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Abstract

It is shown that if the effects of nucleon binding on deep inelastic scattering are considered within many-body realistic descriptions of nuclei which include nucleon-nucleon correlations, the EMC effect in light and medium weight nuclei and nuclear matter can be accounted for in the region $0.2 \leq x \leq 0.5$, but a systematic discrepancy between theory and experiment remains to be explained for $0.5 \leq x \leq 0.9$.

A consistent explanation of the so called classical EMC effect, i.e. the experimental observation [1][2] that in the range $0.2 \leq x \leq 0.9$ ($x = \frac{Q^2}{2M_N\nu}$ being the Bjorken scaling variable, M_N the nucleon mass, Q^2 and ν the four-momentum and energy transfers, respectively) the nuclear structure function per nucleon in the Bjorken limit, $\frac{F_2^A(x)}{A}$, differs

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from the free nucleon structure function $F_2^N(x)$, is still waited for. Of particular relevance is the problem of understanding how much of the measured ratio $R(x) = \frac{F_2^A(x)/A}{F_2^D(x)/2}$ (the superscipt D standing for Deuteron) for nuclei ranging from $A = 4$ to $A = 197$, should be ascribed to exotic effects, and how much to the effects of nucleon dynamics on the Deep Inelastic Scattering (DIS) cross section. Many papers claiming that the effects of nucleon binding can account for the EMC effect, suffer from: i) the omission of an important kinematical factor (the *flux factor* [3] [4]), whose consideration [5] [6] [7] [8] reduces the EMC effect, and ii) the use of an independent particle model, where high momentum and high removal energy components are totally absent. In [6] and [7], the EMC effect was calculated both considering the flux factor as well as adopting a realistic nuclear description which include the effects of Nucleon-Nucleon (NN) correlations generating high momentum and high removal energy components. The conclusions of [6] and [7] were that *a realistic, many-body treatment of nuclear structure effects on DIS cross sections, is able to reproduce the trend of the EMC effect in the region* $0.2 \leq x \leq 0.5$, *i.e. the slope of* $R(x)$, *but for* $0.5 \leq x \leq 0.9$ *and for all nuclei considered (i.e. from* $A = 4$ *to* $A = 56$*) a systematic discrepancy between experimental data and theoretical calculations appears to hold, with the predicted deviation of* $R(x)$ *from unity being much smaller than the experimental one.* Whereas the calculations for few-body systems (presented in [7]) were performed within realistic models for the nucleon spectral function, the calculations for complex nuclei [6] are based upon approximate spectral functions. Although arguments were given in [6] [7] that at $x < 1$ the detailed structure of the spectral function is not very relevant, the recent appearance of a realistic spectral function for nuclear matter [9] represents a good opportunity to check the limits of validity of the results of [6] (preliminary results of our calculations on nuclear matter have been presented in [10]). For an isoscalar nucleus the convolution formula reads as follows (see e.g. [3] and [4])

$$F_2^A(x) = \int_{x \leq z} f(z) F_2^N(\frac{x}{z}) dz \tag{1}$$

where $F_2^N(x) = \frac{1}{2}F_2^p(x) + \frac{1}{2}F_2^n(x)$ ($F_2^{p(n)}(x)$ is the proton (neutron) structure function) and

$$f(z) = \int d^4p\, S(p)\, z\, \delta\left(z - \frac{(pq)}{M_N \nu}\right) \tag{2}$$

$S(p)$ being the relativistic vertex function for the virtual decay $A \rightarrow (A-1)^* + N$, with N denoting an off-shell nucleon with four-momentum p. By disregarding relativistic corrections of order higher than $(\frac{|\vec{p}|}{M_N})^2$ (cf. [6] and [7]), one can replace $S(p)$ by the non-relativistic vertex function, i.e. by the spectral function $P(k,E) =< \Psi_o \mid a_{\vec{k}}^{+} \delta(E - (H - E_A)) a_{\vec{k}} \mid \Psi_o >$ which describes the joint probability of finding in a nucleus a nucleon with momentum $\mid \vec{p} \mid = k$ and (positive) removal energy $E = E_{A-1}^{f*} + E_{min}$ (E_{A-1}^{f*} being the excitation energy of the final $A-1$ system and $E_{min} = M_N + M_{A-1} - M_A$). Within such an approximation, the function $f(z)$ becomes as follows [6] [7]

$$f(z) = 2\pi M_N C_N \int_{E_{min}}^{\infty} dE \int_{k_{min}(z,E,M_{A-1})}^{\infty} P(k,E) k dk \tag{3}$$

where $z = \frac{p^+}{M_N} \equiv \frac{(p_o - p_{\|})}{M_N}$ ($p_{\|} = \frac{(p \cdot q)}{|q|}$) is the light cone momentum fraction carried by the nucleon N and $k_{min} =\mid M_N(1-z) - E \mid$ (this relation is strictly correct only in the limit of nuclear matter, where $M_{A-1} \rightarrow \infty$; the exact relation also valid for a light nucleus is given in [7]). By expanding $F_2^N(x)$ in Eq(1) in powers of z around $z = 1$, and by retaining terms of the order $(\frac{k}{M_N})^2$, one has

$$\begin{aligned} F_2^A(x) \cong\ & F_2^N(x) - xF_2^{N\prime}(x)\left(\frac{< E >}{M_N} - \frac{2}{3}\frac{< T >}{M_N}\right) + \\ & x^2 F_2^{N\prime\prime}(x) + 2xF_2^{N\prime}(x)\frac{2}{3}\frac{< T >}{M_N} \end{aligned} \tag{4}$$

where $F_2^{N\prime}(x)$ and $F_2^{N\prime\prime}(x)$ denote the derivatives of $F_2^N(\frac{x}{z})$ with respect to z and the mean kinetic and removal energies are

$$< T > \; = \; \int dE \int d^3k \left(\frac{k^2}{2M_N}\right) P(k,E) = \int d^3k \left(\frac{k^2}{2M_N}\right) n(k) \tag{5}$$

$$< E > \; = \; \int dE \int d^3k E P(k,E) \tag{6}$$

$n(k) = \int dE\, P(k,E)$ being the nucleon momentum distribution. As is well known, $< T >$ and $< E >$ are linked to the binding energy per nucleon $\mid \epsilon_A \mid$ by the sum rule [11]

$$\mid \epsilon_A \mid = \frac{1}{2}\left[< E > - \frac{A-1}{A-2} < T >\right] \tag{7}$$

By using Eq(7), the coefficient of the first derivative of $F_2^N(x)$ in Eq(4), which governes the behaviour of $R(x)$ for $x \leq 0.5$, becomes $\left\{2 \mid \epsilon_A \mid + \frac{A-4}{3(A-1)} < T >\right\}$, so that, in order to estimate the ratio $R(x)$ up to $x \approx 0.5$, the knowledge of the full spectral function is in principle not required; it suffices to know only the values of $\mid \epsilon_A \mid$ and $< T >$. This is quite a relevant point, for the full spectral function is known only for ^{3}He and nuclear matter, whereas $\mid \epsilon_A \mid$ and $< T >$ have been calculated for several nuclei, both within mean-field and many-body correlated approaches (note that if the values of $\mid \epsilon_A \mid$ and $< T >$ are known, the value of $< E >$ can be obtained from the sum rule (7)). In Table 1, the values of $< E >$ and $< T >$ resulting from many-body calculations in medium weight nuclei are summarized (for details and References to original papers, see [6]).

It is clear from Table 1 and Eq(4), that the increase of $< T >$ and $< E >$ generated by NN correlations produces an increase of the slope of $R(x)$; the net result [6] [7] is a satisfactory explanation of the EMC effect, at least up to $x \approx 0.5$, where the expression (4) can be used. For larger values of x, Eq(5) has to be calculated explicitely and the knowledge of the spectral function is therefore required. In [6] and [7] (see also [12]) various model spectral functions have been adopted and it has been shown that for $x \leq 1$ spectral functions characterized by very different k and E behaviours produce almost the same EMC effect, provided all of them yield similar values of $< T >$ and

$< E >$. As already pointed out, the availability of a realistic spectral function for nuclear matter [9], represents a good opportunity to check again the conclusion of [6] and [7], particularly in view of the fact that $< T >$ and $< E >$ in nuclear matter are sensibly larger than in medium weight nuclei. As a matter of fact, taking $| \epsilon_A |$ and $< T >$ from [9] and using the sum rule, one gets

$$< T > = 38.7 MeV \quad < E > = 70.7 MeV \tag{8}$$

at $k_F = 1.33 fm^{-1}$. These values show that the slope of $R(x)$ for nuclear matter is higher than the one for lighter nuclei, in agreement with the experimental results for the heaviest nucleus for which experimental data were taken, viz. ^{197}Au. Using the light cone momentum distribution (Eq(3)) corresponding to a parametrization [12] of the spectral function of [9], we have obtained $R(x)$ in the whole range of $x \leq 1$ The results of our calculations are presented in Fig.1 and they confirm the conclusions of [6] and [7] also for nuclear matter, i.e. the presence of a sizeable discrepancy at large values of x. A word of caution is in order here, regarding the comparison of calculations for nuclear matter with experimental results for a non-isoscalar nucleus like ^{197}Au. This point, which is strongly related to the A dependence of the EMC effect, presented in Fig.2 for $x = 0.6$, will be discussed in detail elsewhere. In Fig.3 our results for ^{4}He, medium weight nuclei and nuclear matter are summarized. From such a figure, the answer to the question giving the title to this note is straightforward and reinforces the conclusion of [6] and [7], viz. *"If the convolution formula with only nucleonic degrees of freedom is adopted, the trend of $R(x)$ for $x \leq 0.5$ can be explained by binding effects, provided the large values of $< T >$ and $< E >$ arising from correlated nucleons, are used; however a systematic discrepancy between theory and experiment at $x \geq 0.6$ remains to be explained for all nuclei in the range $4 \leq A \leq 197$"*. It is not the aim of this paper to discuss the origin of such a discrepancy; we would only like to mention, in this regard, that: i) any theoretical improvement should also care about the restoration of the momentum sum rule, which is violated by binding effects if only nucleonic degrees of freedom are considered, and ii) more precision data for isoscalar nuclei in the region $0.6 \leq x \leq 0.9$ would be highly necessary in order to quantitatively determine the discrepancy between theory and experiment and to better understand the A dependence of the EMC effect. In closing this note, we would like to point out that:

i) a calculation similar to ours both in the theoretical approach and in the spectral function used has recently appeared [13]; it is gratifying to observe that the results there obtained are in very good agreement with the ones presented in Fig.1;

ii) a recent extrapolation of the available data to $A \to \infty$ [14] has been performed which will allow a more reliable comparison between data and theoretical calculations; however, with the extrapolated data, the overall discrepancies found in the region $x \geq 0.5$ still persists;

iii) whereas at $x \leq 1$ the nuclear structure function $F_2^A(x)$ is not very sensitive to the details of the spectral function, these details can very strongly affect the behaviour of $F_2^A(x)$ at $x > 1$ ([7] [15]). Calculations with the exact spectral function of [9], as well as with various approximate spectral functions are in progress and will be published elsewhere [16].

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References

[1] R.G. Arnold et al., Phys.Rev. Lett.**52** (1984) 727

[2] European Muon Collaboration, J. Ashman et al., Phys. Lett.B202 (1988) 1004

[3] L.L. Frankfurt and M.I. Strikman, Phys. Lett. **B183** (1987) 254

[4] R.L. Jaffe, Nucl.Phys. **A478** (1988) 3c

[5] G.L. Li, K.F. Liu and G.E. Brown, Phys.Lett.**B213** (1988) 531

[6] C. Ciofi degli Atti and S. Liuti, Phys. Lett. **B225** (1989) 215

[7] C. Ciofi degli Atti and S. Liuti, Phys. Rev. **C41** (1990) 1100

[8] H.Jung and G.A. Miller, Phys.Lett. **B200** (1988) 351

[9] O. Benhar et al. Nucl.Phys.**A505** (1989) 267 and private communication;

[10] C. Ciofi degli Atti and S.Liuti, in "2^{nd} *Workshop on Hadronic Physics with Multi-GeV electrons*", (1990), Dourdan, France, eds. B. Frois and J.F. Mathiot, to appear in Nuclear Physics A

[11] D.S. Koltun, Phys.Rev.**C9** (1974) 484

[12] C. Ciofi degli Atti, S. Liuti and S. Simula, Phys.Rev. **C41** (1990) R2474;

[13] A.E.S. Dieperink and G.A. Miller, Preprint, University of Washington (1991)

[14] D.Day, private communication and D.Day, I.Sick and J.S. McCarthy, to be published

[15] J.Rozynek and M.C.Birse, Phys.Rev.**C38** (1988) 2201

[16] O.Benhar, C.Ciofi degli Atti, S. Liuti and S.Simula, in preparation

Table Caption

Table 1. Values of $< T >$ and $< E >$ resulting from calculations within mean field approaches (*Independent Particles*) and many-body approaches (*Correlated Particles*).

Figure Captions

Fig.1 The EMC effect in nuclear matter compared with experimental data for ^{197}Au [1]. The theoretical curve corresponds to Eqs(1) and (3), which were calculated by using a parametrization [12] of the spectral function of [9].

Fig.2 The experimental A dependence of the EMC effect for $x = 0.6$ [1], compared with theoretical predictions: *independent particle models* (squares) and *correlated nucleons* (stars). The dashed and dotdashed lines have been drawn in order to better show the trend of the theoretical results for medium weight nuclei.

Fig.3 The EMC effect in ^{4}He, ^{12}C, ^{56}Fe and nuclear matter. All theoretical curves have been obtained by using the correlated many-body approach described in the text (see also [6] and [7]). Experimental data from [1]

Table 1

Nucleus	Nucleons in the Nucleus	$< T >$	$< E >$
$12 < A < 56$	*Independent particles*	$\approx 17 MeV$	$\approx 25 MeV$
$12 < A < 56$	*Correlated particles*	$\approx 35 MeV$	$\approx 50 MeV$

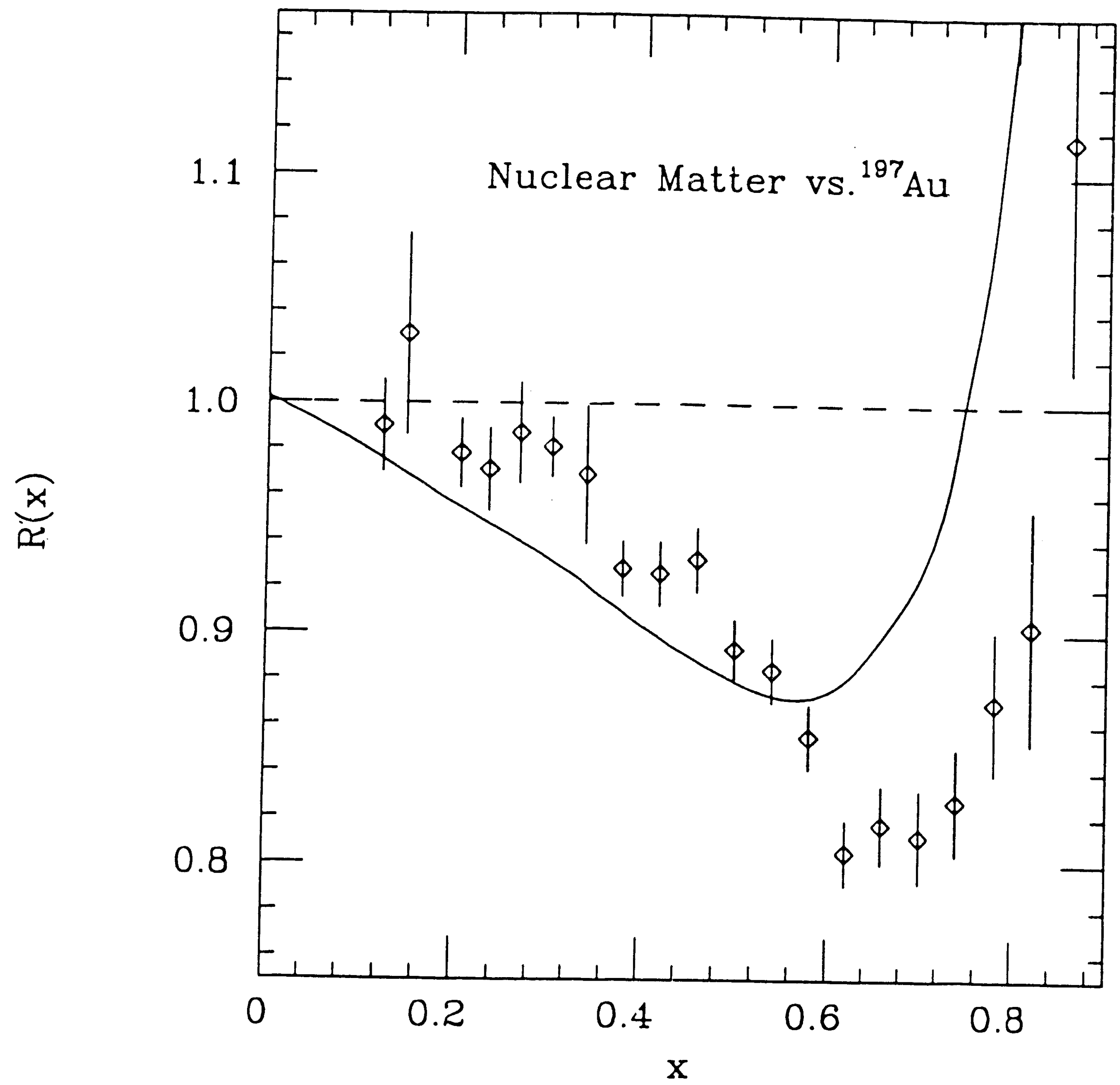

Fig.1 C.Ciofi degli atti and S.Liuti "The Classical EMC Effect..."

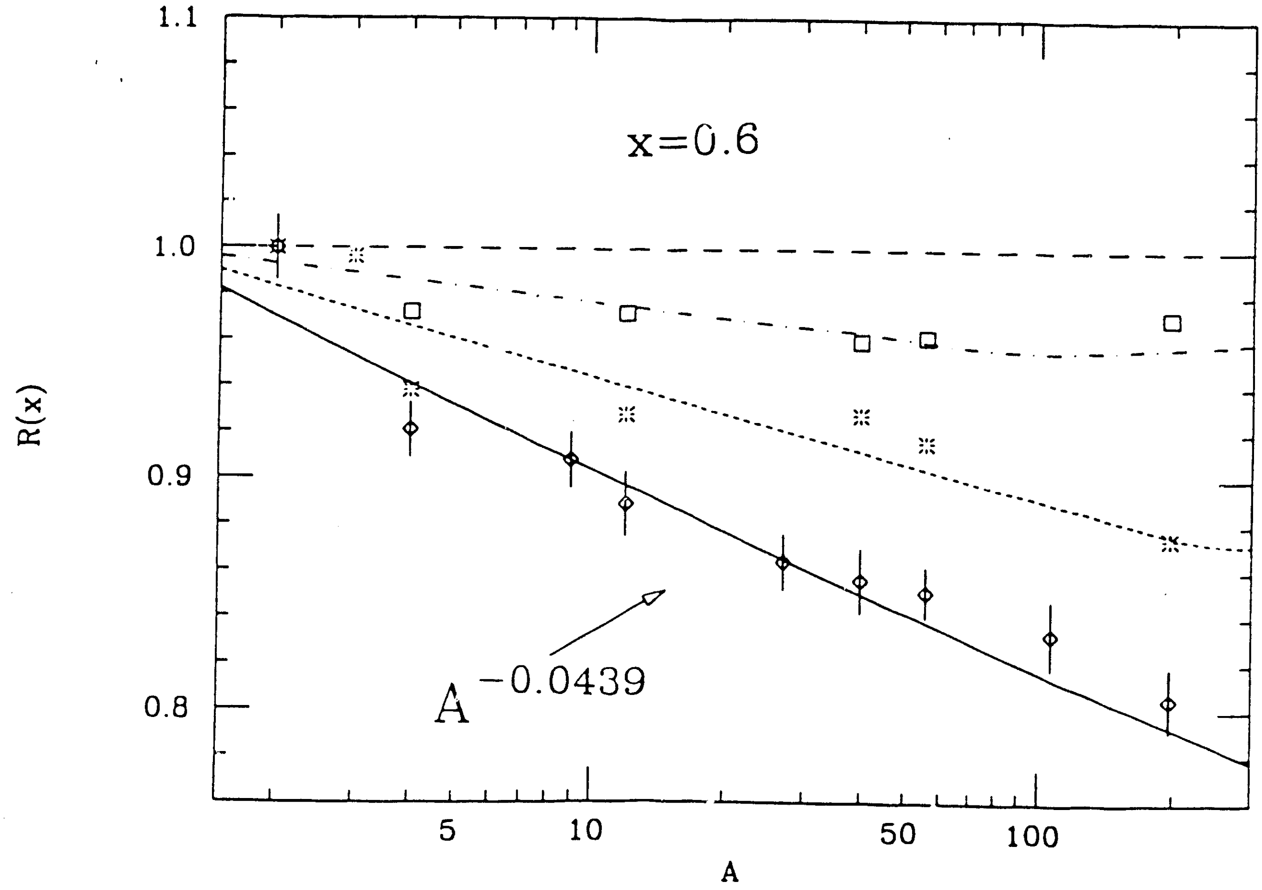

Fig.2 C.Ciofi degli atti and S.Liuti "The Classical EMC Effect..."

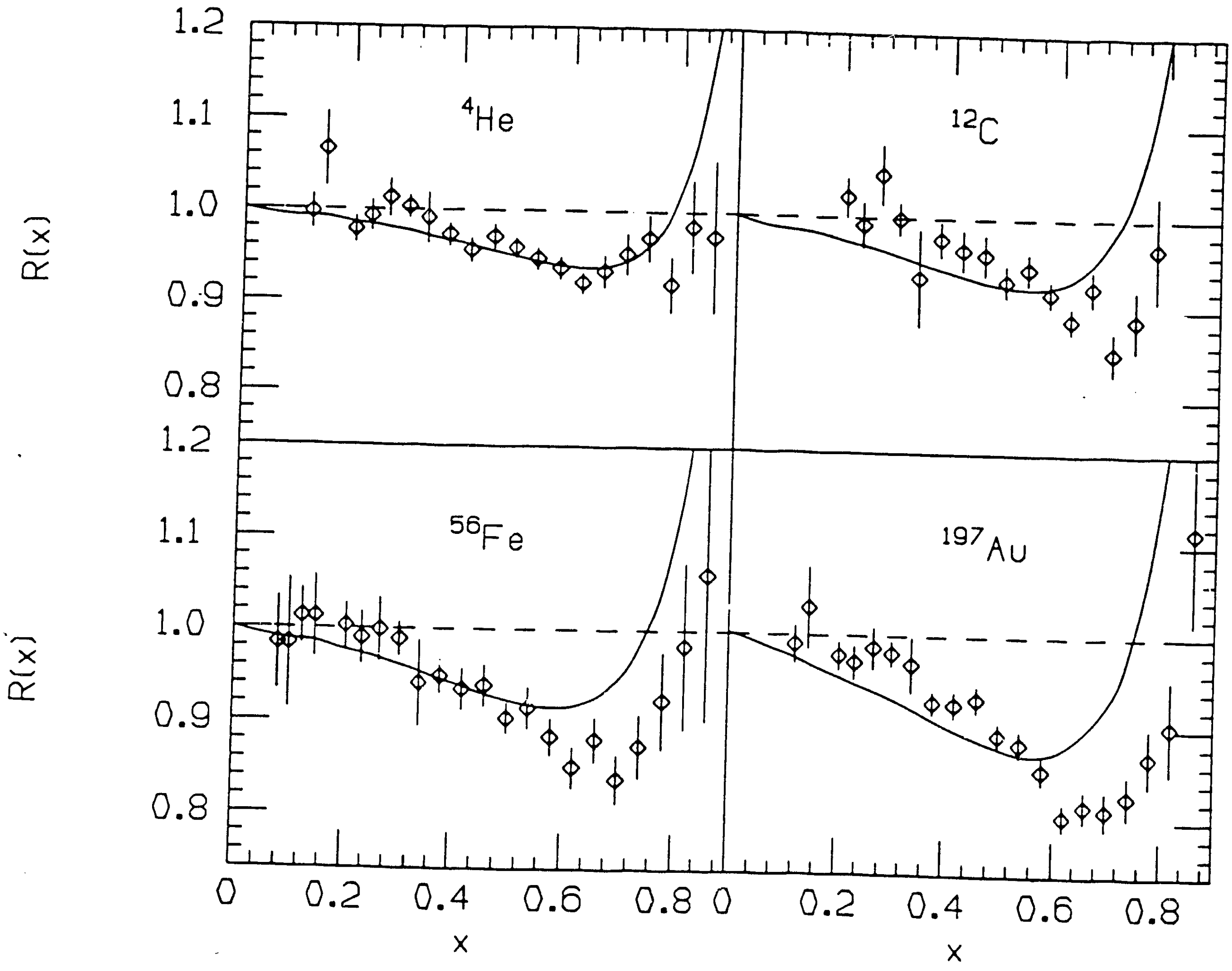

Fig.3 C.Ciofi degli atti and S.Liuti "The Classical EMC Effect..."

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