CERN-TH-6254/91

Nuclear Effects in Deuteron and the Gottfried Sum Rule *

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Abstract

Recent NMC data on the ratio of the deep inelastic structure functions F_2 per nucleon for deuterium relative to hydrogen are analysed in the context of the Gottfried sum rule. It is shown that the discrepancy between Gottfried sum rule's prediction and NMC data analysis may be interpreted as a nuclear effect in deuterium as it is suggested by several models. This fact, applied to nuclear-deuterium measured ratios, modifies the standard picture of nuclear effects.

CERN-TH-6254/91
September 1991

*Partially supported by CONICET-Argentina.

Recently, the New Muon Collaboration (NMC) [1] experiment has provided values for the ratio of the structure functions F_2^n/F_2^p obtained in deep inelastic scattering of muons on hydrogen and deuterium targets, exposed simultaneously to the beam. The data cover the kinematic range down to $x = 0.004$ and $Q^2 = 0.4GeV^2$.

Assuming that nuclear effects are not significant in deuterium, i.e.

$$F_2^D = \frac{1}{2}(F_2^p + F_2^n) \tag{1}$$

NMC gives values for $F_2^p - F_2^n$, expressed as

$$F_2^p - F_2^n = 2F_2^D \frac{1 - \frac{F_2^n}{F_2^p}}{1 + \frac{F_2^n}{F_2^p}} \tag{2}$$

where

$$\frac{F_2^n}{F_2^p} \equiv 2\frac{F_2^D}{F_2^p} - 1 \tag{3}$$

The absolute deuteron structure function was taken from a fit to previous data obtained in other experiments [2].

In the quark-parton model the difference above is expressed in terms of the quark momentum distributions, namely

$$F_2^p - F_2^n = \frac{x}{3}(u_v - d_v) + \frac{2x}{3}(\bar{u} - \bar{d}) \tag{4}$$

In QCD this expression is valid in leading order or up to the next to leading order in the DIS scheme. This last relation together with the assumption of flavour symmetric sea ends, using the valence distributions normalization, with the well known Gottfried sum rule [3]

$$\int_0^1 \frac{dx}{x}(F_2^p - F_2^n) = \frac{1}{3} \tag{5}$$

The value for the Gottfried sum rule derived in this way from NMC data on F_2^D/F_2^p and a fit for F_2^D is significantly below the quark-parton model prediction [1]. Several explanations for this discrepancy have been recently suggested [2].

The main purpose of this paper is to develop the ideas of our previous communication [4] in which it was shown that this discrepancy is due to nuclear effects in deuterium. An analysis of the ratio between deuterium and hydrogen structure functions allows us to derive the ratios for proton structure functions in nuclear targets relative to that in hydrogen by using nuclear-deuterium NMC measurements. This was done by means of a modified version of the Gottfried sum rule which deals with both nuclear structure functions and parton distributions.

The measurable nuclear effects in deuterium protons are in agreement with predictions of several models such as the light cone approach to the deuteron structure function [5], parton recombination model [6],pionic effects in deuteron [7],etc.. On the other hand, the picture that emerges when comparing nuclear structure functions with those of free protons differs from the standard comparision, done up to now, with deuterium protons.

In order to take into account nuclear effects in deuterium, one can define bound nuclear structure functions, F_2',by means of

$$F_2^D = \frac{1}{2}(F_2'^p + F_2'^n) \tag{6}$$

$$F_2'^p = \frac{1}{\beta_D} F_2^p \tag{7}$$

Due to isospin symmetry one expects the β_D factor to be the same for proton and neutron structure functions. Then the difference between bound nucleon structure functions is expressed as

$$F_2'^p - F_2'^n = 2F_2^D \frac{1 - \frac{F_2'^n}{F_2'^p}}{1 + \frac{F_2'^n}{F_2'^p}} = \frac{1}{\beta_D}[\frac{x}{3}(u_v - d_v) + \frac{2x}{3}(\bar{u} - \bar{d})] \tag{8}$$

The ratio $F_2'^n/F_2^p$is related to the one reported by NMC,$F_2^n/F_2^p \mid_{NMC}$,through

$$\frac{F_2^n}{F_2^p} \mid_{NMC} \equiv 2\frac{F_2^D}{F_2^p} - 1 = \frac{F_2'^n}{F_2^p} + \frac{1}{\beta_D} - 1 \tag{9}$$

$$F_2'^p - F_2'^n = 2F_2^D[\frac{2}{\beta_D(\frac{F_2^n}{F_2^p} \mid_{NMC} + 1)} - 1] \tag{10}$$

Our parameter β_D can be estimated by using the NMC data combined with a quark distribution parametrization. Notice that the distributions in Eq.(8) should be those of an unbound proton. Unfortunately, data coming from deuteron targets are always used in the fits. However, the inclusion of the β_D parameter at this level does not modify our conclusions. We decided to use the very recent Morfin and Tung parametrization (s-fit in DIS scheme) [8], which is symmetric in the sea ($\bar{u} = \bar{d}$), as is the case in almost any parametrization. These parton distributions are consistent with neutrino and muon deep inelastic data as well as Drell Yan pair production [9]. The pertinent analysis incorporates experimental systematic errors which are the dominant ones according to recent deep inelastic scattering experiments. The form adopted in reference [8], is motivated by QCD and is particularly useful in exploring the small x behaviour of the distribution. The values obtained for the $\frac{1}{\beta_D}$ are listed in Table 1 and presented in Fig.1. We should notice that entirely similar results are obtained using other parametrizations, for example B_- or B_0 fits of Kwiecinsky, Martin, Stirling and Roberts [10], which also incorporate theoretical QCD results leading to the singular behaviour of the gluon and sea quark distributions as well as modifications due to shadowing effects.

A remarkable feature of the Gottfried sum rule is that it is an extraordinary amplifier of nuclear effects. In fact, an amount of antishadowing as small as 3% causes a deviation in the integrand as big as 37%. This explains why the beta function is almost independent of the parton distribution used and why up to now this deuteron nuclear effect has been safely neglected in many analysis. As we have mentioned, deuterium data is actually used in the extraction of parton distributions, but no significant change is detected there when β_D is included.

We have also analysed the effect of using a common fit to the SLAC, BCDMS and EMC-NA28 data [11] for structure functions instead of NMC data. This phenomenological parametrization is based on a detailed comparision of high statistics measurements and fits data in a wide x and Q^2 range. The resulting $\frac{1}{\beta_D}$ values are compared with NMC ones in Fig.1.

Notice that the points in Fig.1 exhibit the familiar features of nuclear effects, in particular the antishadowing peak for $x \sim 0.2$ and a pronounced decrease when x tends to one. What seems unusual there is the persistency of antishadowing for small x, however it must be remembered that this curve relates deuterium protons to hydrogen ones (and not nuclear to deuterium ones), and that shadowing for small x values should be strongly dependent on A. Notice also that a very recent calculation of shadowing in lepton -deuteron scattering [12] shows that this effect amounts to less than 2%.

Close, Qiu and Roberts [6] have computed the modifications to the proton structure functions and parton distributions as a result of including parton recombination. In their calculation of fusion processes with no final state partons, initial state recombination, they found dominant those involving two partons from two different nucleons. Their result depends slightly on model assumptions such as the extent to which partons leak out of th nucleon and the input parton distributions. The $A^{1/3}$ dependence comes from a multiplicative factor related to the two parton number density and an approximation [13] for extremely small x and large A. In any case, a neat enhancement of the structure function, even in deuterium as we shall see, is predicted in all the x range. As a consecuence, the difference between the free and bound structure functions, ΔF_2, is found to have a maximun at $x \sim 0.2$ and remain positive as x tends to 0. The two parton number density can be calculated for deuterium using a light cone nucleon wave function, avoiding in this way the above mentioned approximation, which is not valid for a light nucleus. Our estimate using a toy harmonic oscillator wave function, adjusted in order to predict a correct charge radius for the deuteron [14], implies an effect about ten times smaller than that for Fe, which is in complete agreement with $\frac{1}{\beta_D}$ values at $x < 0.4$. This model [6] also predicts a modification in the valence distributions but is small for $x < 0.2$ and it almost cancels in the difference $u_v - d_v$. Clearly for a more qualitative analysis a convenient wave function and set of distributions must be chosen and other effects as final state recombination processes must be included.

Another interesting feature is the Q^2 dependence of the $\frac{1}{\beta_D}$ function at $x > 0.5$. Figure 2 shows the shape of $\frac{1}{\beta_D}$ function for different Q^2 values, extracted from the phenomenological fits of reference [11]. A remarkable dependence is seen for x values greater than 0.5. This cannot be interpreted as an erroneous extrapolation of the parametrizations as they fit hydrogen and deuterium data down to $Q^2 = 4GeV^2$ for the $x = 0.65$ bin and $Q^2 = 5GeV^2$ for $x = 0.75$. The upper Q^2 bound is about $200GeV^2$ for both bins. The Q^2 dependence also explains the discrepancies between our shadowing estimates at $Q^2 = 4GeV^2$ and other model estimates based on the data obtained at greater Q^2.

Nuclear effects are commonly extracted from the analysis of structure functions relative to deuterium under the belief that they are negligible in it. The present evidence shows that this could not be the case.

Equation (10) can be applied, after a trivial modification, to heavy nuclei structure functions in order to extract the ratio between the structure functions of protons in different nuclei and hydrogen. This allows also a test of consistency of our proposal. For example we consider protons in calcium

$$F_2^{Ca} = \frac{1}{2}(F_2'^p + F_2'n) \tag{11}$$

$$F_2'^p - F_2'^n = 2F_2^{Ca}\frac{1 - \frac{F_2'^n}{F_2^p}}{1 + \frac{F_2'^n}{F_2^p}} \tag{12}$$

Taking

$$F_2^{Ca} = F_2^D \frac{F_2^{Ca}}{F_2^D}|_{NMC} \tag{13}$$

$$\frac{F_2'^n}{F_2^p} = 2\frac{F_2^{Ca}}{F_2^D}\frac{F_2^D}{F_2^p}\beta_{Ca} - 1 \tag{14}$$

we have

$$\beta_{Ca} = \frac{1}{\frac{F_2^{Ca}}{F_2^D}}\left[\frac{1}{\frac{F_2^D}{F_2^p}} - \frac{x}{3}(u_v - d_v)\frac{1}{2F_2^D}\right] \tag{15}$$

Our results are summarized in Table 2 and Fig.5a. The ratios used as input data are from NMC measurements in different Q^2 ranges [15]. In order to determine them at a fixed Q^2, the data can be parametrized as a function of Q^2 in every x bin, as it was done for deuterium in Ref.[15]. These ratios show no significant Q^2 dependence in the measured region; in spite of that,we take the data at the mean Q^2 value of each bin. It would be interesting to verify if that is so in the high x bins over a wide Q^2 range $(4 - 100GeV^2)$,where the deuteron $\frac{1}{\beta_D}$ function has a strong dependence. This is not possible with the considered data. The calcium-deuterium ratio can be obviously recovered using the ratio for deuterium at suitable x and Q^2 values

$$\frac{F_2^{p(Ca)}}{F_2^{p(D)}} = \frac{\beta_D}{\beta_{Ca}} \tag{16}$$

which agrees with the input ratio as can be seen in Table 2, showing the consistency of our treatment. Similar results for carbon and helium are shown for completeness in figures 4 and 5.

We would like to briefly analyze the extracted ratios of the structure functions relative to free proton in the context of recombination and rescaling models [6]. The advantage of this analysis is that recombination processes, which are also present in deuterium, are not biased and different features may emerge.

At very small x, radiative recombination [6][13] seems to be responsible for shadowing. The model can be adjusted in order to show a strong A dependence, but this implies also an x dependence for the effect [16]. In the following region of x not so extremely small, initial state recombination producing antishadowing is expected to be the dominant process. In this case the x and A dependences are not correlated and, as the two-parton recombination mechanism involving two different nucleons is dominant, one can expect a weak A dependence as it is the case. Let us finally remember that almost any rescaling model succesfully describes facts for $x \geq 0.25$ [17].

The obtained ratios relative to free proton show the following distinctive features: at very small x the amount of shadowing is smaller when compared to the nuclei deuterium ratios. For example it is 93%, 83% and 65% at $x = 0.007$ for Ca, C and He respectively. This implies a stronger A dependence to be implemented in the models. However, our results also show that this implementation should include an A dependence in the shadowing saturation point (x_4 in Ref.[16]). The crossover points, called x_5 in Ref.[16] are shifted towards smaller values, which is consistent with the mentioned model. Note that the A dependence of this point implies that the dominance of shadowing over antishadowing at small x depends on a lengh scale which decreases with A (as for example the intranuclear distances). In the intermediate x region antishadowing dominates as predicted. The antishadowing peak is more pronounced when ratios to proton are used and its relative change has a weaker A dependence. Finally, the crossover point x_3 [16], that labels the end of antishadowing, is shifted towards larger x values and it decreases as A increases, which means that the nuclear effect at $x > 0.2$ is dominated by distances increasing with A(as for example the confinement radius).

In conclusion,we consider NMC data of Ref.[1] as a clear evidence of nuclear effects in deuterium targets. These effects when correctly taken into account, show that the value of the Gottfried sum rule is compatible with the quark parton model expectation . At the same time, these effects are consistent with the QCD based parton recombination analysis or with a direct extrapolation of what is observed in larger nuclei.

It is well known that nuclear effects are commonly extracted from the analysis of structure functions ratios relative to deuterium in the belief that they are negligible in it. The present evidence shows that this is not the case and that the composite nature of deuterium at the nuclear level has to enter in the QCD inspired models for those effects.

We warmly acknowledge M. Arneodo, M. Botje, G. van Middelkoop and E. Rondio of NMC for their important comments and critizism. We also thank J.Morfin for his kind help. One of the authors (CAGC) would like to thank J.Ellis and the CERN Theory Division for the nice hospitality extended to him.

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Tables.

x	F_2^D	$F_2^n/F_2^p \mid_{NMC}$	$\frac{1}{\beta_D}$
0.007	0.349	0.985	1.017
0.015	0.356	0.959	1.013
0.030	0.359	0.928	1.011
0.050	0.355	0.921	1.024
0.080	0.346	0.879	1.022
0.125	0.329	0.837	1.034
0.175	0.307	0.801	1.048
0.250	0.268	0.722	1.047
0.350	0.210	0.629	1.036
0.450	0.153	0.463	0.935
0.550	0.103	0.412	0.896
0.700	0.048	0.312	0.770

Table 1 Values for $\frac{1}{\beta_D}$ corresponding to the experimental x points. The F_2^D and $F_2^n/F_2^p \mid_{NMC}$ figures are included for completness.

x	Q^2	$\frac{F_2^{Ca}}{F_2^D}\|_{NMC}$	$\frac{1}{\beta_{Ca}}$	$\frac{F_2^{Ca}}{F_2^D}\|_{16}$
0.0035	0.60	0.780	0.799	0.780
0.0055	0.94	0.782	0.796	0.782
0.0085	1.40	0.831	0.841	0.831
0.0125	1.90	0.859	0.867	0.859
0.0175	2.50	0.899	0.907	0.899
0.0250	3.40	0.938	0.947	0.938
0.0350	4.70	0.949	0.960	0.949
0.0450	5.70	0.978	0.990	0.978
0.0550	6.80	0.966	0.979	0.966
0.0700	8.10	0.988	1.002	0.988
0.0900	9.70	1.020	1.035	1.020
0.1250	12.0	1.022	1.036	1.022
0.1750	14.0	1.034	1.047	1.034
0.2500	19.0	0.983	0.993	0.983
0.3500	24.0	0.984	0.995	0.984
0.4500	30.0	0.929	0.940	0.929
0.5500	35.0	0.869	0.874	0.869
0.6500	41.0	0.917	0.908	0.917

Table 2 Values for $\frac{1}{\beta_{Ca}}$ extracted from NMC's F_2^{Ca}/F_2^D and Milsztajn et al. [11] parametrization for F_2^n/F_2^p. In the last column we include the computed values for F_2^{Ca}/F_2^D from Eq.16

Figure Captions

Figure 1 The ratio between deuterium and free proton structure functions, $\frac{1}{\beta_D}$, obtained from NMC [1] data and Morfin and Tung distributions [8] using Eq.8. The errors were estimated from those in the structure function data. The continuos line comes from the Milsztajn et al. [11] parametrization for F_2^D and F_2^p.

Figure 2 The same as figure 1 but for different Q^2 values; $Q^2 = 4GeV^2$ continuos line, $Q^2 = 36GeV^2$ dashes, $Q^2 = 100GeV^2$ dots.

Figures 3,4,5 a The same as figure 1 but for Helium, Carbon and Calcium respectively using NMC data of Ref.[15] and Milsztajn et al. parametrizations [11]

b Helium, Carbon and Calcium ratios relative to deuterium as reported by NMC respectively.

Figure 1

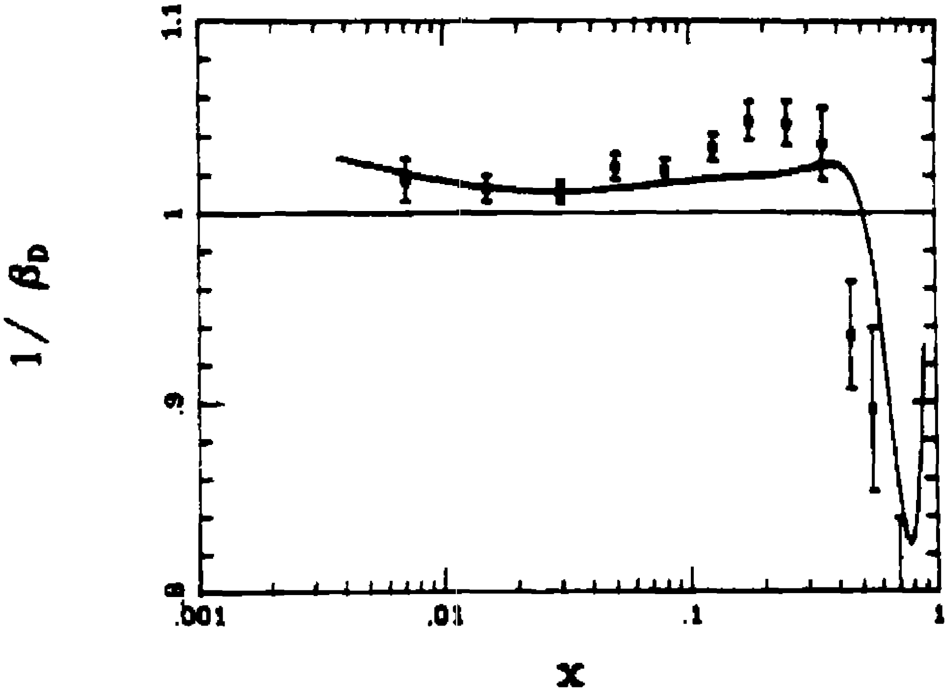

Figure 2

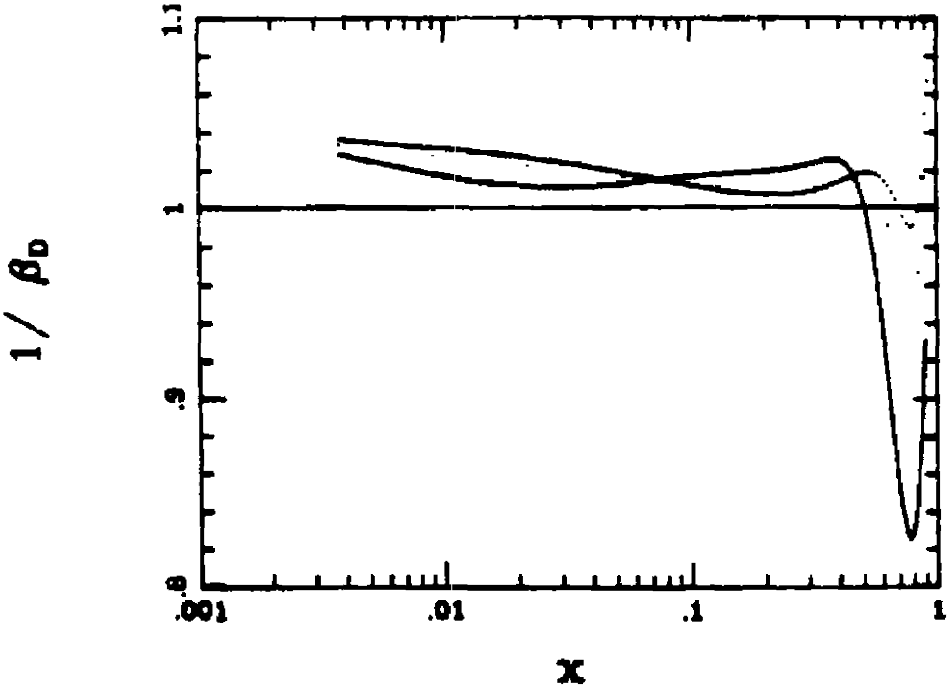

Figure 3a

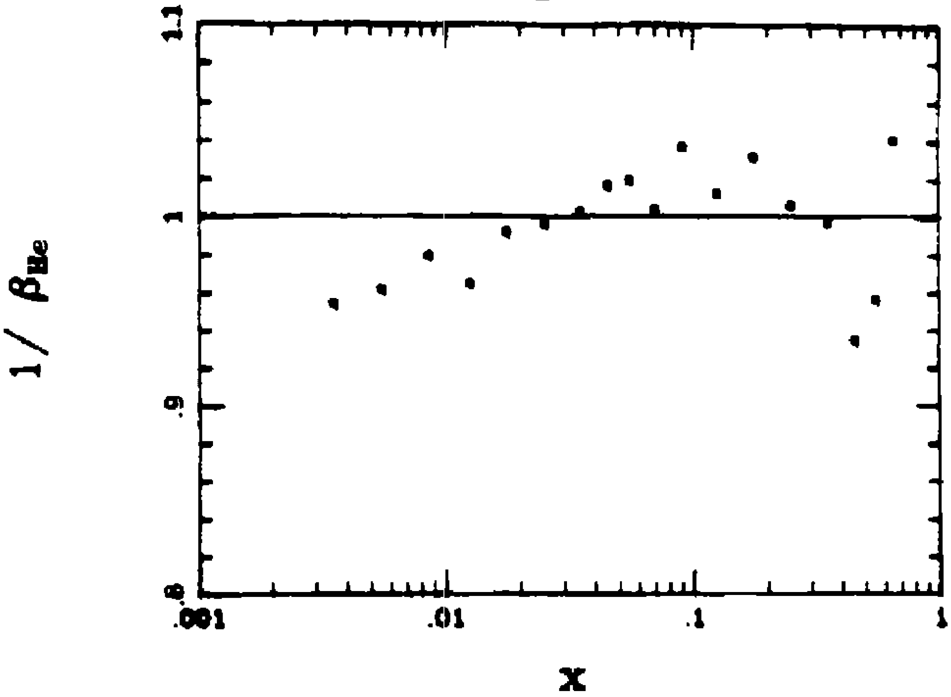

Figure 3b

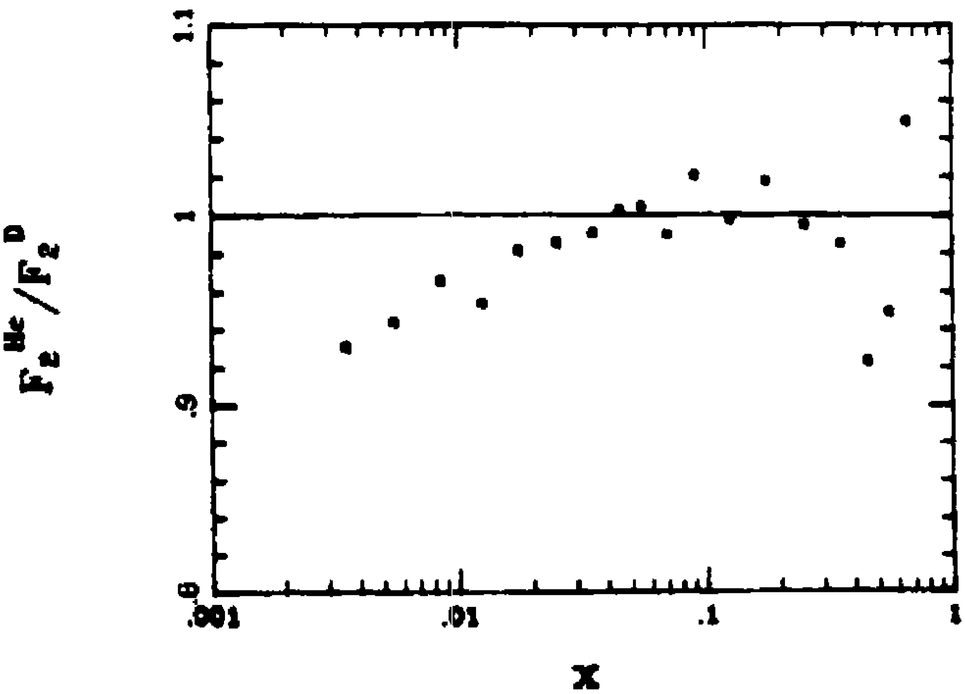

Figure 4a

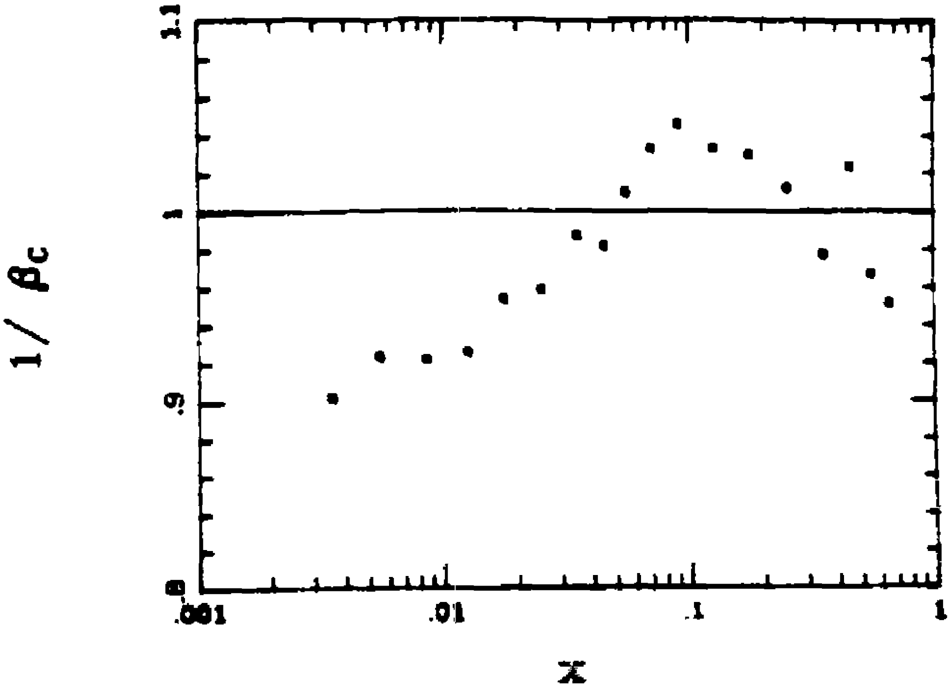

Figure 4b

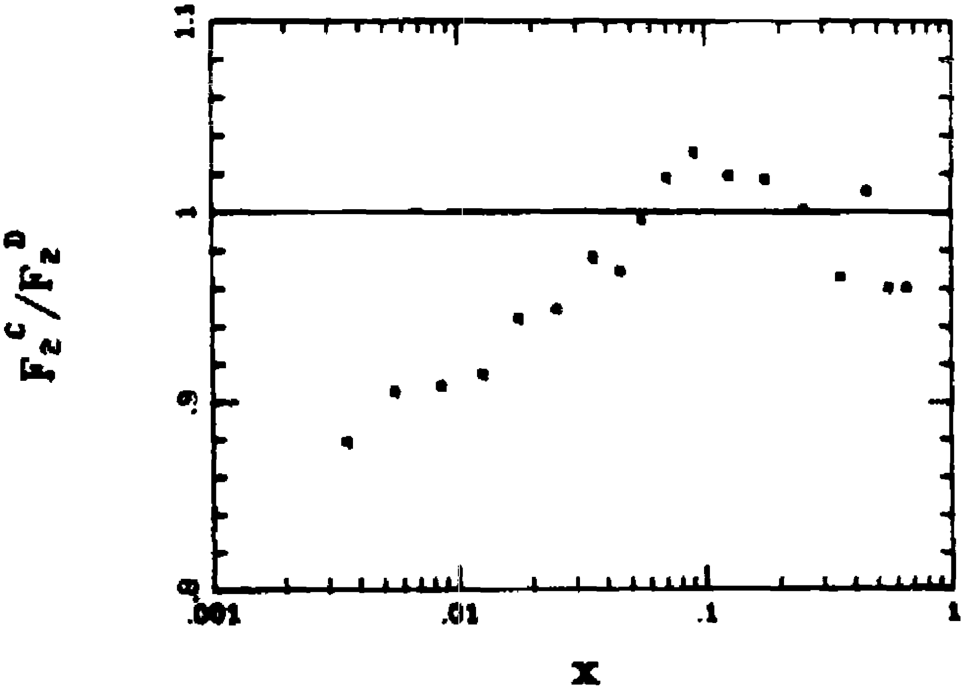

Figure 5a

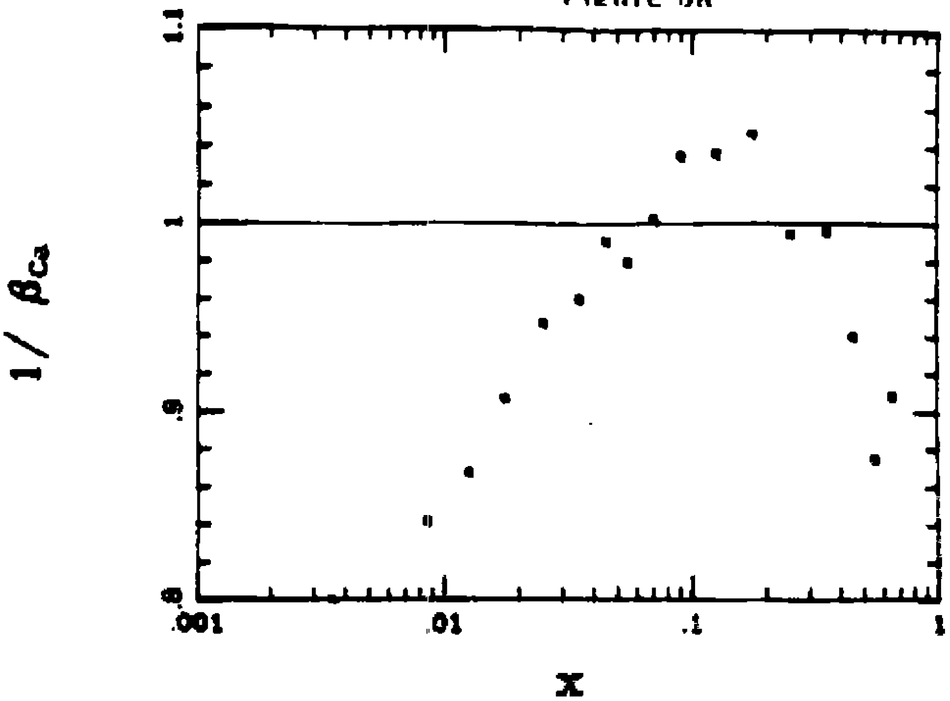

Figure 5b