FR8100569

SOME ISSUES IN PHOTONUCLEAR PHYSICS

C. Tzara
DPh-N/HE, CEN Saclay, BP 2, 91190 Gif-sur-Yvette, France

Let us consider the simplest processes induced by the electromagnetic interaction the emission or absorption of one photon. Their cross sections are unambiguously related to definite characteristics of the target, the charge and current form factors associated with the target transition $|a\rangle \rightarrow |b\rangle$:

$$\langle b|\int d^3r\, e^{i\vec{q}\cdot\vec{r}}\rho(r)|a\rangle \quad \text{and} \quad \langle b|\int d^3r\, e^{i\vec{q}\cdot\vec{r}}\,\vec{\epsilon}\cdot\vec{J}(r)|a\rangle$$

with $\vec{\epsilon}\cdot\vec{q} = 0$

In reality what is measured is different because higher order e.m. effects are unavoidable :

(i) in photonuclear reactions, the radiative corrections, which are indeed negligible as long as the velocity imparted to the target or the emitted particles is small ;

(ii) in contrast, the corrections to Born approximation in electron scattering :

- distortion of the electron wave,
- two-photon exchange,
- radiative corrections,

are far from negligible and pose eventually difficult problems.

For the purpose of the following discussion, these will be considered as correctly handled, so that the final outcomes of the measurements are really form factors. At high energy, the so-called shadow effect comes into play. Whatever model is invoked to interpret it, the process is a one-photon and, as such, provides a form factor.

It is also known that by equating the form factors to the Fourier transforms of the charge and current operators taken between intrinsic nuclear states, one assumes implicitly that the final nuclear state with total momentum q : $|b,q\rangle$ is identical with $|b,0\rangle\, e^{i\vec{q}\cdot\vec{R}}\, e^{-i\omega t}$, where R is the nucleus center-of-mass coordinate. The smaller is the recoiling velocity, $(q/Am_c)^2 \ll 1$, the better is the approximation. For heavy nuclei, this condition is insured in practice, because of the limit to momentum transfer set by the smallness of the cross section. For very light nuclei, however, this condition is violated in some existing experiments; some scrutiny is required when analyzing the data in term of spatial densities.

With these reservations one may say that a photo- or electro-reaction cross-section provides a measure of the Fourier transform of a diagonal or a transition density of the target nucleus. Weak interaction gives similarly form factors, but with much less flexibility, whereas the reactions mediated by the strong interaction

Workshop on nuclear physics with real and virtual photons
from collective states to quarks in nuclei.
Bologne, Italy, November 25 - 28, 1980.
CEA - CONF 5554

are testing the properties of the "target + projectile" system.

Such a presentation of the Nuclear Electromagnetic Interaction, which emphasizes its conceptual simplicity, should not mask the complexity, and related difficulties, which arise when a microscopic interpretation of the measured form factors is attempted.

The root of the difficulty is in that the chosen nuclear constituents are always composite systems.

At the simplest level, the description of the nucleus is made in terms of nucleonic degrees of freedom. Their mutual and Electromagnetic Interactions contain phenomenological ingredients: an N-N potential, a model for the charge and current densities.

In a further step, the forms of these interactions are determined from the mesons-nucleon dynamics.

In order to handle processes above the mesons threshold, the meson coordinates must be kept explicitly in the formalism. Still the meson-nucleon dynamics is largely in a phenomenological form. One must accept this unsatisfactory state of affair as long as a fundamental theory of structureless constituents, if any, is not operative.

The first approach noted above is fitted to a large class of properties of most nuclei. The theory of their Electromagnetic Interaction utilizes as much as possible the continuity equation applied to the charge and current density operators :

$$\vec{\nabla}_r \cdot \vec{J}(r) = -i/\hbar c \, [\, H, \rho(r)]$$

It must not be forgotten that it is an operator equation acting, through the nuclear Hamiltonian H, on the nucleon coordinates. Otherwise one is led to untenable conclusions. For instance, following Foldy, one obtains its formal solution :

$$\vec{j}(r) = \frac{i}{4\pi\hbar c} \vec{\nabla}_r \cdot \int \frac{[\, H, \rho(r')]\, d^3r'}{|\underline{r} - \underline{r}'|}$$

whose long range behaviour is contrary to all expectations. Furthermore, the current matrix element of this irrotational current :

$$\sim \langle b | \int d^3r \, e^{i \underline{q}\cdot\underline{r}} \, \vec{\epsilon} \cdot \vec{j}(r) \, | a \rangle$$

would be identically zero, the solenoidal part of the current surviving alone! The valid procedure is to manipulate the operator inside the matrix element in such a way that it splits in two pieces having opposite parities for a given angular momentum, and to use in the electric part the continuity equation. In the version by Foldy [1], the electric matrix element takes the form :

$$-i/\hbar c \langle b | \int_0^1 ds \int d^3r \, e^{i s \underline{q}\cdot\underline{r}} \, \vec{\epsilon} \cdot \vec{r} \, \rho(r) \, | a \rangle (E_b - E_a)$$

One notes that the retardation factor is somewhat damped by the integration over s .
The magnetic one reads :

$$i \langle b | \int_0^1 s\,ds \int d^3r\, e^{is\mathbf{q}\cdot\mathbf{r}} (\vec{\epsilon} \times \vec{q}) \cdot (\vec{r} \times \vec{j}(r) | a\rangle + i \langle b | \int d^3r\, e^{i\mathbf{q}\cdot\mathbf{r}} (\vec{\epsilon} \times \vec{q}\,) \cdot \vec{m}(r) | a\rangle$$

These expressions apply equally to the virtual photon absorption, with ν fixed by the electron kinematics.

The predicted value of an electric matrix element depends therefore on the form chosen for $\rho(r)$ in term of nucleon coordinates, on the wave function of the initial and final states and on the computed eigenenergies E_a and E_b (and not on the experimental ones). A striking evidence for its dependence on the nuclear Hamiltonian is provided by the electric dipole sum rule, whose value is porportional to the expectation value of the double commutator in the ground state :

$$\langle a | \left[\int d^3r (\vec{\epsilon}\cdot\vec{r}\,) \rho(r), \left[\Sigma t_i + \Sigma V_{ij} , \int d^3r\, \vec{\epsilon}\cdot\vec{r}\, \rho(r) \right] a \right\rangle$$

The computation of a magnetic matrix element requires additional choices, that of the form of $\vec{m}(r)$ and of $\vec{j}(r)$, insofar as the latter is not determined by, but only constrained by the continuity equation.

Is it possible from the analysis of the data on electromagnetic nuclear processes to determine H, $\rho(r)$ and $\vec{j}(r)$ without appealing to the underlying level? Actually the question, in its generality, is far too ambitious. But partial answers do emerge, principally from the consideration of the electric processes and charge form factors.

1. The experimental value of the photon absorption cross section, integrated up to about 140 MeV, reaches approximately 1.8 times the T.R.K. value and 1.4 for the deuteron [2]. This finding is consistent with the following assumptions :

i) The long wavelength limit is a good approximation.
ii) The dipole absorption above 140 MeV contributes negligibly to the integrated cross section.
iii) The charge operator is well approximated by its impulse approximation, non relativistic, one-body form: $\rho_1(r) = e/2 \sum_i \{ \rho_S(r-r_i) + \tau_3^i \rho_V(r-r_i) \}$
iv) The NN potential contains an exchange part.

2. The photodisintegration of the deuteron up to $\sim$ 140 MeV confirms that :

i) The process is dominated by the E1 absorption.
ii) The charge density operator $\rho_1(r)$ is a good approximation of the complete one, $\rho(r)$.

3. The quasi-free charge scattering on the deuteron is compatible with the assumptions :

i) $\rho(r)$ has the one-body form $\rho_1(r)$ complemented with relativistic corrections, necessitated by the momenta reached in this type of experiments ($\sim$ 350 MeV/c) [3].

ii) The wave functions are solutions of a "realistic" NN potential, R.S.C. or Holinde-Machleidt II for instance.

4. The monopole charge form factor of the deuteron, which dominates at moderate momentum transfer the small angle electron scattering, supports the preceding conclusions.

5. The experimental value of the deuteron quadrupole moment $Q = 0.286 \pm 0.0015$ fm^2, considerably more precise than the above-mentioned experimental quantities, is correctly reproduced with $\rho(r) = \rho_1(r)$ (the relativistic terms barely contributes) and a wave function with P_D = 6 to 7 %, with a notable exception, the wave function derived from the H.M. II potential, which yields P_D = 4.3 % and Q_d = 0.287 fm^2 [4].

6. Similar data on the ^{3}He generally confirm the picture obtained from the data on the deuteron, at least at moderate momentum transfers.

7. In heavier nuclei, the precise experimental charge form factors are well predicted again by assuming $\rho(r) = \rho_1(r)$ and wave functions computed by Gogny.

The accuracy of the data concerning electric transverse transitions is only 5 to 10 % and 1 to 5 % for the charge form factors. Within these uncertainties, it seems that the one-body part of the charge operator suffices to predict correctly the experimental data. One notes even that the deuteron quadrupole moment is better reproduced without meson-exchange corrections [5], especially with the H.M. II wave function (which, incidentally, gives a better agreement with the measured cross section for the deuteron photodisintegration at forward angle [6]).

The magnetic nuclear interaction is generally said to be "more" sensitive to the meson-exchange current. In the present phenomenological framework, it means that $\vec{m}(r)$ and $\vec{j}(r)$, or one of these two operators, contain many-body parts. Let us first try the assumption that, like $\rho(r)$, $\vec{m}(r)$ is well approached by its one-body part :

$$\vec{m}_1(r) = \frac{e\hbar}{2Mc} \frac{1}{2} \sum_i \left\{ \mu_s(r-r_i) + \tau_3^i \mu_v(r-r_i) \right\} \vec{\sigma}_i$$

and, therefore, that the meson-exchange corrections arise in the convective magnetization density. Now, from the exchange character of the NN potential, it ensues that the continuity equation applied to the one-body charge density operator $\rho_1(r)$ is consistent with a current containing a one- and a two-body part :

$$\vec{\nabla}_r \left\{ \vec{j}_1(r) + \vec{j}_2(r) \right\} = -i/\hbar c \left[\sum t_i + \sum v_{ij} , \rho_1(r) \right]$$

8. The magnetic moment of the deuteron receives from $m_1(r)$ the contribution :

$$\mu_1 = (\mu_p + \mu_n)(1 - 3/2\, P_D)$$

and from the orbital magnetization associated with the one-body current $j_1(r) =$

$$= e/2Mc \sum_i \left\{ \vec{p}_i\, \rho(r-r_i) + \rho(r-r_i)\, \vec{p}_i \right\} \ : \ \mu_1' = 3/4\, P_D$$

In the frame of the impulse approximation, one must add the contribution $\Delta\mu_{rel.}$ from the relativistic terms in the one-body current. Its exact value requires the knowledge of the wave function. Assuming for the N-N potential the H.M. II solution, which fixes P_D = 4.3 % and equating the one-body contribution to the experimental value :

$$\mu_1 + \mu'_1 + \Delta\mu_{rel} = 0{,}8574 \quad (N.M.)$$

one gets

$$\Delta\mu_{rel} = -0{,}0022$$

The H.M. II potential was not included in the systematic analysis made in ref. [5]. But, as a general rule, to smaller P_D correspond smaller corrections to the magnetic moment due to relativistic nucleon motion and to meson-exchange current. This points again towards the adequacy of the H.M. II interaction ; this should be confirmed by the calculation of the various corrections. This N-N interaction should also be used in the estimation of the thermal neutron radiative capture by the proton and of the cross section for the threshold electrodisintegration.

At any event, it is clear that an extensive set of precise data on electric and magnetic nuclear processes is very efficient in discriminating between the possible NN potentials and forms of nuclear currents, provided a comparable precision is reached by the theory. This means calculating the contributions of the N-body currents, which, in the phenomenological framework, are not all determined by the continuity equation. In particular, starting from the one-body charge and spin densities $\rho_1(r)$ and $\vec{m}(r)$, it is only possible to get an information on the part of the current linked to $\rho_1(r)$ by the continuity equation. For instance

$$V_{ij} = c\ \vec{\tau}_i \cdot \vec{\tau}_j\ (\vec{\sigma}_1 \cdot \vec{\nabla}_{r_{ij}})(\vec{\sigma}_j \cdot \vec{\nabla}_{r_{ij}})\ f(r_{ij})$$

the O.P.E. potential, yields the two-body current identified to the "pair" and the exchanged-meson current. But terms like the many-body parts of the charge and spin density operators and the divergenceless currents are neither determined nor ruled out by the continuity equation.

The methods used in practice for obtain them in a definite form resorts to an underlying theoretical model, generally that of nucleons interacting by exchanging mesons. The calculations proceed by evaluating the contributions of a reasonable set of processes, where the photon is coupled to the different particles considered in the model. This approach is efficient, it is fitted to incorporate the nucleon isobars degrees of freedom, and has the advantage of being applicable to high energy nuclear states, where the mesons appear as real particles [7]. But great care must be exercised to avoid inconsistencies of various type [8,9,10] : violation of gauge invariance due to the selection of a set of processes, use of nuclear wave functions incompatible with the nucleon-mesons dynamics utilized in the calculation of the E.M. interaction etc...

The requirement of consistency is sometimes considered as academic because, after all, at the present stage of accuracy of the experimental data, the M.E.C. and other corrections are precisely enough evaluated.

But whenever one faces precise experimental data (the deuteron moments, for example) or peculiar experimental conditions (for instance, far from the nucleon quasi-free kinematics), it is necessary, and perhaps rewarding, to respect the consistency requirement.

The case of complex nuclei ($A \geqslant 3$) intensifies the difficulties. Applying to them the procedure adapted to the deuteron presupposes that the potential, in the nuclear Hamiltonian, is merely the sum of the free NN potential for all nucleon pairs. But in principle, the NN interaction in a nucleus should differ from the form it assumes in an isolated two-nucleon system. Indeed, the best many-body calculations using a realistic N-N potential fail to reproduce important nuclear characteristics. For the A=3 nucleus, the binding energy and the proton density are not correctly predicted (assuming that a central depression in the ^{3}He proton density truly exists [11]). For heavier nuclei, the predicted density is 40 % above the measured one [12]. These observations seem to indicate that the nuclear Hamiltonian is really more complicated than a simple extrapolation of the two-body Hamiltonian. Therefore these many-body currents which are participating in the continuity equation differ from those derived in the case of the deuteron ; it is tempting to conclude that the corrections to Impulse Approximation are of a different kind than in the two-nucleon case.

This reasoning may be delusive. The fact that in the reduced Hamiltonian the nucleon interaction looks different does not necessarily mean a change in the "full" Hamiltonian from which the reduced one is obtained by a unitary transformation eliminating the mesonic degrees of freedom. In the interest of further developments, it is even recommended to stick to one definite "full" Hamiltonian, valid for any nucleus. In this case, the expressions derived for the many-body currents and already tested on the two-nucleon systems are useful in every nuclei. Of course, the wave functions needed to compute the current matrix elements must be compatible with the full Hamiltonian, or, in other words, the reduced Hamiltonian must originate from the full one.

Apart from the Hamiltonian using the free NN potential, not successful as we saw above, there exists for the heavy nuclei an effective one derived by Gogny and collaborators by fitting various properties of a few spherical nuclei and of the infinite nuclear matter. It is difficult to perceive its link with the more fundamental level. At least is it successful in predicting correctly diagonal and transition charge densities in a number of nuclei [13]. It would be of interest to systematically subject this model to the test of transverse electric and magnetic processes.

As for the A=3 nucleus, attempts are presently made to improve the theory by adding a three-nucleon potential to the Hamiltonian, with mitigated success [14].

One may ask, however, if it is licit to modify the reduced Hamiltonian by simply adding multi-nucleon forces without changing the two-nucleon potential. In the derivation of the effective potential from the original interaction, the nucleus eigenenergies enter explicitly. Its expression depend therefore on the particular nucleus under investigation. The question is whether this dependence is weak or not. A thorough study of the tri-nucleon system in the framework of meson-nucleon field theory should enlighten the point.

The nuclear underlying dynamics, that of nucleons interacting through meson exchange, is nowadays clearly established, and sometimes quantitative accounts have been achieved. Many difficulties remain to be solved, especially in complex nuclei. Is it not too early, then, to attribute apparent failures of the mesons-nucleon description to new degree of freedom?

In order to prove that the exchanged mesons influence the nuclear properties, it was imperative to handle accurately the situation at the level of the Impulse Approximation, as shown by the study of the thermal neutron radiative capture rate on the proton. Similarly, to assert the presence of new degrees of freedom, the predictions of the mesons-nucleon model and the experimental data must be precise enough to demonstrate a significant disagreement.

The claim that a meaningful disagreement exists between predicted and measured cross sections for the deuteron photodisintegration at moderate energies [15] seems premature in view of the uncertainties plaguing the experimental data and the dispersion of the calculated cross sections [7]. The quest for a deeper level of interpretation is quite natural, especially because of the attractiveness of Q.C.D. The question is how to choose among the many possible experimental conditions those which offer the best chance to observe some new effects. A possible tactic is to select processes for which the mesons-nucleon model predict a minimal rate.

[1] L.L. Foldy, Phys. Rev. 92 (1953) 178.

[2] R. Bergère, Nuclear physics with electromagnetic probes, Lecture Notes in Physics 108 (1979) 138 (Springer Verlag).

[3] J. Mougey, Nuclear physics with electromagnetic probes, Lecture Notes in Physics 108 (1979) 124 (Springer Verlag).

[4] K. Holinde, R. Machleidt, Nucl. Phys. A256 (1976) 479.

[5] E. Hadjimichael, Nucl. Phys. A312 (1978) 341.

[6] H. Arenhövel and W. Fabian, Nucl. Phys. A282 (1977) 397.

[7] J.M. Laget, Nucl. Phys. A312 (1978) 265.

[8] P. Stichel and E. Werner, Nucl. Phys. A145 (1970) 257.

[9] M. Gari and H. Hyuga, Z. für Physik A277 (1976) 291.

[10] W. Fabian and H. Arenhövel, Nucl. Phys. A258 (1976) 461.

[11] I. Sick, in Proceedings of Workshop on few body systems and electromagnetic interactions, Frascati (1978).

[12] H. Kümmel, K.H. Luhrmann and J.C. Zabolitsky, Phys. Rep. 36 (1978) C1.

[13] B. Frois, Nuclear physics with electromagnetic probes, Lecture Notes in Physics 108 (1979) 52 (Springer Verlag).

[14] J. Torre, J.J. Benayoun and J. Chauvin (preprint).

[15] E. Hadjimichael and D.P. Saylor, contribution to Saclay Symposium (1980).