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Exclusive Electrodisintegration of Few-Body Nuclear Systems (*) (**).

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Summary. — Potentialities of exclusive electrodisintegration of few-body nuclear systems as source of information on $\mathcal{N}\mathcal{N}$ potential and on interaction effects like meson exchange currents (MEC) and isobar configurations (IC) are discussed. Results obtained at the Saclay electron linear accelerator on the (e, e'p) reaction on deuteron and ^{3}He are reviewed.

PACS. 21.40. – Few-nucleon systems.
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(**) Presented by S. FRULLANI.

1. – Exclusive electrodisintegration.

The electrodisintegration of a nucleus studied by final-state measurement of the diffused electron in coincidence with another particle emitted in the disintegration process (fig. 1*a*)) may be shown to have a cross-section given by [1,2]

$$\frac{d\sigma}{d\boldsymbol{k}'\,d\boldsymbol{p}'} = c(\varrho_{00}f_{00} + \varrho_{++}f_{++} + \varrho_{0+}f_{0+}\cos\alpha + \varrho_{+-}f_{+-}\cos 2\alpha)\,, \tag{1}$$

where c is a kinematical factor, $\varrho_{\gamma\bar{\gamma}}$ are kinematical functions depending upon the electron vertex and describing the polarization density matrix of the virtual photon, $f_{\gamma\bar{\gamma}}$ are the nuclear-system response functions to the electromagnetic probe and α is the angle between the plane defined by the incident and diffused electrons and the plane containing the emitted particle. Subscripts $\gamma\bar{\gamma}$

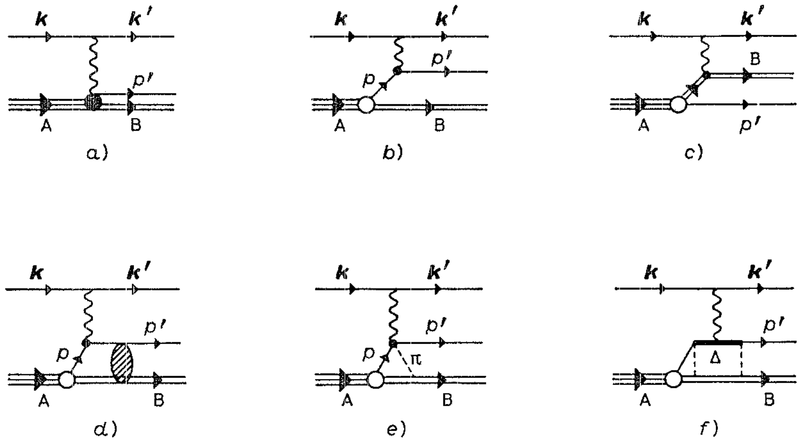

Fig. 1. – Different processes contributing in the (e, e'p) scattering *a*) on a nucleus' *b*) impulsive knock-out, *c*) exchange term, *d*) final-state interactions, *e*), *f*) examples of meson exchange currents and isobar configuration contribution.

indicate the contribution of the longitudinal (00) and transverse (++) polarization terms and of the interference longitudinal-transverse and transverse-transverse terms, respectively. As may be seen, when eq. (1) is integrated over the emitted-particle momentum, so as to obtain the inclusive cross-section corresponding to a measurement in which only the diffused electron is detected in the final state, the dependence on interference terms vanishes. The cross-section depends only on longitudinal and transverse structure functions. If we specify

(1) M. GOURDIN: *Nuovo Cimento*, **21**, 1094 (1961).
(2) T. DE FOREST: *Ann. Phys.* (*N. Y.*), **45**, 365 (1967).

the exclusive reaction to the case in which the emitted particle measured is a proton and assume that the nuclear current is only the sum of the currents of the constituent protons:

$$J^\mu_A(\boldsymbol{r}) = \sum_{i=1}^{A} j^\mu(\boldsymbol{r}_i)\,\delta(\boldsymbol{r}-\boldsymbol{r}_i)\,, \tag{2}$$

the A(e, e′p)B electrodisintegration process can be considered as the result of the virtual photon interacting directly with the emitted proton (fig. 1*b*)). According to this assumption, it can be shown (³) that from the four structure functions, a common factor, describing the virtual decay of a nucleus A in a proton with momentum p and a residual nucleus B, can be factorized out:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\boldsymbol{k}'\,\mathrm{d}\boldsymbol{p}'} = c\left|\langle\psi_{\mathrm{B}}|a(p)|\psi_{\mathrm{A}}\rangle\right|^2(\varrho_{00}g_{00}+\varrho_{++}g_{++}+\varrho_{0+}g_{0+}\cos\alpha+\varrho_{+-}g_{+-}\cos 2\alpha)\,. \tag{3}$$

This relation is usually rewritten as

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\boldsymbol{k}'\,\mathrm{d}\boldsymbol{p}'} = cS_{\mathrm{p}}(p, E)\,\sigma_{\mathrm{ep}} \tag{4}$$

where $S_{\mathrm{p}}(p, E)$ is the proton-hole spectral function that is related to the joint probability to find a proton with momentum p and removal energy E in the target nucleus (⁴). σ_{ep} is the cross-section of the electron scattering process on a bound proton with initial momentum p. Thus eq. (4) describes a process (fig. 1*b*)) in which the nuclear-structure information is entirely contained in the spectral function and can be easily deduced from the measurement of $\mathrm{d}\sigma/\mathrm{d}\boldsymbol{k}'\mathrm{d}\boldsymbol{p}'$ if σ_{ep} is assumed to be known from our knowledge of the electron-proton interaction.

Under eq. (4) validity conditions, from the measurement of initial and final electron momenta ($\boldsymbol{k}$) and ($\boldsymbol{k}'$), respectively, and of emitted proton momentum ($\boldsymbol{p}'$), the energy-momentum conservation relation enables the deduction of the internal variables p and E. It is then possible, in theory, to explore the total spectral function variability by choosing convenient kinematical configurations.

However, mechanisms other than the impulse approximation diagram of fig. 1*b*) contribute also to the scattering process. Diagrams already considered in a conventional scattering theory are depicted in fig. 1*c*) and *d*). The former illustrates the emission of a proton following interaction of the probe with the residual nucleus (exchange term), while the latter diagram takes into account the distortion suffered by the emitted proton in the nuclear field of the residual nucleus (final-state interaction).

(³) S. FRULLANI and J. MOUGEY: *Single particle properties of nuclei through* (e, e′p) *reactions*, sect. **3**, to be published in *Adv. Nucl. Phys.*

(⁴) D. H. E. GROSS and R. LIPPERHEIDE: *Nucl. Phys. A*, **150**, 449 (1970).

The nucleus being a system in which the nucleons interact, eq. (2) is not strictly valid. A gauge-invariant nuclear system built by a nucleon-nucleon ($\mathcal{N}\mathcal{N}$) potential generated by meson exchange necessitates also two-body currents ([5]). Moreover, the nucleonic current in nuclei is not restricted to being that of a free nucleon and, indeed, virtual excitation and de-excitation of nucleon resonances play a role in the nuclear force ([6]). Consequently electrodisintegration process computations must also consider meson exchange currents (MEC) and isobar configurations (IC) in nuclei. Figures 1*e*)-*f*) are examples of diagrams illustrating just such effects.

Mechanisms beyond impulse approximation destroy the simple factorized structure of eq. (4). On the other hand, they open the way to investigating, also with electrodisintegration, some much finer aspects of nuclear structure and reaction mechanisms, involving nucleonic and nonnucleonic degrees of freedom. An extended study may disentangle the various contributions to amplitude providing kinematical conditions are chosen such that the different diagrams and interference terms have a selective weight.

2. – Few-body nuclear systems.

Two- and three-body nuclei are the best suited to be investigated for the above-mentioned study. At present, it is possible to predict nuclear-state properties derived directly from realistic $\mathcal{N}\mathcal{N}$ interactions for two- and three-body systems only. Only for these nuclei do we have spectral functions for which the suitability of various potentials can be tested. Moreover, other mechanism diagrams that differ from the impulse approximation can be computed in a reliable way ([7,8]) and MEC and IC contributions deduced consistently according to the realistic potential used.

a) *Deuteron*. The spectral function gives nucleon momentum density distribution directly and is the square of the Fourier transform of deuteron wave function:

$$S(p, 2, 2) = \varrho(p) = \left|\int u(r) j_0(pr)\, r\, \mathrm{d}r\right|^2 + \left|\int w(r) j_2(pr)\, r\, \mathrm{d}r\right|^2 , \tag{5}$$

where u and w are the radial wave functions for S- and D-state, respectively. Figure 2 shows the two wave functions in momentum space, for three realistic potentials predicting different D-state percentages in the deuteron. It may be

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([5]) See, *e.g.*, R. J. Blin-Stoyle: in *Mesons in Nuclei*, edited by M. Rho and D. H. Wilkinson, Vol. **1** (Amsterdam, 1979).
([6]) A. M. Green: *Rep. Prog. Phys.*, **39**, 1109 (1976).
([7]) W. Fabian and H. Arenhovel: *Nucl. Phis. A*, **258**, 461 (1976).
([8]) J. M. Laget: *Phys. Rep.*, **69**, 1 (1981).

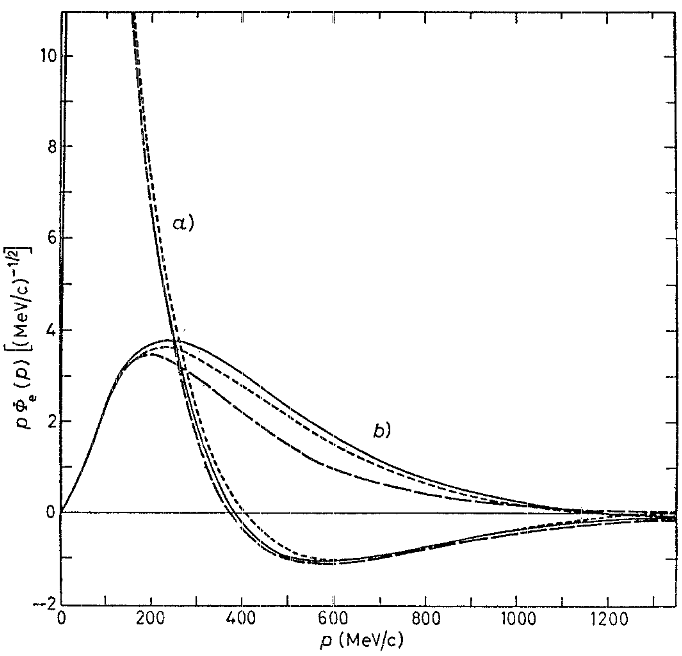

Fig. 2. – Radial part of the deuteron wave function predicted by different $\mathcal{N}\mathcal{N}$ potentials (adapted from ref. (3), sect. 5): *a*) *S*-wave, *b*) *D*-wave, ——— RSC; – – – Paris; — — — HM2. The three potentials have a *D*-state percentage of 6.47, 5.46 and 4.32, respectively.

seen that the interval of values for p in which $\varrho(p)$ is most sensitive to the potential chosen lies between 300 and 500 MeV/c. Figure 3 reports the result of the Fabian and Arenhövel analysis (9) of the transverse form factor in inclusive electrodisintegration. Curves indicate isolevel lines, in the momentum-transfer–final-system relative energy plane, of the relative changes in the form factor when MEC and IC are included in addition to the more conventional diagrams. In the exclusive reaction, structure functions will be affected diversely by MEC and IC contributions, but it is expected (9) that, for relatively high values of E_{np}, the results shown in fig. 3 may be used as a useful guide to choose kinematical conditions in which their importance is selectively relevant. It may be seen from fig. 3 that, in correspondence with the quasi-elastic peak maximum, MEC and IC are expected to be small. Therefore, this kinematical condition is particularly suited, through the study of momentum density distribution, to deduce the $\mathcal{N}\mathcal{N}$ interaction which gives the best description of the data. Unfortunately, experimental limitations, connected with the electron accelerators currently available, prevent from taking measurements in the more favourable

(9) W. Fabian and H. Arenhövel: *Nucl. Phys. A*, **314**, 253 (1979).

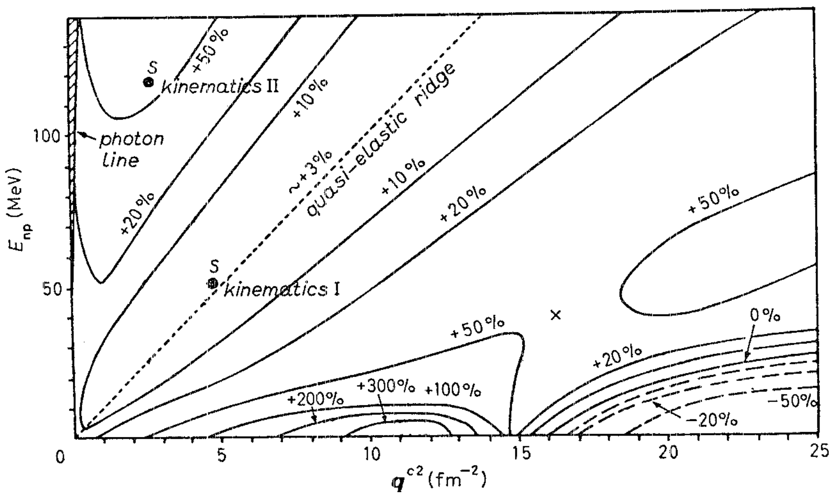

Fig. 3. – Contour plot of the changes (%) of the transverse form factor by interaction effects (MEC and IC) (adapted from ref. ([9])).

interval of p values ($300\ \mathrm{MeV}/c < p < 500\ \mathrm{MeV}/c$). Higher-energy, higher-duty-cycle accelerators are needed to overcome this limitation.

The measurements ([10]) taken at Saclay were obtained under the two kinematical conditions indicated by S in fig. 3; one in and the other out of quasi-elastic ridge kinematical conditions. The results are shown in fig. 4 and compared with different theoretical predictions. The impulse approximation analysis ([10]) is reported in fig. 4*a*). Points taken in the two different kinematic conditions follow a single curve reasonably well. In the highest-momentum part of the distribution, the considered $\mathcal{N}\mathcal{N}$ interactions give a sizable difference in the prediction of the momentum density distribution. Data obtained seem to agree better with a potential predicting a low D-state percentage.

Arenhövel's ([11]) and Laget's ([12]) respective analyses of the data, in terms of cross-sections, are reported in fig. 4*b*) and *c*). Both analyses use RSC potential and include final-state interaction, as well as MEC and IC contributions. The data are reasonably well reproduced, even if a systematic deviation of the data from the curves is observed at the highest momenta, more so in the Laget analysis. In order to size up the importance of MEC and IC contributions found in computations, we quote the results of Arenhövel ([11]). In kinematics I the cross-section is increased by at most 15 %, while in kinematics II the ef-

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([10]) M. Bernheim, A. Bussière, J. Mougey, D. Royer, D. Tarnowski, S. Turck-Chieze, S. Frullani, G. P. Capitani, E. De Sanctis and E. Jans: *Nucl. Phys. A*, **365**, 349 (1981).

([11]) H. Arenhövel: *Nucl. Phys. A*, **384**, 287 (1982).

([12]) J. M. Laget: private communication. The results shown are preliminary.

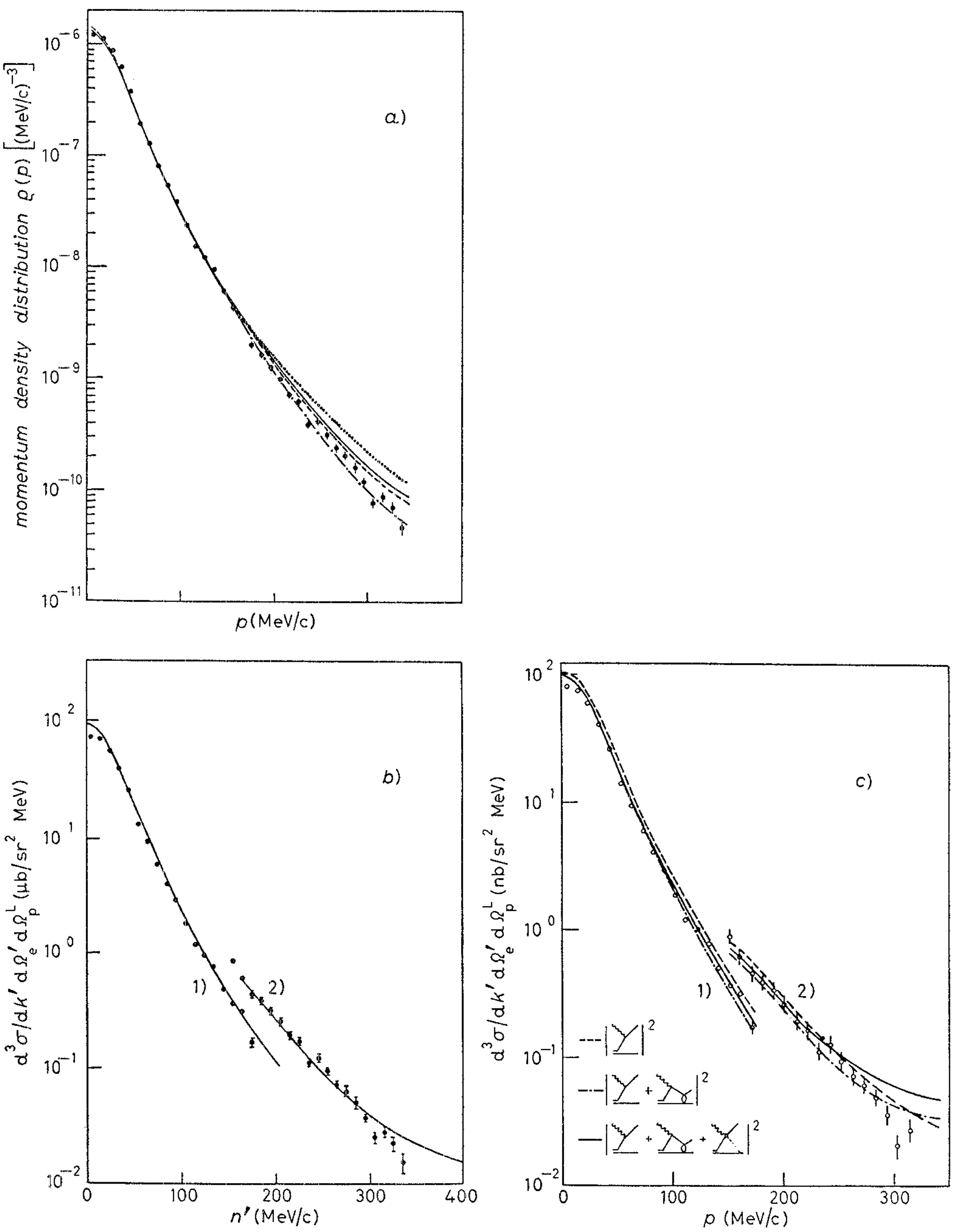

Fig. 4. – *a*) Impulse approximation analysis of the d(e, e'p)n reaction (from ref. (10)): $E = 500$ MeV; ··· Hulten-Yamaguchi, —— RSC, - - - Paris, —·—·— HM2; *b*) and *c*) complete analysis of Arenhövel (ref. (11)) and Laget (ref. (12)): 1) kinematics I: $k' = 395$ MeV/c, $q^L = 450$ MeV/c; 2) kinematics II: $k = 353$ MeV/c, $q^L = 350$ MeV/c.

fect increases from about 8% at the lowest momentum to about 54% at the highest one measured. The theoretical computation sensitivity to the choice of the $\mathcal{N}\mathcal{N}$ interaction has been studied by ARENHÖVEL (11) for RSC, Paris and de TourreilSprung potentials. The difference in results, in the momentum interval considered, has been found to be 10% at the most. Analysis with the HM2 potential, which, according to fig. 2, would be expected to give a greater difference, is lacking.

A third set of measurements has recently been taken under kinematic condition defined by $E_{np} = 179$ MeV, $q^{c2} = 1.66\ \text{fm}^{-2}$, thus beyond the region shown in fig. 3. In this condition the effect of IC is expected to be very important (11). In terms of the initial momentum, the explored region is just between 300 and 500 MeV/c and covers the interval in which, in terms of impulse approximations, an approximate factor of two (13) is expected between RSC and HM2 results. The aim is, on the one hand, to test the size of the IC contribution and, on the other hand, to check if, when all processes are considered in addition to the impulse approximation, a sizable difference still remains between the results expected using different $\mathcal{N}\mathcal{N}$ interactions. The respective data analysis is in progress.

b) ^{3}He. Electrodisintegration studied by means of the (e, e′p) reaction has two channels, corresponding to the case in which the residual system is either a bound deuteron (2-body break-up) or an unbound neutron-proton pair (3-body break-up). By definition (see eqs. (3) and (4)) the spectral function is the square of the overlap integral, in momentum space, between the target ground state and the residual nucleus.

At present, three computations of the spectral function based on realistic $\mathcal{N}\mathcal{N}$ interactions exist. Two of them, DIEPERINK *et al.* (14) and MEIER *et al.* (15), use a ^{3}He wave function derived according to the Faddeev technique, while the third one (CIOFI *et al.* (16)) is computed by using the variational method. Figure 5 shows the spectral function as first quoted as an example. The strength of the 2-body break-up is localized at $E=5.5$ MeV (corresponding in the figure to $E' = -2.2$ MeV), while the 3-body break-up spreads over the region beyond the threshold at 7.7 MeV ($E' = 0$). At the moment, contrary to the case for the deuteron, no systemic analysis has been carried out to study the relative im-

(13) S. FRULLANI and J. MOUGEY: *Single particle properties of nuclei through* (e, e′p) *reactions*, sect. **8**, to be published in *Adv. Nucl. Phys.*
(14) A. E. L. DIEPERINK, T. DE FOREST, I. SICK and R. A. BRANDEBURG: *Phys. Lett. B*, **63**, 261 (1976).
(15) H. MEIER-HAJDUK, CH. HAJDUK, P. U. SAUER and W. THEIS: *Nucl. Phys.*, to be published.
(16) C. CIOFI DEGLI ATTI: *Proceedings of the Miniconference on the Study of Few-Body Systems with Electromagnetic Probes*, edited by C. CIOFI DEGLI ATTI, E. PACE and G. SALMÉ (Amsterdam, 1981), to be published.

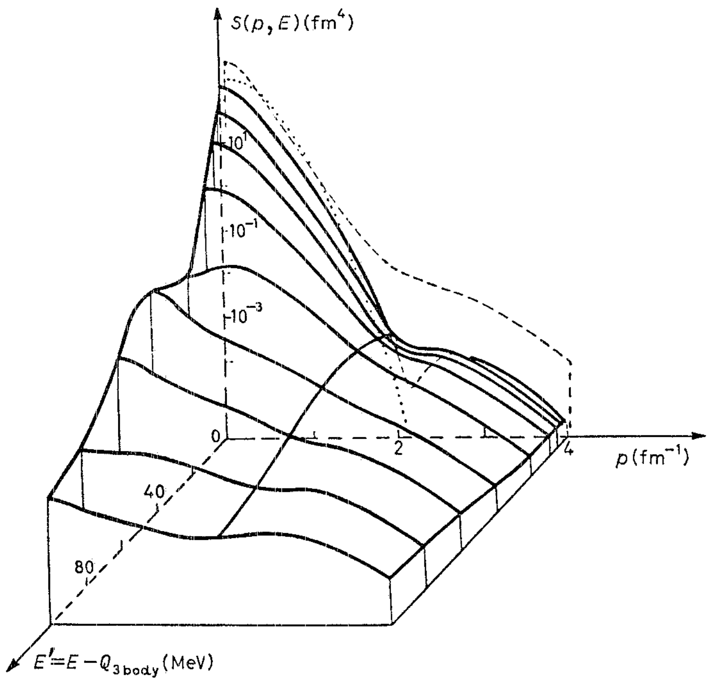

Fig. 5. – ^{3}He spectral function (adapted from ref. (14)).

portance of the different diagrams contributing to the amplitude in the general treatment of the reaction in different kinematical conditions.

Measurements (17) have been taken in two different kinematic configurations corresponding, in terms of momentum transfer and centre-of-mass energy of the final hadronic system, more or less to the conditions considered for the deuteron. Figure 6 reports such data together with the relative impulse approximation analysis. The momentum density distribution $\varrho(p) = S(p, 5, 5)$ corresponding to the 2-body break-up is reported in *a*), whereas *b*) shows the momentum density distribution for the 3-body break-up channel obtained by integrating the spectral function from threshold up to $E = 20$ MeV. The data are compared with results from both Faddeev and variational computations that use the RSC potential. The computation sensitivity to the choice of the $\mathcal{N}\mathcal{N}$ interaction has been studied (15) for RSC and Paris potentials and it was found that the results, in the considered range of p and E, differ by less than 10 %. The agreement shown in fig. 6 is satisfactory, even if in the case of 2-body break-up a systematic deviation is observed at high momentum values.

(17) E. Jans, P. Barreau, M. Bernheim, J. M. Finn, J. Morgenstern, J. Mougey, D. Tarnowski, S. Turck-Chieze, S. Frullani, F. Garibaldi, G. P. Capitani, E. De Sanctis, M. K. Brussel and I. Sick: *Phys. Rev. Lett.*, **49**, 974 (1982).

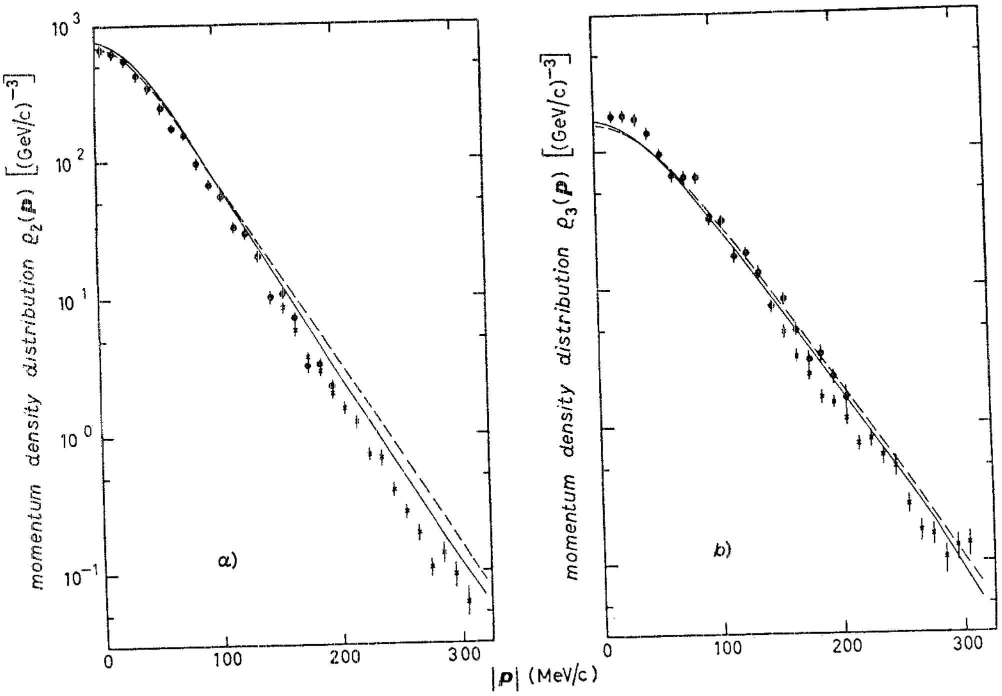

Fig. 6. – Impulse approximation analysis of *a*) 2-body and *b*) 3-body ($E < 20$ MeV) break-up channels of the (e, e′p) reaction on ^{3}He. Full and dashed curves represent computed results obtained with the spectral function of Dieperink *et al.* ([14]) and Ciofi degli Atti *et al.* ([16]), respectively. Meier *et al.* ([15]) spectral function gives the same results as that of ref. ([14]) (from ref. ([17])). • kinematics I, × kinematics II.

However, the agreement becomes very poor for the 3-body break-up when the data measured at $E > 20$ MeV are considered. The comparison between a preliminary reduction of experimental data and the spectral function computed by Meier *et al.* ([15]) shows a significant discrepancy, especially at low momentum values ([18]).

Figure 7 reports Laget's analysis ([19]) of data for $E < 20$ MeV, with the additional processes besides the impulse approximation diagram included. Agreement seems better in 2-body rather than 3-body break-up, where a discrepancy incompatible with the statistical accuracy of data is observed. In the case of a 2-body channel, the effect of the final-state interaction is to decrease the cross-sections by a maximum of 10 % and 40 % for kinematics I and II, respectively. The interaction of the emitted proton with another nucleon of the residual system

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([18]) E. Jans: Thesis, Amsterdam (1982).
([19]) J. M. Larget: *Proceedings of the Workshop on the Use of Electron Rings for Nuclear Physics Research in Intermediate Energy Region, Lund, October 5-7, 1982*, and private communication.

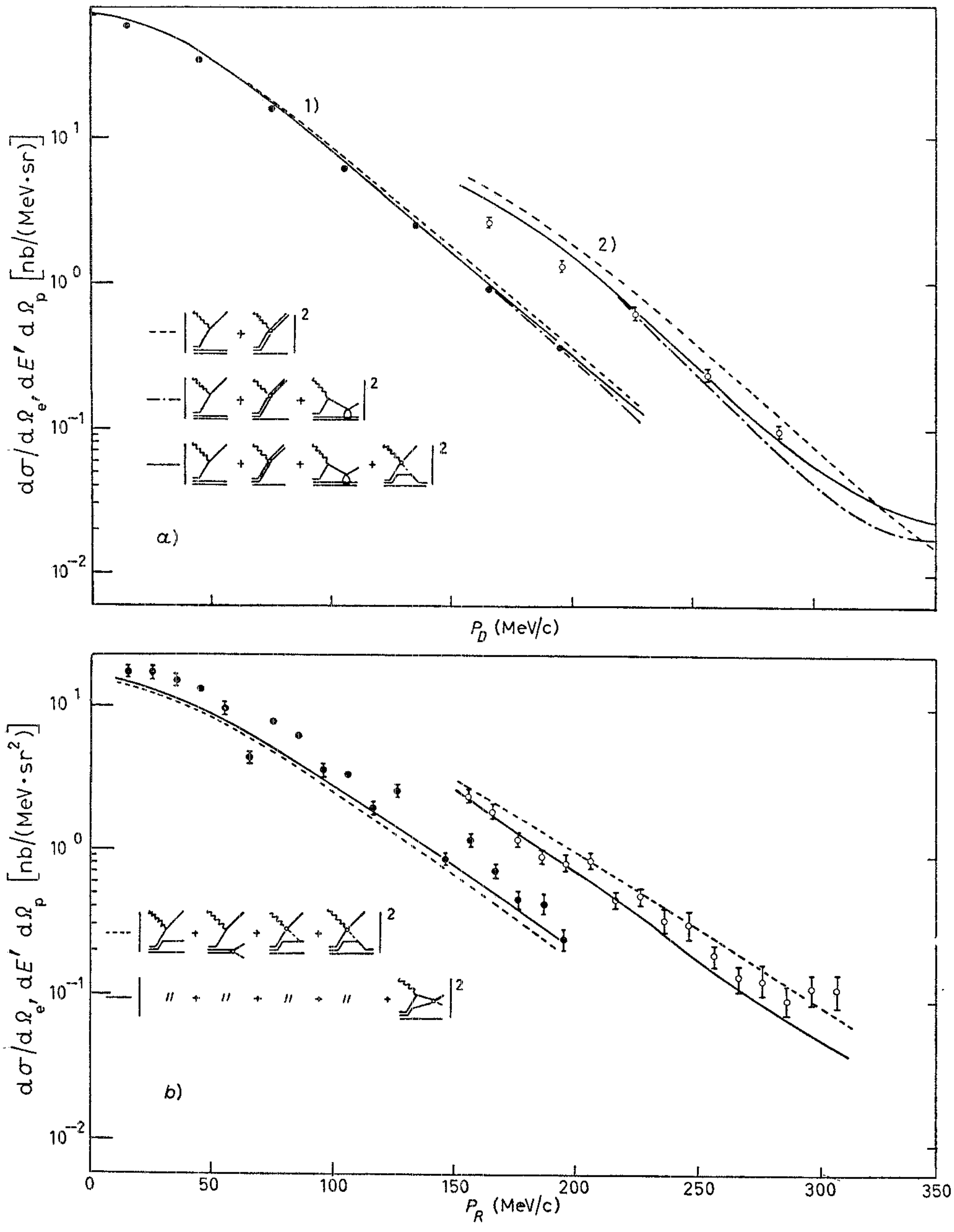

Fig. 7. – Comparison between theoretical ([19]) and experimental ([17]) cross-sections of the (e, e'p) reaction on ^{3}He (adapted from ref. ([19])). *a*) ^{3}He(e, e'p)d, 1) kinematics I, 2) kinematics II; *b*) ^{3}He(e, e'p)pn.

pair provides a contrasting result in the case of 3-body break-up. The cross-section increases by 10 % at the most for kinematics I and decreases by a maximum of 40 % for kinematics II. The effect of meson exchange currents is to increase the cross-section by at most 5 % and 20 % in the two kinematics, respectively.

As afore said, data so far obtained call for this analysis to be extended to $E > 20$ MeV.

3. – Conclusions.

At this stage of a complex experimental program that will still go on for several years, centred on the study of few-body nuclear systems with exclusive electrodisintegration, it is possible to delineate some reached points.

The agreement shown in fig. 4*b*), *c*), between the experimental data and two different analyses that take into account all the contributions expected to enter in the amplitude of the reaction, gives confidence on the realiability and possibly on the unambiguity in treating nonconventional effects as MEC and IC. This should be confirmed by other checks in different kinematical conditions and clarifications must be found on the existing discrepancies between data and computed distribution in the ^{3}He case (fig. 7). If a consensus is reached that these effects can be controlled with accuracy, tight limits may be put on the best-suited $\mathcal{N}\mathcal{N}$ potential, studying the reaction in convenient kinematical regions.

Channels with the residual system in continuum must be particularly well studied for the comprehension of reaction mechanisms and also to possibly enlight the problem of deep hole states in heavier nuclei.

● RIASSUNTO

Si discutono le possibilità che offre lo studio dell'elettrodisintegrazione di sistemi nucleari a pochi corpi per fornire informazioni sul potenziale nucleone-nucleone e sugli effetti d'interazione quali le correnti di scambio (MEC) e le configurazioni isobariche (IC). In tale contesto sono discussi i risultati ottenuti all'acceleratore lineare di elettroni di Saclay nello studio della reazione (e, e'p) su deuterio ed ^{3}He.

Эксклюзивное электрорасщепление ядерных систем, состоящих из нескольких частиц.

Резюме (*). — Обсуждаются возможности эксклюзивного электрорасщепления ядерных систем, состоящих из нескольких частиц, как источник информации о $\mathcal{N}$-$\mathcal{N}$ потенциале и эффектах взаимодействия, подобных MEC и IC. Анализируются результаты, полученные на электронном линейном ускорителе Сакле, для (e, e'p) реакции на дейтерии и ^{3}He.

(*) *Переведено редакцией.*