THE ISOSPIN STRUCTURE OF THE 3-NUCLEON FORM FACTORS

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1 MOTIVATION FOR AN ISOSCALAR-ISOVECTOR SEPARATION

Isospin is a good symmetry for the strong interaction. Nuclear observables are therefore easier to interpret by considering their isospin projections. The properties of the electromagnetic current of hadrons [1] impose isospin 0 and 1 to be the relevant components for nuclear studies with electromagnetic probes. Thus, an isoscalar-isovector (IS-IV) separation is not simply another way of presenting data. It helps to disentangle different physical processes that are mixed before separation. A well known example is the subject of meson-exchange corrections (MEC) where the physical processes are of different nature for the isoscalar and isovector pieces. Therefore an IS-IV separation is crucial to the understanding of the two independent isospin components. The purpose of the present contribution is to give the results of such a separation in the case of the 3-nucleon form factors. This approach may also be useful for a comparison of electromagnetic and weak properties : the electromagnetic observables have both IS and IV components, whereas the charged weak interactions (such as beta-decay or muon-capture) are purely of isovector character. In the 3-nucleon system, the IS-IV separation also allows a direct means of comparison with the only other fully calculable system, the deuteron, by providing a common isospin basis. Such a separation is indeed trivial for the deuteron, where the elastic form factors are purely of IS nature and where the IV observable is provided by the electrodisintegration at threshold.

2 APPLICATION TO THE 3-BODY ELASTIC FORM FACTORS

The IS-IV separation in the 3-body system requires the knowledge of the charge and magnetic form factors of both helium-3 and tritium. The necessary information for tritium has only recently become available with the data of Juster et al. [2], over a momentum transfer range from 0 to 30 fm^{-2}, covering the first diffraction minimum and the secondary maximum of the charge and magnetic form factors.

Strictly speaking, because of the Coulomb repulsion between the two protons in helium-3, the isospin symmetry for the helium-3 and tritium nuclei can only be exact if the electromagnetic interaction is switched off. But these electromagnetic symmetry breaking effects are predicted to be small [3] for the charge distribution. Therefore in the following discussion such effects will be neglected.

Our definitions for the isoscalar and isovector components are summarized in Table 1.

TABLE 1 : Definition of isoscalar (IS) and isovector IV) components used in the present analysis.

$F(q^2 = 0) = 1$ charge and magnetic
$F_c^{IS} = [2\ F_c(^3He) + F_c(T)]\ /\ 2$
$F_c^{IV} = [2\ F_c(^3He) - F_c(T)]\ /\ 2$
$F_m^{IS} = [\mu(^3He)\ F_m(^3He) + \mu(T)\ F_m(T)]\ /\ 2$
$F_m^{IV} = [\mu(^3He)\ F_m(^3He) - \mu(T)\ F_m(T)]\ /\ 2$

From a mathematical point of view, to obtain the values of the isoscalar and isovector form factors, one requires the knowledge of helium-3 and tritium form factors at the same values of q^2. Experimentally this is not the case. For this reason a functional representation of the form factors has been used. The experimental data and theoretical results for both helium-3 and tritium have been fitted using a SOG (Sum Of Gaussians) expansion [4]. Such a procedure has several advantages :

- First, it provides a simple parametrization of the form factors, directly in q-space. The Fourier-transformed expansion in r-space represents the charge (or magnetization) density. Therefore the "mathematical" result of the fit can be "physically" constrained in r-space to the large r behavior required by the binding energy.

- Second, such a fitting procedure imposes a "smooth" behavior to the experimental data : for a given q^2 value, the result of the fit also depends on the neighbouring data points and is therefore not allowed to show too narrow a structure.

- Third, SOG allows a model independant estimate of the RMS charge and magnetic radii. A careful comparison with the results of polynomial fits for the radii shows deviations of less than 5.10^{-3} [5] and hence an agreement at a level much better than the present statistical and systematic uncertainties.

- Finally, a functional representation of the form factors allows a straightforward longitudinal-transverse separation. Such a "global" analysis has been applied to the Saclay tritium data [2] : the charge and magnetic form factors are disentangled by a unique fit to all the experimental cross-sections. For a clear consistency requirement, the same form factor expansion was used for helium-3. However, since the original cross-sections for helium-3 were not available for some of the published experiments, the SOG expansions for charge and magnetic helium-3 form factors have been fitted separately.

The helium-3 charge form factor

For the helium-3 charge form factor, data from several laboratories exist. In the low q^2 region, the most precise experiments are those of Dunn et al. [6] and Ottermann et al. [7]. These two experiments are in fair agreement, but disagree with the normalization of the data of McCarthy et al. [8] by about 3% [5]. The most important consequence of this disagreement concerns the RMS radius. Indeed, for $q^2=0$, any charge form factor measurement should converge to 1. An overall systematic difference between the experimental data provides therefore different slopes at the origin and consequently different RMS radii. Data at low q^2 have also been collected by Szalata et al. [9], Retzlaff et al. [10] and Collard et al. [11]. The RMS charge radius is however less sensitive to these data because of their uncertainties. The location of the first diffraction minimum and also the amplitude of the following maximum are determined by the data of McCarthy et al. [8], Bernheim et al. [12] and Arnold et al. [13] (this last set of data has been corrected for the magnetic contribution to the values of $A(q^2)$ [5]).

We have re-analyzed [5] the whole set of form factors, using the SOG method, up to 35 fm^{-2}. The normalization of each set of low q^2 data has been determined by a least -square analysis : in the first step, the normalization of each data set was fitted to the data of Ottermann et al. ; in the second step, the overall common normalization factor was determined by again minimizing the χ^2 with the constraint $F(0)=1$.

This renormalization only influences the RMS radius value and is irrelevent for the high q^2 behavior where uncertainties are much larger than the renormalization itself. The best χ^2 was obtained for the renormalization factors reported in Table 2. The largest renormalization factor of 2.8% is needed for the McCarthy et al. data ; this value is consistent with the normalization uncertainty of ± 3% quoted by the authors themselves [8].

TABLE 2 : Renormalization factors used in the present analysis for the different helium-3 experimental data sets.

Data	Renormalization Factors	
	Charge	magnetic
Dunn et al. [6]	1.002	1.002
Ottermann et al. [7]	1.007	1.007
McCarthy et al. [8]	0.972	0.972
Szalata et al. [9]	1.007	-
Retzlaff et al. [10]	0.992	-
Collard et al. [11]	0.987	-
Bernheim et al. [12]	1.000	-
Arnold et al. [13]	1.000	-
Cavedon et al. [16]	-	1.000

The tritium charge form factor

For the tritium charge form factor, 3 sets of data are available : Collard et al. [11], Beck et al. [14] and the recent Saclay data from Juster et al. [2]. The disagreement between the different sets is much larger than for the helium-3 case : the eventual renormalization factors may exceed Y0%. This clearly indicates an inconsistency between the data sets : the very recent measurement by the MIT group [15] should clarify this open question. Because of this lack of consistency between data sets we decided to use only the recent Saclay data, which cover the widest q^2 range.

The tritium and helium-3 magnetic form factors

For tritium, the magnetic data are derived from the same experiments as the previously described charge data [2,11,14]. Here again, only the Saclay data were retained.

For helium-3 data have been measured in the low q2 range by Dunn et al. [6], Ottermann et al. [7], McCarthy et al. [8] and Collard et al. [11], and at high q^2 by Cavedon et al. [16]. The renormalization factors applied to these magnetic data are the same as the one used for the charge since they have been measured simultaneously. Again for the high q^2 data such small renormalizations are of little importance. Table 2 sums up all of these helium-3 renormalization factors.

SOG results

An example of the fits obtained is shown on Fig.1 for the tritium charge form factor (Saclay data only). The shadowed band includes the statistical and systematic uncertainties. On Fig.2, our fits to the charge form factors of helium-3 and tritium are compared to the calculation of the Hannover group [5,17]. The IS-IV separations for the charge and magnetic form factors (that will be discussed in the next section) use these results (shadowed bands).

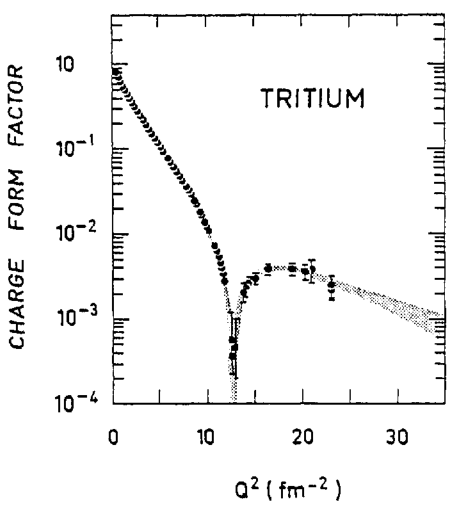

Fig.1 : SOG fit result for the tritium charge form factor. The fit result is the shadowed band that includes statistical and systematic uncertainties. The experimental points are from Juster et al. [2].

The RMS radii values obtained by these SOG fits are :

Charge	$r_c(^3He) = 1.93 \pm 0.03$ fm	Magnetic	$r_m(^3He) = 1.93 \pm 0.07$ fm
	$r_c(T) = 1.81 \pm 0.05$ fm		$r_m(T) = 1.80 \pm 0.09$ fm

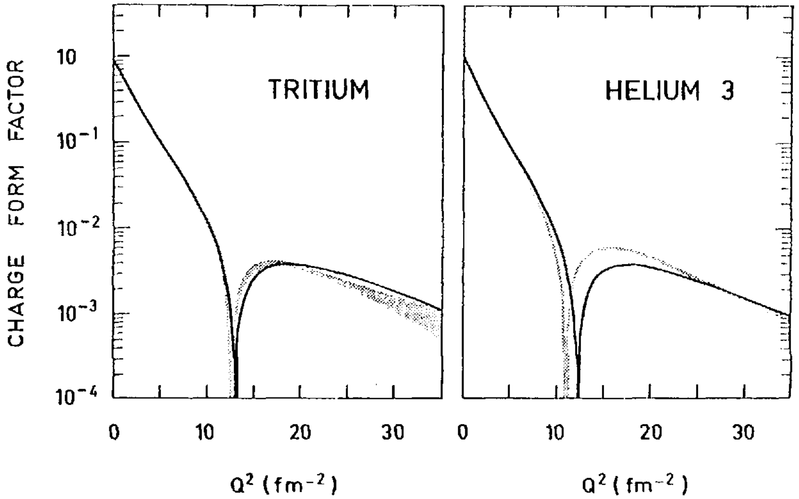

Fig.2 - Fitted charge form factors of helium-3 and tritium (shadowed bands) and theoretical calculations of the Hannover group [5,17] with PV coupling (black line).

(The values of the above tritium RMS radii slightly differ from the values in [2] where all the published tritum data were taken into account). The quoted uncertainties add quadratically the statistical error and two systematic errors : 0.02 fm for the normalization and 0.01 fm for the SOG method itself (the small influence of the Gaussian width and positions in r-space) [5].

Using these values of the charge RMS radii, we get the following pointlike-proton RMS charge radii (after unfolding the nucleon size) :

pointlike-proton $r_c(^3He) = 1.74 \pm 0.03$ fm

$r_c(T) = 1.66 \pm 0.06$ fm

These pointlike-proton RMS radii can be used to obtain the "isoscalar-charge" and "difference-charge radii, as defined by Friar et al. [3] :

pointlike-proton $r_c(IS) = 1.72 \pm 0.03$ fm

$r_c(D) = 0.43 \pm 0.17$ fm

3 RESULT OF THE ISOSCALAR-ISOVECTOR SEPARATION

In this section, the results of our IS-IV separation for the 3-body form factors are discussed. The aim is essentially to compare the experimental results with one of the most complete calculations, the one of the Hannover group [5,17], without prejudice on the validity of other calculations.

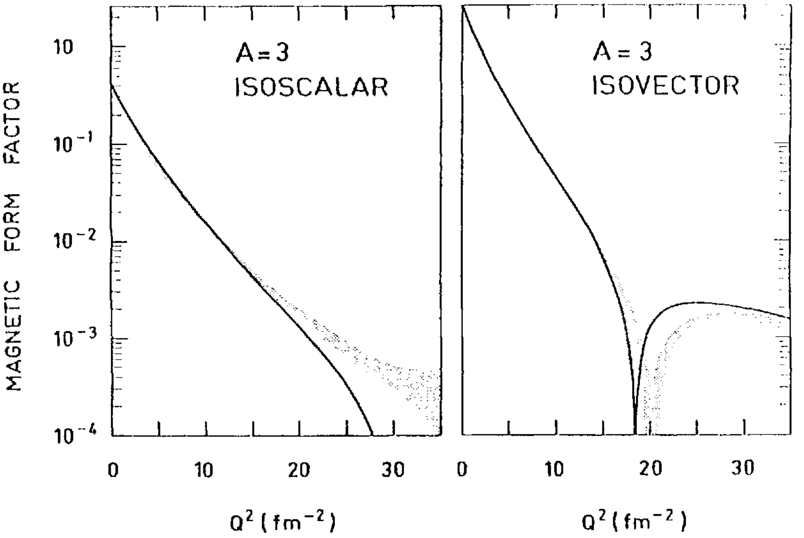

Fig.3 - Isoscalar-Isovector separation for the A=3 magnetic form factors (same notation as for Fig.2).

Fig.3 shows the IS-IV separation for the 3-body <u>magnetic</u> form factors :

1 - For the IS magnetic part, there is a clear agreement between theory and experiment, up to 20 fm^{-2}. Surprisingly, this agreement is achieved by the impulse approximation (IA) alone : therefore the IS magnetic form factor provides a direct test on the one-body operators. Nevertheless, the seeming absence of contributions beyond IA raises a question for the $\rho\pi\gamma$ MEC term, that contributes for 50% at 25 fm^{-2} for the purely IS deuteron magnetic form factor [18,19]. Another interesting feature of the IS deuteron magnetic form factor is the location of its first diffraction minimum beyond 30 fm^{-2} while this mimimum is between 10 and 15 fm^{-2} for the three other form factors (see Fig.3 and Fig.4). As for the deuteron magnetic form factor, this may be due to strong S-D and D-D contributions : the IS magnetic form factor may therefore be a good candidate for studying the 3-nucleon D-state, where 3-body force effects could be favoured [20].

2 - The IV magnetic part is clearly dominated by MEC contributions. In fact it provides some of the most clear cut evidences for MEC in a "pure" bound state observable : until now the best evidence was obtained in the deuteron backward angle electrodisintegration at threshold [18], also a pure IV transition. This again demonstrates the importance and the good quantitative theoretical description that can be

achieved for IV MEC in few body systems. It is worth noting that this good description can only be obtained when the nucleon form factor in MEC-diagrams is assumed to be F_1 and not G_E : this also confirms what has been observed for the deuteron [18]. Nevertheless a complete understanding of this choice does not yet exist : a careful treatment of relativistic effects should clarify this situation.

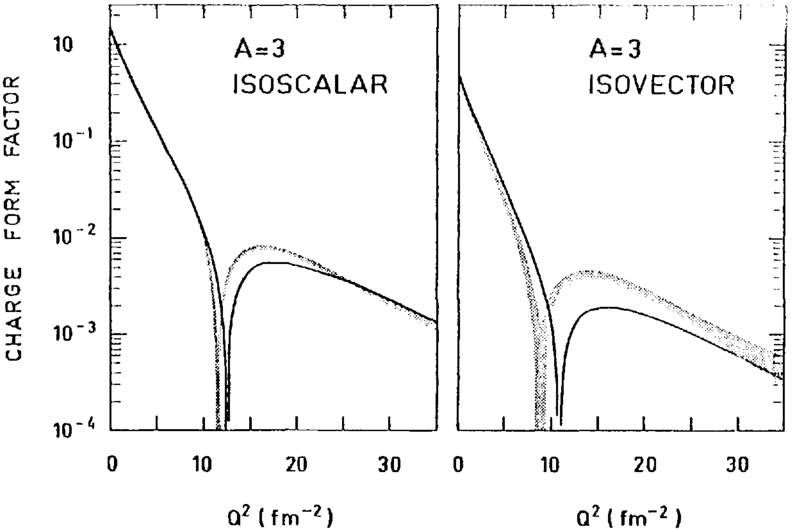

Fig.4 - Isoscalar-Isovector separation for the A=3 charge form factors (same notation as for Fig.2).

Fig.4 shows the IS-IV separation for the 3-body charge form factors. Here, there is not good agreement between theory and experiment, especially in the region of the second diffraction maximum. The disagreement holds both in the IS and IV components. For charge form factors, the theoretical constraints on the MEC terms are not as strong as for the IV magnetic case. MEC are here of relativistic order, and therefore much more uncertain. The theoretical calculation of the Hannover group [5,17], which uses a pseudo-vector (PV) pion-nucleon coupling for the MEC contributions, reproduces very well the tritium charge form factor (see Fig.2). It only fails to reproduce the amplitude of the second maximum of helium-3, in a region where the experimental points are neither very accurate nor very compatible between experiments. An experimental clarification in this region seems (at least to the author) of (great) interest. One has to be very careful with respect to the effect of this PV-coupling : the use of a pseudo-scalar (PS) coupling would completely change the conclusion, in the sense that a good agreement would be achieved for the IV part whereas the disagreement would be worsened for the IS part. The ambiguity between PS and PV couplings is a theoretical problem beyond the scope of this contribution.

CONCLUSION

The IS-IV separation of the 3-nucleon elastic form factors has required a careful re-analysis of the existing experimental data, followed by the functional representation (SOG) of their q^2 behavior. A first result has been the extraction of a "consistent" set of experimental values for the RMS radii. The IS-IV separation itself yields very clear conclusions for the magnetic part : evidence for a good control over the one-body operators and for the IV MEC calculations is found. For the charge form factors the possible conclusions about the disagreement between theory and experiment are dominated by the still open and puzzling PS-PV problem : further theoretical constraints on the MEC in charge form factors are required.

This work results from a collaboration between Saclay and Hannover. In particular, S. Platchkov, P. Sauer and C. Cortes-Sack have been deeply involved in the analysis that I have presented here.

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