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MOMENTUM DISTRIBUTION AND TWO-BODY SHORT RANGE CORRELATIONS IN $^{16}O(e,e'p)$

Presented by G.P. Capitani at
"Topical Workshop on
Two-Nucleon Emission Reactions"
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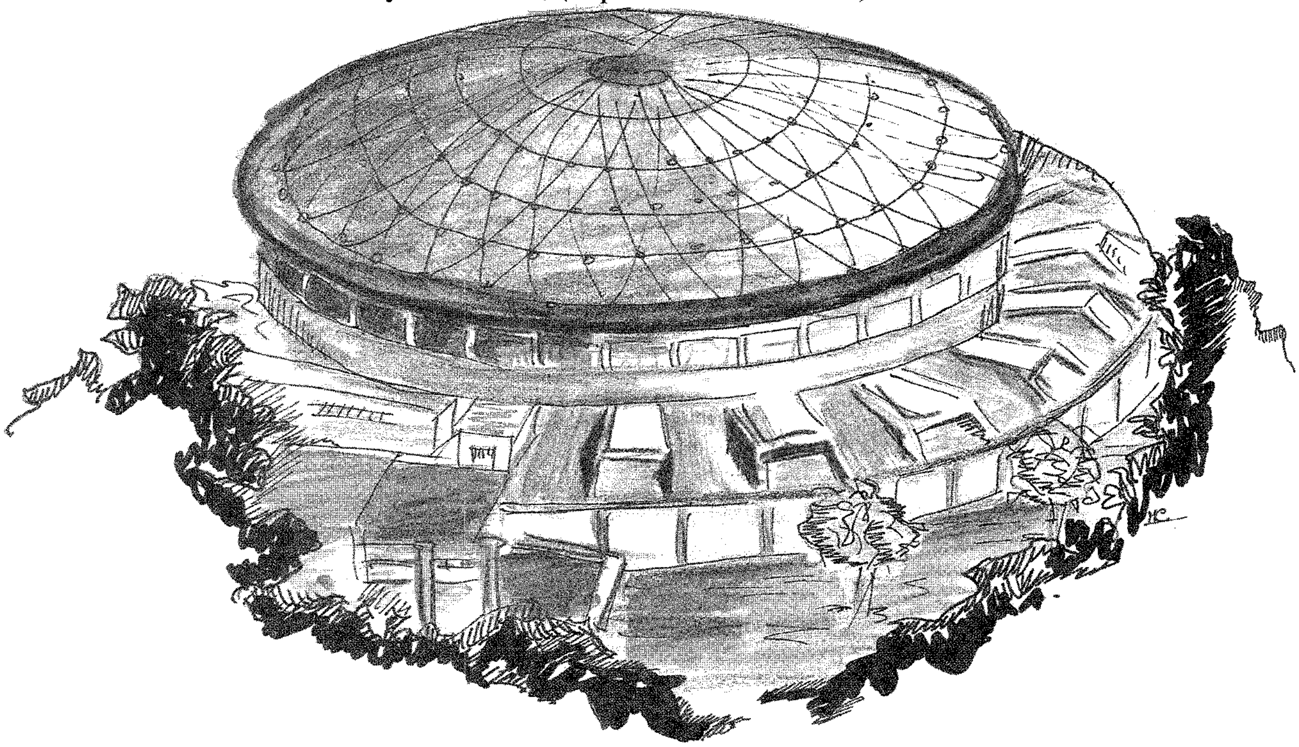

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MOMENTUM DISTRIBUTION AND TWO-BODY SHORT RANGE CORRELATIONS IN $^{16}O(e,e'p)$

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INTRODUCTION

Knock-out proton reactions in electron scattering, in the quasi-elastic domain, prove to be a powerful way to study mean-field properties of nuclei at relatively low removal energies and recoil momenta.

Verified predictions of the shell model demonstrate that under these conditions, neutrons and protons in nuclei are essentially individual particles moving in an average potential. However, as energy and momentum transfer increase, and when the quasi-elastic condition is no longer satisfied, new degrees of freedom emerge; residual nucleon-nucleon interactions become relevant, even predominating, for particular kinematics.

In a more refined analysis of these reactions, it is necessary to explicitly introduce such ingredients as meson exchange currents (MEC), pion production, nucleon excitations, relativistic effects, final state interactions (FSI) and, of special relevance for what concerns the present measurements, two-nucleon short-range correlations.

The most evident effect of two-nucleon short-range correlations is an enhancement of the single nucleon momentum density distribution, $n(k)$, for high momenta [1-4]. As this effect has not yet been unambigously detected in other than few-body nuclei (i.e. up to ^4He), we decided to study it for ^{16}O, by means of the $(e,e'p)$ reaction, using the experience and tradition obtained in Saclay in light nuclei [5-10]. ^{16}O was chosen because it is the sole non few-body nucleus for which there exist many modern calculations of the single nucleon momentum distribution [1-4].

THEORETICAL AND EXPERIMENTAL PANORAMA

The evaluation (and the cross-check with experiments) of the momentum density distribution $n(k)$ has always been considered of primary importance in Nuclear Physics.

In Fig. 1a $n(k)$ for ^{16}O, as computed by Negele [11], is shown. An independent particles model (IPM) is used with a mean-field, density dependent, wave function. Short-range correlations are missing.

Short range correlations were first taken into account in finite nuclei phenomenologically (Jastrow type correlations). Except for the pioneering work of Brueckner and collaborators, non phenomenological nucleon-nucleon correlation calculations, especially for light nuclei, have only appeared in recent years. The new calculations are either of the Brueckner type [1] (^{16}O, dot-dashed line in Fig. 1b), or are "microscopic" [2] (^{12}C,^{16}O, solid line in Fig. 1b, ^{40}Ca), [3] (^{16}O,^{40}Ca) and [4] (^{16}O).

We can make some general observations and commments:

i) Up to momenta of the order of 300 or 350 MeV/c all calculations (mean-field or not) give essentially the same results. However, from about 300 or 350 MeV/c, those computations that take into account short-range correlations give significantly higher momentum components; at momenta of 500 or 600 MeV/c, the latter calculations are about three or even four orders of magnitude greater than the mean-field computations. See Fig. 1a,1b.

ii) The Brueckner type calculations by Van Orden at al. [1] and the microscopic calculations of Benhar et al. [2] take correlations into account explicitly. They generate similar momentum distributions, also at high momenta, although the former generate more high momentum components than the latter. At momenta higher than 350 MeV/c the values of ref. [3] are smaller than these by an order of magnitude. These results can be exlpained because: a) Brueckner like computations can take into account two- and more-nucleons correlations; b) ref. [2] considers only two-nucleon correlations; c) in ref. [3] two-nucleon correlations are introduced directly only in the one-body density matrix (not in the wave-function).

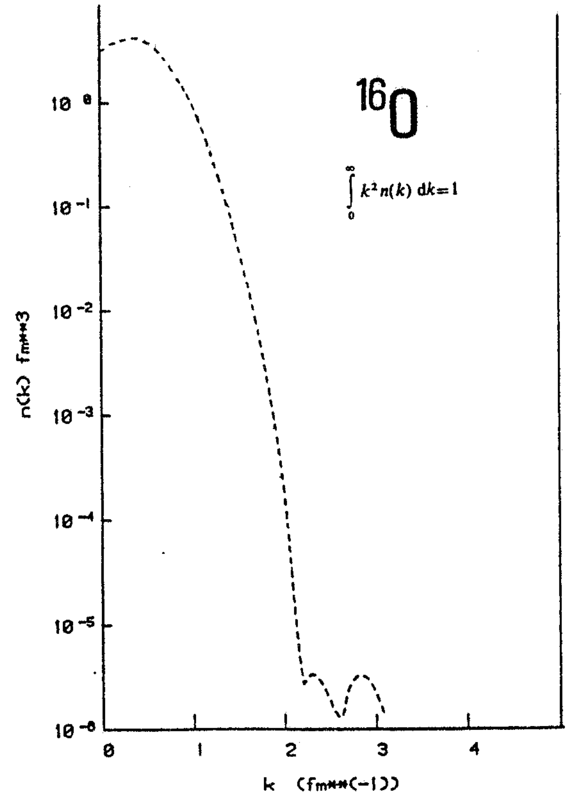

Fig. 1a

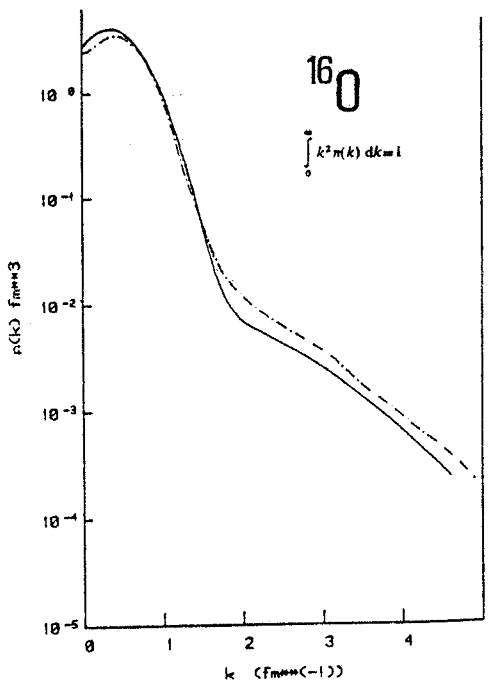

Fig. 1b

Hence we can reasonably infer that two-nucleon correlations are mainly responsible for the enhancement of $n(k)$ at high momenta.

Recent inclusive and exclusive electron scattering experiments on few-body nuclei [6-10] show evidence of short-range correlations effects at high momenta. In contrast, for light nuclei such as ^{16}O clear experimental evidence for correlations is lacking in spite of interesting results from (γ, p) reactions.

THE PHYSICAL METHOD

With regard to the current situation, both from a theoretical and experimental point of view, a measurement of $n(k)$ at high momenta in ^{16}O with the $(e, e'p)$ reaction seems opportune and feasible. In fact it is reasonable to assume that the dominant mechanism, in an electron scattering reaction selecting an initial high momentum nucleon, is the following: the incident electron interacts with one nucleon of a strongly interacting nucleon pair (this is why high momentum components exist!); then there is the emission of the struck nucleon by the usual $(e, e'p)$ mechanism, the other member of the pair retaining its initial momentum (quasi-free reaction) and escaping from the nucleus; the other $A-2$ nucleons, with a reasonable hypothesys, are in effect "spectators"; their average momentum is zero.

In this case the $(e, e'p)$ reaction, as sketched in Fig 2., is no longer strictly exclusive; there is an undetected emitted nucleon which carries all of the recoil momentum. This, together with the peculiarity to have the remaining part of nucleus at rest, yields the kinematical signature of the two-body mechanism.

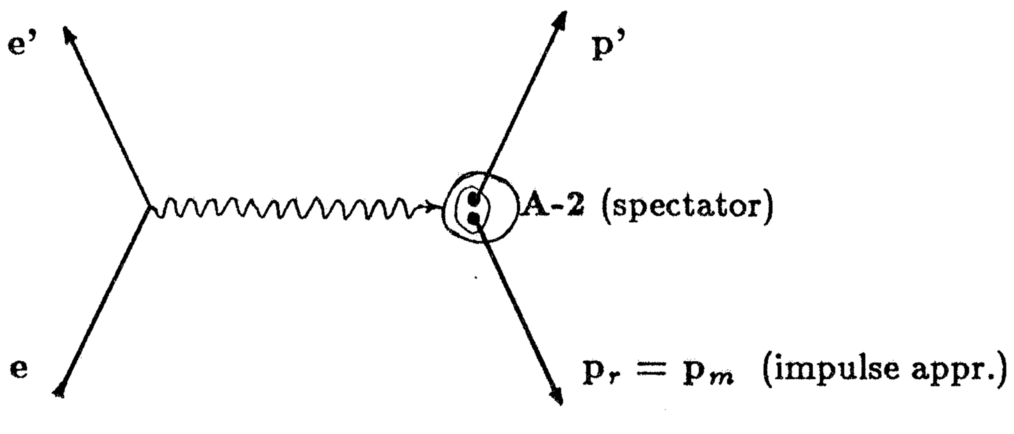

Fig. 2

One can then write the average missing energy, E_m, in terms of the recoil (missing) momentum p_m:

$$E_m = \{[(m_r^2 + p_m^2)^{1/2} + m_s]^2 - p_m^2\}^{1/2} + m_p - m_A. \tag{1}$$

m_r is the recoiling mass, m_s is the spectator $(A-2)$ mass, m_A is the target mass. This formula gives the locus, in the (E_m, p_m) plane, of the two-nucleon absorption mechanism. Note in the present case (^{16}O) that $E_m \approx 160\ MeV$ for $p_m = 550\ MeV/c$.

That the two-nucleon absorption mechanism is a good hypothesis was established at Saclay for $^3He(e,e'p)$ [8] and $^4He(e,e'p)$ [10] (Fig. 3b, 3b).

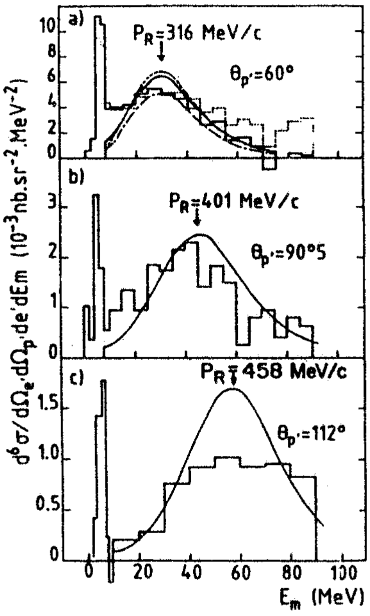

Fig. 3a

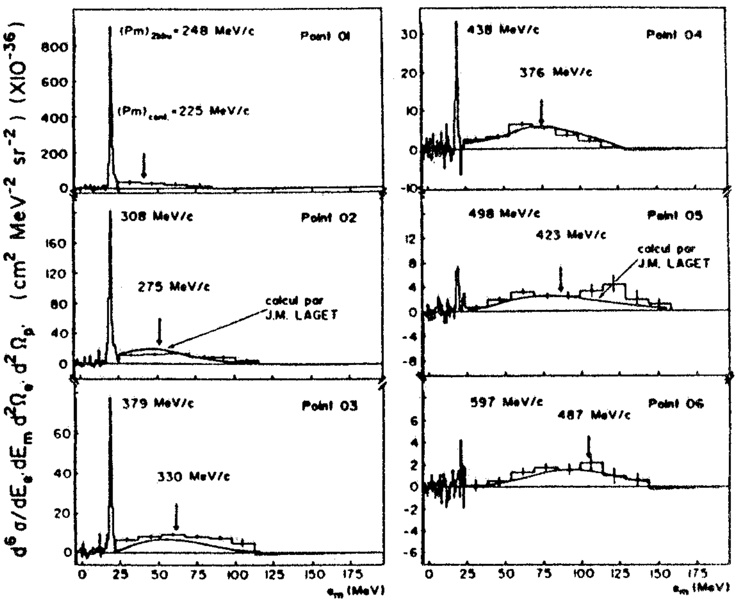

Fig. 3b

As is well known, in plane wave impulse approximation ($PWIA$) (i.e. no FSI, no MEC, ...), we can write for the $(e,e'p)$ cross-section:

$$\frac{d^6\sigma}{de'dp'd\Omega_{e'}d\Omega_{p'}} = K\sigma_{ep}S(E_m, p_m), \tag{2}$$

e' is the momentum of scattered electron, p' that of the knocked-out proton and S is the spectral function. The (proton) momentum density distribution $n(k)$ is then simply given by:

$$n(k) = \frac{n(p_m)}{Z} = \frac{1}{Z}\int_0^\infty S(E_m, p_m)dE_m, \tag{3}$$

with the normalization:

$$\int n(k)d^3k = 1. \tag{4}$$

Note that in Fig. 1a and 1b the normalitation is sligthly different.

The simplest way to take into account FSI, MEC, Δ exitation and others effects, is to perform a "model dependent analysis" in which:

$$K\sigma_{ep}S(E_m, p_m) = \frac{d^6\sigma_{exp}^{PWIA}}{dV^6} = \frac{d^6\sigma_{exp}}{dV^6}\left|\frac{d^6\sigma^{PWIA}/dV^6}{d^6\sigma^{TOTAL}/dV^6}\right|_{MODEL}. \quad (5)$$

For reliable results, the chosen model must be as complete and accurate as possible, but this procedure, as with model dependent analyses in general, is somewhat tautological!

EXPERIMENTAL METHOD

The present experiment was performed at the Saclay Linear Accelerator with the two high resolution magnetic spectrometers ("600" and "900") of the $HE1$ hall. A waterfall target, developed at I.S.S., Rome [12], was used.

In Table A are summarized the main experimental parameters.

TABLE A

e	$=$	$590\ MeV$
e'	$=$	$267\ MeV\ - 425\ MeV$
$\theta_{e'}$	$=$	$21\ deg$
p'	$=$	$400\ MeV/c\ - 615\ MeV/c$
$\theta_{p'}$	$=$	$49\ deg\ - 139.3\ deg$
$\Delta\Omega_{e'}$	$=$	$4.8\ mst$
$\Delta\Omega_{p'}$	$=$	$6.8\ mst$
ΔE_m	$\approx$	$1.5\ MeV$
Δp_m	$\approx$	$6.0\ MeV/c$
beam current	$\approx$	$5\ \mu A$
target thickness	$=$	$100. \pm 2.\ mg\ (H_2O)$

The desire to reach high recoil momenta and to span a wide E_m while maximizing the cross-section and minimizing the accidental coincidences, strongly constrains the kinematics.

We used an electron beam of 590 MeV (the maximum reliable energy available with a duty factor (DF) of 1%) as a compromise between a reasonable DF (to minimize the accidental to true event rate ratio) and a high incident electron energy (to have more freedom in choosing broader and different kinematical conditions). The scattered electron angle, $\theta_{e'}$, was fixed to the minimum possible angle (21° with the "900" spectrometer) in order to maximize the σ_{ep} cross-section. All other relevant kinematical parameters practically spanned, over the different kinematical conditions used, their own full attainable range.

We had to accept severe compromises:

i) $\omega = e - e'$ was large compared to quasi-elastic peak value and varied from one kinematics to another; this means that MEC and Δ exitation will be large and variable;

ii) $T_{p'}$ also varied from one kinematic condition to another and could not be optimized to reduce FSI;

iii) for the most relevant kinematics (i.e. E, F', G', H', in Table B and C) E_m exceeded the real pion production threshold.

We note that i) and ii) are essentially due to the limits of the Saclay facility, but iii) is intrinsic to the physics involved. We can say that we are at the limits of the capabilities of present day experimental facilities, either from the point of view of beam energy (less than ideal kinematical conditions and limitations in maximum p_m and E_m) or from DF (insufficient at high beam currents with respect to accidental rates).

In Tables B and C are reported the two different sets of kinematical conditions used.

TABLE B

" low p_m " kinematics

e	e'	$\theta_{e'}$	p'	$\theta_{p'}$	Point
590.	425.	21.0	564.0	49.0	A
590.	425.	21.0	503.0	71.0	B
590.	418.	21.0	443.0	88.1	C
590.	370.	21.0	474.0	73.0	D
590.	354.	21.0	443.0	79.2	E

TABLE C
" high p_m " kinematics

e	e'	$\theta_{e'}$	p'	$\theta_{p'}$	Point
590.	397.	21.0	614.0	91.0	A'
590.	397.	21.0	575.0	103.2	B'
590.	397.	21.0	515.0	115.2	C'
590.	397.	21.0	450.0	129.4	D'
590.	388.	21.0	400.0	139.3	E'
590.	358.	21.0	400.0	130.5	F'
590.	328.	21.0	400.0	122.4	G'
590.	298.	21.0	400.0	118.5	H'

In the Fig. 4 is shown the covered (E_m, p_m) phase-space.

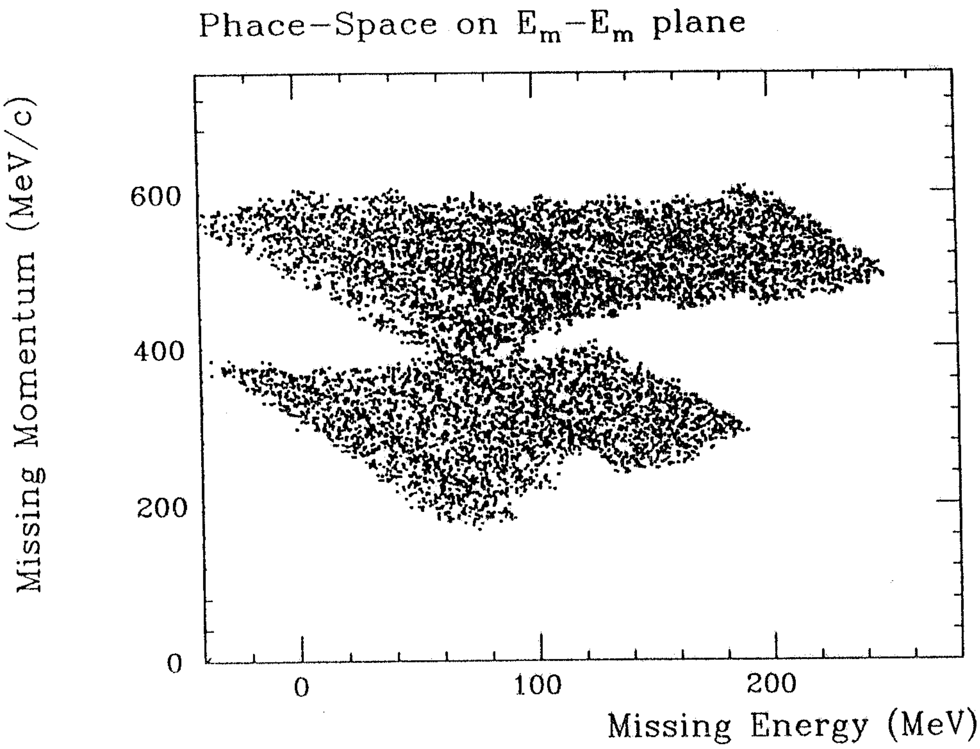

Fig. 4

EXPERIMENTAL DATA

The results we present are to be considered preliminary; refinements are expected. Beyond standard experimental corrections such as for detector efficiencies and phase-space acceptances, no other corrections were performed. We have not yet evaluated radiative (RC), FSI or MEC corrections, and we have only crudely taken into account contributions to the spectral function from real pion electroproduction.

In Fig. 5 we present the data, in the missing momentum region between 280 and 360 MeV/c, for different missing energies; $1p_{1/2}$ and $1p_{3/2}$ peaks are still clearly visible.

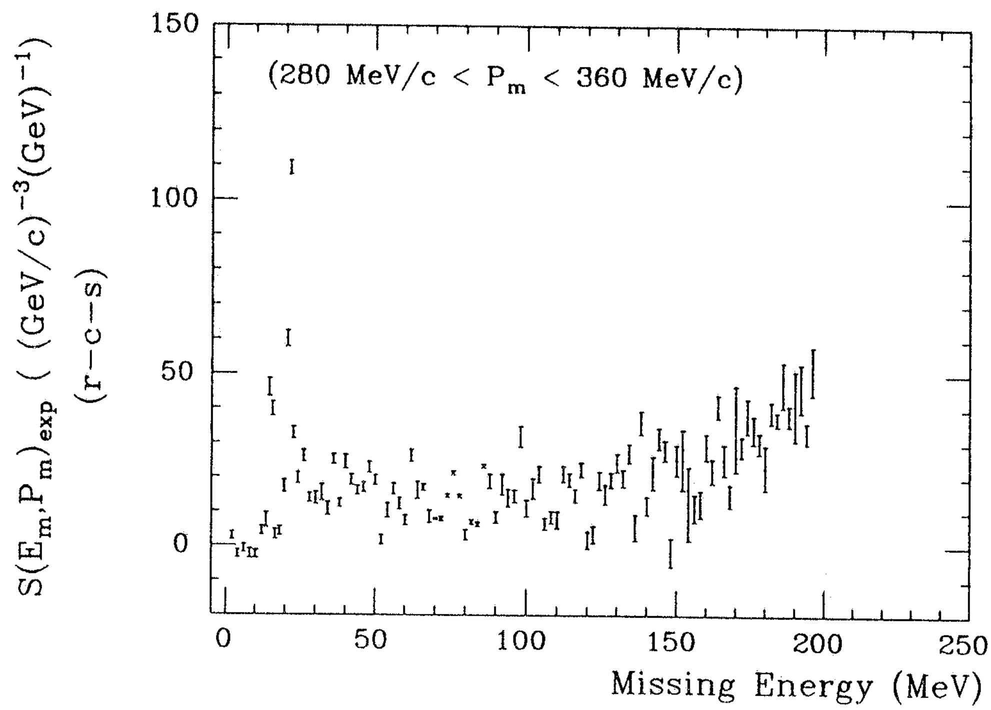

Fig. 5

In Fig. 6 the same data are grouped in wider E_m bins. The experimental cross-sections are divided by $K\sigma_{ep}$, using the $CC1$ prescription of De Forest [13], to get the "experimental" spectral function. This may be a questionable operation, but it is the only way to coherently present data taken under different kinematical conditions. Hence, following established useage, we shall call the results obtained "reduced cross-sections" (r-c-s).

In Fig. 7 are presented the r-c-s for missing momenta between 480 and 560 MeV/c.

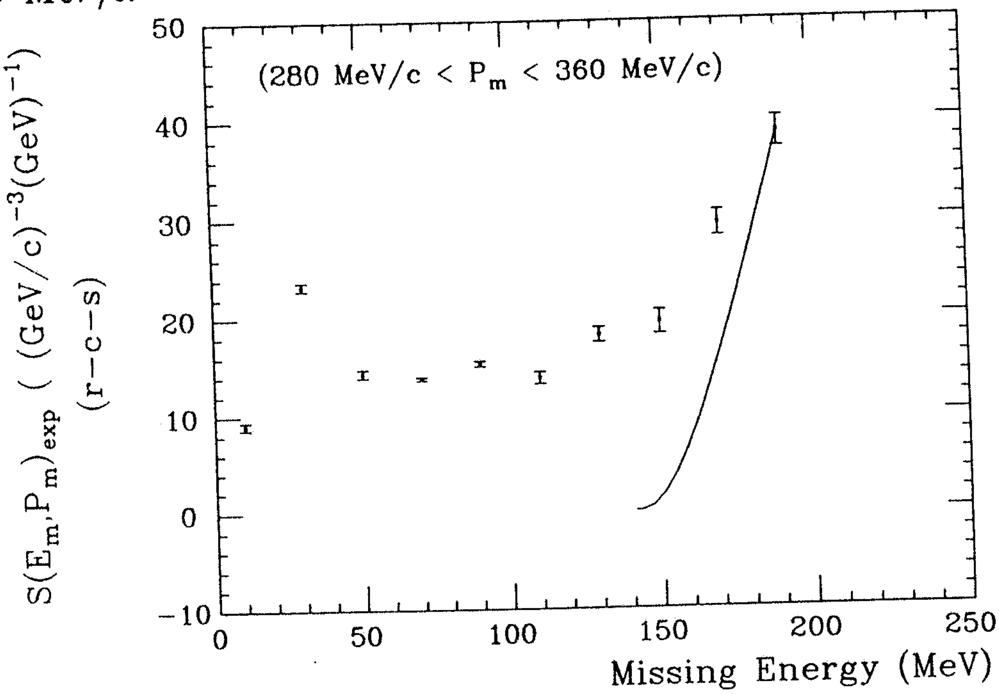

Fig. 6

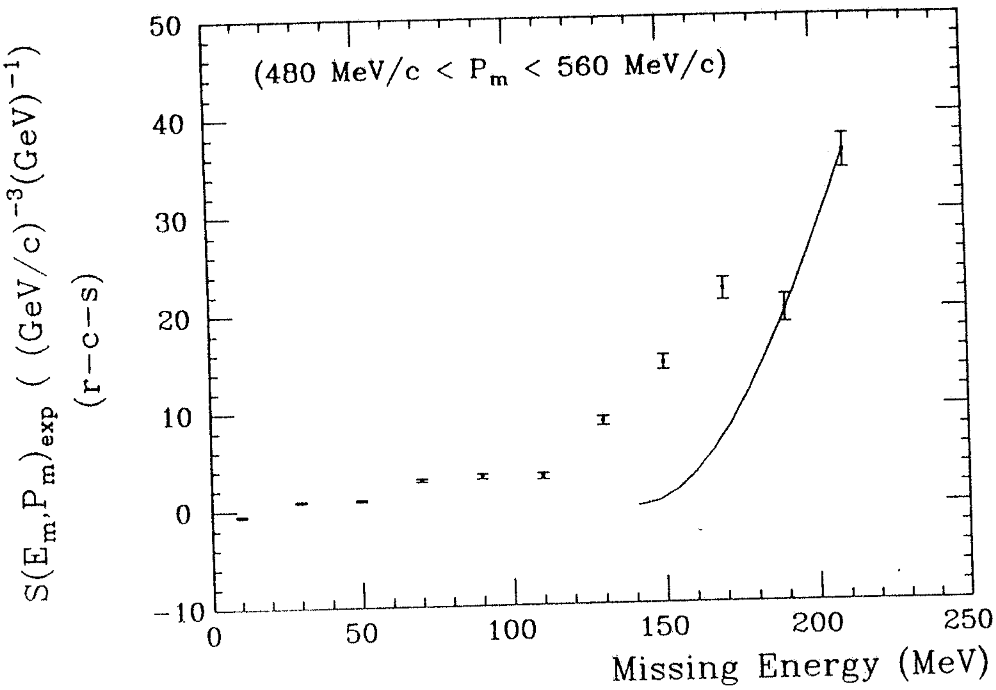

Fig. 7

We observe that in the "transition region" at $p_m \approx 310$ MeV/c (Fig. 6) there is still strength in the one-nucleon peaks and, as we do not yet expect to have a significant contribution from the two-nucleon absorption mechanism, we infer the strong rise at higher E_m (beyond the pion production threshold) to be essentially due to real pion producing reactions. On the other hand, at $p_m \approx 510$ MeV/c (Fig. 7) the one-nucleon contribution has disappeared; we can see a broad peak in the region where we expect the two-nucleon mechanism to occur ($E_m \approx 160$ MeV as from eq. 1). Here we have even greater contributions from real pions.

In order to infer a first estimate for $n(k)$ we have subtracted out the real pion contribution assuming that at higher E_m the r-c-s are dominated by real pion production. We assume also that at threshold the pion contribution is negligeable (in fact the pion contribution is artificially and increasingly enhanced by the non-pertinent division by $K\sigma_{ep}$ as E_m increases). Hence, the solid curves presented in Fig. 6 and in Fig. 7 give a kind of "upper limit hypothesis" to the contribution to the r-c-s from real pions; these curves result from a parabolic fit using the higher E_m datum and a zero value for the r-c-s and his first derivative at pion production threshold.

In Fig. 8 we show our $n(k)$ (diamonds) values after subtraction of pion contributions (obtained from integration of our two sets of data). Also shown are the calculations of ref. [2] (solid line) and ref. [11] (dashed line).

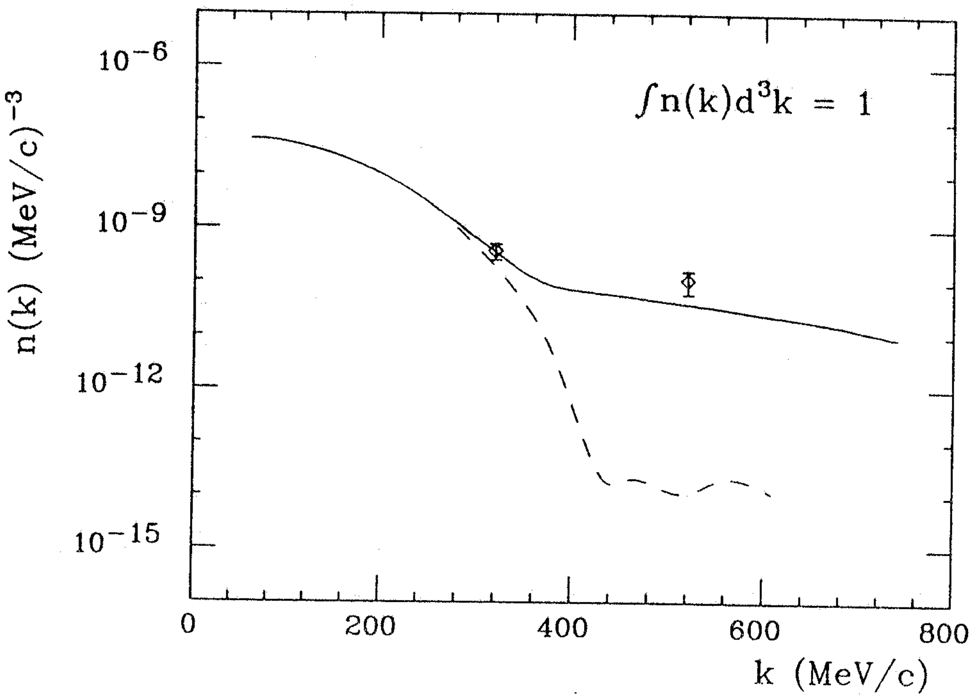

Fig. 8

CONCLUSIONS AND REMARKS

Even in this primitive and pioneering state of the art and at this provisory stage of our data reduction and analysis, it is evident that pure mean-field computations are ruled out for the high end of the momentum distributions: it is more and more evident that short range correlation do exist, and that is not possible to evaluate various nuclear properties without taking them into account. It is regrettable that with today's facilities it is not possible to do much more than that; even when our data are completely and properly reduced and analyzed with better corrections, it will be not possible to choose between the modern computations. This leaves a formidable and very interesting task for future facilities.

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