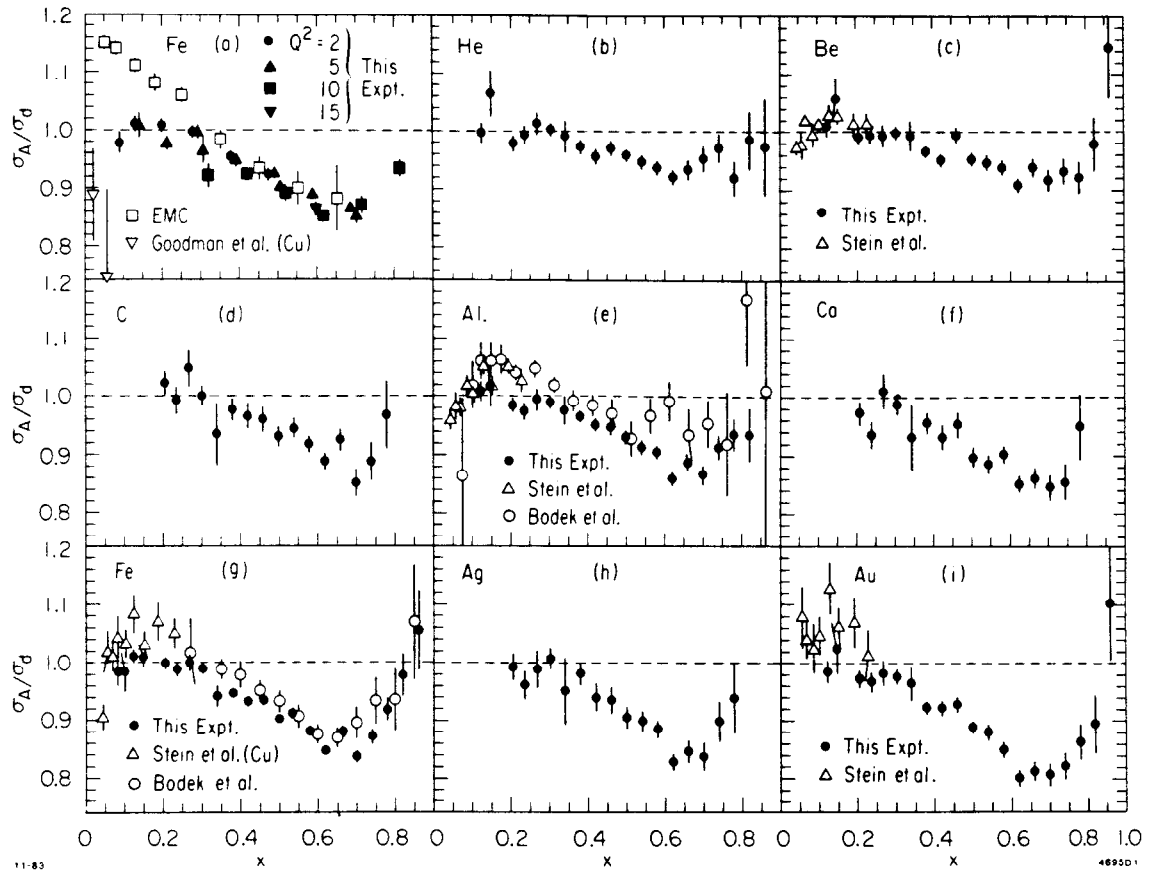


Fig. 1

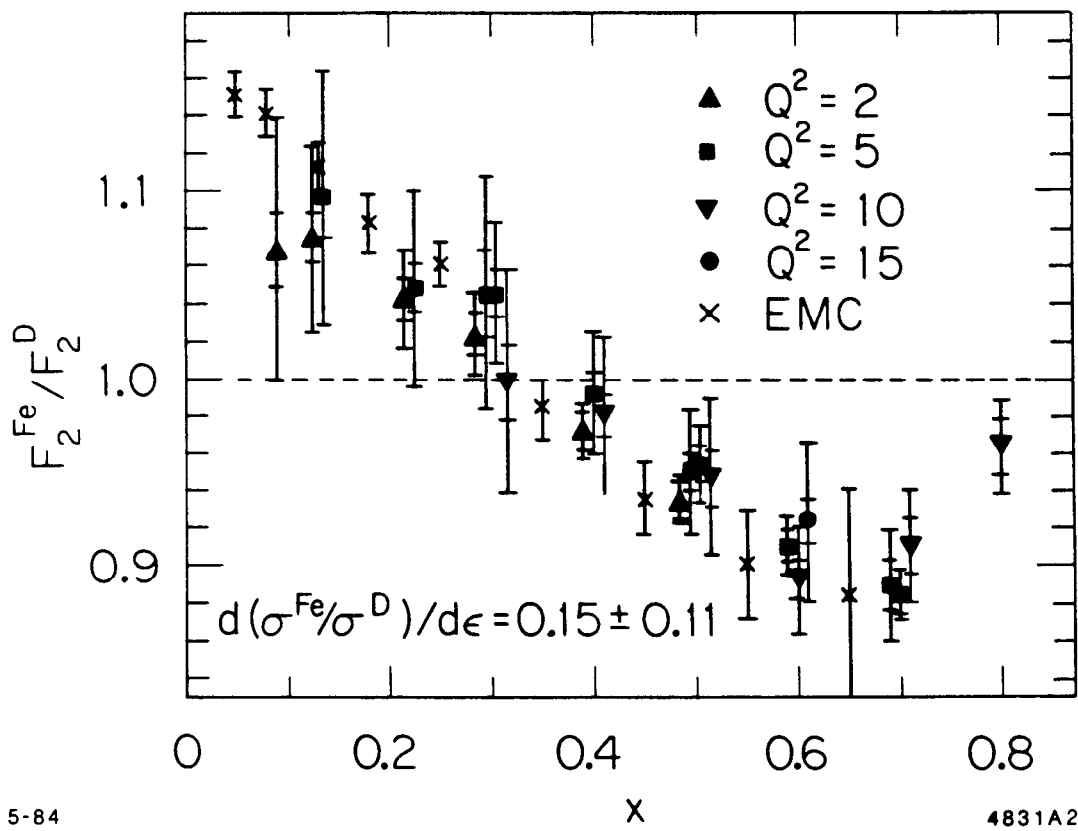


Fig. 2

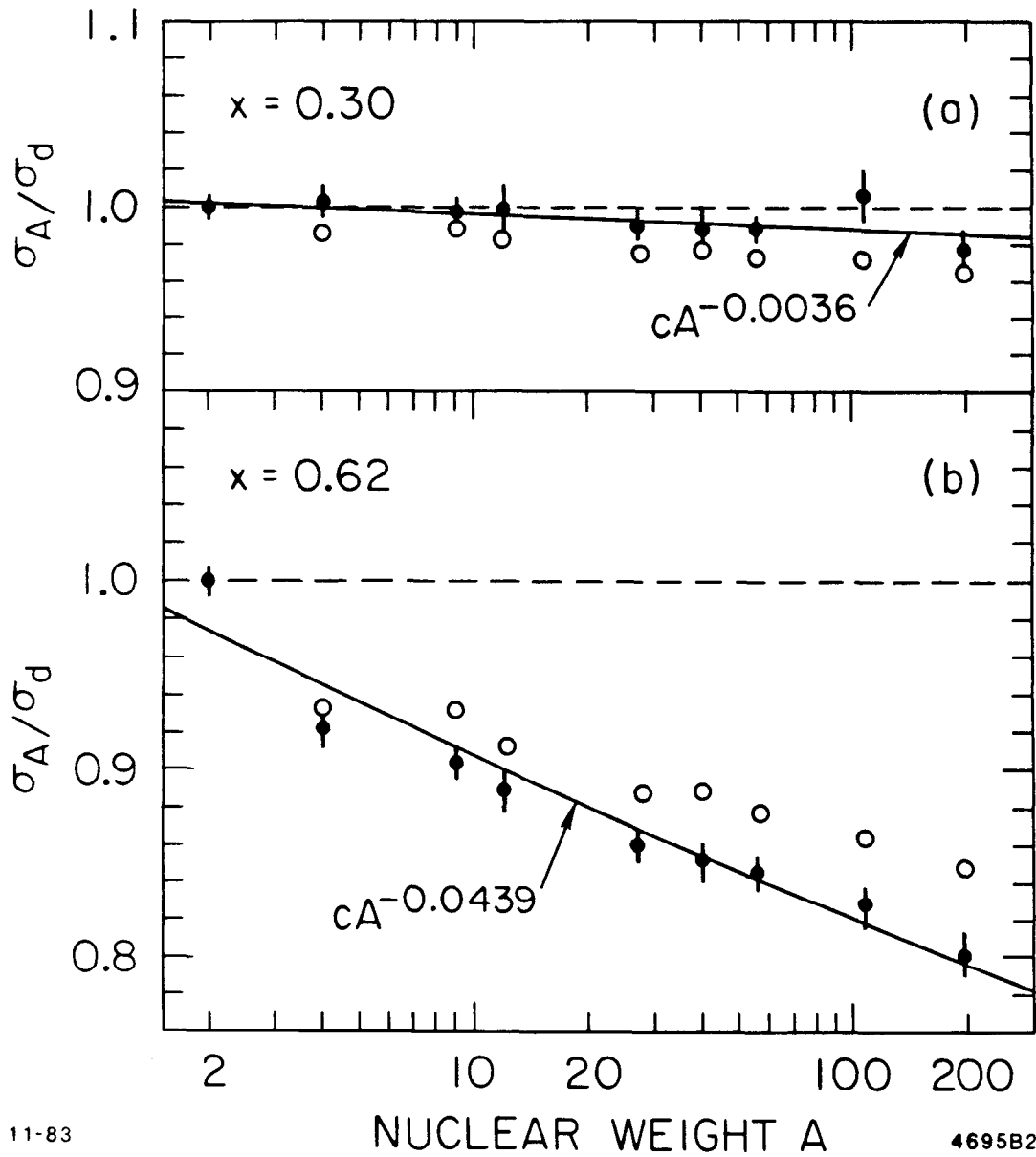


Fig. 3

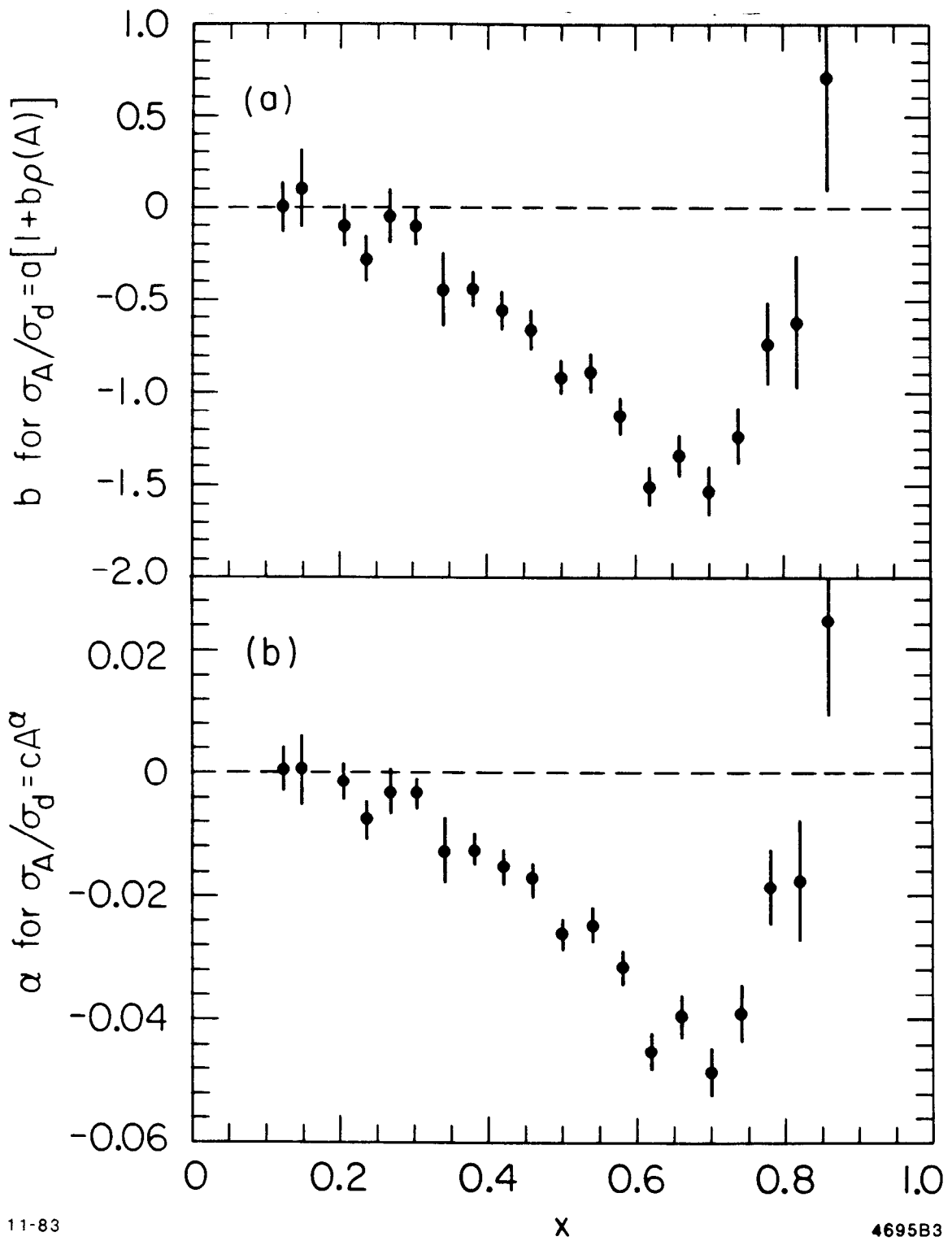


Fig. 4