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PHOTODISINTEGRATION OF THE TRINUCLEONS*

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ABSTRACT

A brief review of the experimental and theoretical status of the problem of the electromagnetic interactions with the trinucleon system is presented. Elastic and inelastic electron scattering as well as two-body and three-body photodisintegration are covered in some detail. Binding energy calculations and sum rule results (σ_{-1}) are discussed and a brief introduction to the related weak interaction problem is included.

INTRODUCTION

The basic purpose of trinucleon investigations has been to add to our understanding of nucleon-nucleon (N-N) interactions. The three-nucleon system was deemed especially appropriate for such studies because it was thought that, for these simplest of complex nuclei, theoretical uncertainties could be minimized. The ground state properties of ^3He and ^3H provided the first, and still important, test of those aspects of the N-N interaction that cannot be examined directly in N-N scattering experiments. The n-d scattering and breakup reactions allowed extension of the study to the two-body and three-body continuum states. Because the photon and electron are amenable to Born approximation treatment, their interaction with the nucleus has permitted further extension of the study to include simple bound state to continuum transition processes. Here it was hoped to find even more stringent tests of the form of the N-N interaction; for example, it is here that meson exchange effects appear to be surfacing.

Our purpose today is to review, very briefly, the recent experimental situation and its theoretical interpretation.¹ The fact that the general features of the low energy three-nucleon data have been found to be somewhat insensitive to the details of the N-N force may be a disappointment to some. On the other hand, it does indicate what success can be achieved with a correct theory and a reasonable approximation to the main features of the N-N interaction.

BOUND STATE PROPERTIES

The low energy photodisintegration and low momentum transfer electron scattering experiments are primarily sensitive

to the asymptotic properties of the bound state, hence the binding energy. I wish to point out that recent variational results with local potentials,² including all angular momentum states of the potential, indicate a bound of 7.75 MeV for the three-nucleon binding energy for the RSC and GB potentials. (A check of this result by the local potential Faddeev groups is eagerly awaited.) The experimental triton binding energy is 8.48 MeV. However, the singlet N-N potentials were fitted to p-p scattering data, whereas ^3H has only n-n and n-p singlet interactions. Separable potential calculations indicate that the calculated binding energy of 7.75 MeV may not be as far off as it seems: for potentials fitted to low energy scattering parameters, $V_{nn} \neq V_{np}$ adds about 0.35 MeV to the binding energy.³ In addition, finite size Coulomb energy calculations fail to account for the $^3\text{H} - ^3\text{He}$ binding energy difference by 0.1 to 0.15 MeV, which may indicate a charge asymmetry in the nucleon-nucleon force. Thus, it seems possible that realistic potential calculations, for what is actually a hybrid ^3He without Coulomb interactions ($V^s = V_{pp}$), should be expected to yield only about 8.0 MeV binding.

I would also like to emphasize that the N-N interaction must become absorptive (therefore complex) above the threshold for π , 2π , K, etc. production, where N-N scattering is no longer elastic. We mock this up in our real potential models by introducing a strong repulsion at short range. But this is only an approximation, and perhaps it is a poor one. Any calculation that depends strongly on the short range behavior of these potentials must therefore be suspect.

ELECTRON SCATTERING

Closely related to the binding energy

question is the form factor from elastic electron scattering. This reaction, which leaves the ground states of ^3He and ^3H intact, provides a reasonable test of the charge densities resulting from the wave functions generated by the various variational² and Faddeev⁴ calculations. Because the trinucleons are spin $1/2$ systems, the elastic scattering data can be analysed in terms of charge and magnetic moment form factors, as is the case for the nucleons.⁵ In the non-relativistic Born approximation treatment of the e-N interaction, these form factors have a simple interpretation in terms of the Fourier transforms of the charge and magnetic moment densities of the nucleus. However, meson exchange currents complicate the interpretation of these densities in terms of the trinucleon wave functions.

The most recent data⁶ is for ^3He , which is shown in Fig. 1 and 2. This experiment extended the previous measurement⁷ of the charge form factor beyond the region in momentum transfer ($q^2 < 8 \text{ fm}^2$), where all reasonable three-body models fit the data, to reveal a diffraction minimum and a broad secondary maximum. In addition, the rms magnetic radius was found to be $1.95 \pm .11 \text{ fm}$ as opposed to the old value of $1.74 \pm .10 \text{ fm}$.

Fig. 1. The ^3He charge form factor; the curve is a phenomenological fit yielding an rms radius of 1.88 fm .

Fig. 2. The ^3He magnetic moment form factor; the curve is a phenomenological fit yielding an rms radius of 1.95 fm .

Theoretical fits to the high q^2 charge data have not been especially successful. Variational and Faddeev results (non-relativistic calculations) for the RSC potential come closer to fitting the position of the diffraction minimum than the magnitude of the second maximum. Variational results² for the HJ and GB potentials have similar shortcomings, as is shown in Fig. 3. Various possibilities come to mind: relativistic corrections, three-body potentials^{2,8}, baryon resonance contributions, etc. However, it should be noted that the two-photon exchange process is not included in this list; work on electron scattering from the deuteron⁹ makes this appear to be a highly unlikely solution to the problem. Because a fit to the magnitude of the second maximum appears to be extremely difficult to obtain, this part of the data probably provides a rich source of information about the trinucleon system; however, such large momentum transfers imply a probe of very small internucleon distances, which is just where our N-N interaction models are poorly approximated.

The low q data appear to be more significant for classical photonuclear physics. In this region of momentum

Fig. 3. Variational results for the ${}^3\text{He}$ charge form factor for the Hamada-Johnston and Gammel-Brueckner potentials compared with experiment (dashed curve).

transfer one determines the shape of the charge and magnetic moment distributions that are important in the calculation of transition matrix elements. The best available data on the trinucleons determined from elastic electron scattering are listed in Table I.

Let us examine the radii using the form factor analysis of Schiff.⁵ For the charge form factor one has:

$$F_c({}^3\text{He}) = (F_p + \frac{1}{2} F_n) F_1 - \frac{1}{3} (F_p - F_n) F_2$$

$$F_c({}^3\text{H}) = (F_p + 2F_n) F_1 + \frac{2}{3} (F_p - F_n) F_2,$$

where F_p and F_n are the proton and neutron charge form factors and F_1 and F_2 are the form factors of the S state and interference between the S and S' states respectively:

$$F_1 = \int \exp(i\vec{q} \cdot \frac{2}{3} \vec{\rho}) u^2(r, \rho) d^3r d^3\rho$$

$$F_2 = -3 \int \exp(i\vec{q} \cdot \frac{2}{3} \vec{\rho}) u(r, \rho) v_1(r, \rho) d^3r d^3\rho$$

(Defined in this way, $F_2 > 0$ for small q , so that $F_c({}^3\text{He})/F_c({}^3\text{H}) < 1$.) For the magnetic moment form factors one has

Table I. The rms radii of the trinucleons as determined by the low q data of elastic electron scattering of Ref. 6 and 7.

	charge	magnetic
${}^3\text{H}$	$1.70 \pm .05$	$1.70 \pm .05$
${}^3\text{He}$	$1.88 \pm .05$	$1.95 \pm .11$

$$\mu({}^3\text{He}) F_m({}^3\text{He}) = \mu_n F_p F_1 + \frac{2}{3} (\mu_p F_p + \mu_n F_p) F_2 + (\mu({}^3\text{He}) - \mu_n) F_x$$

$$\mu({}^3\text{H}) F_m({}^3\text{H}) = \mu_p F_p F_1 + \frac{2}{3} (\mu_n F_p + \mu_p F_p) F_2 + (\mu({}^3\text{H}) - \mu_p) F_x$$

where F_x describes the isovector exchange moment form factor and we assume

$$F_p^{\text{mag}} = F_n^{\text{mag}} = F_p^{\text{ch}} = F_p.$$

If, in addition, we assume for simplicity that $F_n = 0$ and $\mu_p = -3/2 \mu_n$, then we can easily show that

$$F_c({}^3\text{He})/F_p = F_1 - \frac{1}{3} F_2$$

$$F_c({}^3\text{H})/F_p = F_1 + \frac{2}{3} F_2$$

$$F_m({}^3\text{He})/F_p = .89(F_1 - \frac{1}{3} F_2) + .11 F_x/F_p$$

$$F_m({}^3\text{H})/F_p = .94(F_1 + \frac{2}{3} F_2) + .06 F_x/F_p.$$

From this oversimplified form factor analysis we can draw several conclusions:

- 1) $F_2 > 0$ implies that $r_c({}^3\text{He}) > r_c({}^3\text{H})$;
- 2) $r_m({}^3\text{He}) > r_c({}^3\text{He})$ implies that F_x must fall off faster than $F_c({}^3\text{He})$, such that $r_x > r_c({}^3\text{He})$;
- 3) r_x increases $r_m({}^3\text{He})$ relative to $r_c({}^3\text{He})$ and will have the same effect on ${}^3\text{H}$, so that $r_m({}^3\text{H}) > r_c({}^3\text{H})$;
- 4) from the relation

$$F_m({}^3\text{H})/F_p = .94 F_c({}^3\text{He})/F_p + .94(\frac{5}{9}) F_2 + .06 F_x/F_p$$

it is clear that F_2 and F_x have the opposite effect, but one expects F_2 to dominate making $r_m({}^3\text{H}) < r_c({}^3\text{He})$.

Thus one would expect from the data on ${}^3\text{He}$ and the above analysis that

$$r_m({}^3\text{He}) > r_c({}^3\text{He}) > r_m({}^3\text{H}) > r_c({}^3\text{H}) .$$

Indeed, this relationship is found to hold in the Faddeev calculations--see, for example, Tjon, et al.⁴ Therefore, we see that (1) the low q data are reasonably explained by a good three-body theory using N-N interactions that account for the main features of the N-N scattering data and (2) a remeasurement of $F_m({}^3\text{H})$ would probably show an increased value for $r_m({}^3\text{H})$.

Inelastic electron scattering awaits the coming of precision coincidence measurements of the new accelerators. The low momentum transfer experiments (high incident electron energy) will provide further information about the ${}^3\text{He}$ -pd vertex, which must be matched by valid three-nucleon bound state calculations.¹⁰ The higher momentum transfer experiments will begin to tell us about something other than the asymptotic form of the trinucleon bound state--they will begin to map out the actual momentum distribution within the nucleus. Low energy inelastic electron scattering data¹¹ have received interpretation in terms of virtual photon theory¹² and are discussed under the section on two-body photodisintegration.

PHOTODISINTEGRATION SUM RULES

We have already heard from Jim O'Connell about the various sum rules that exist in photonuclear physics and related fields. Let me summarize some numerical results in the trinucleon system for the bremsstrahlung weighted sum rule. Theoretically one has¹³

$$\sigma_{-1} = \frac{2}{3} \pi^2 \alpha (3r_m^2 - r_v^2)$$

$$\sigma_{-1}(\frac{1}{2}) - \frac{1}{2} \sigma_{-1}(\frac{3}{2}) = \frac{1}{3} \pi^2 \alpha r_v^2 ,$$

where the isovector radius r_v and the matter radius r_m are defined by

$$r_v^2 = (Nr_n^2 - Zr_p^2)/2$$

$$r_m^2 = (Nr_n^2 + Zr_p^2)/3 .$$

Calculating the isovector and matter radii from electron scattering data (the proton and neutron rms squared radii are assumed to be 0.64 fm² and 0.126 fm² respective-

ly) one obtains

$$\sigma_{-1}(\frac{1}{2}) = 1.34 \text{ mb}$$

$$\sigma_{-1}(\frac{3}{2}) = 1.06 \text{ mb} .$$

These numbers provide an interesting comparison with the experimental data. The cloud chamber data of Gorbunov et al¹⁴ give the following:

$$\sigma_{-1}(2) = 1.34 \pm .05 \text{ mb}$$

$$\sigma_{-1}(3) = 1.42 \pm .07 \text{ mb} .$$

Since we know that

$$\begin{aligned} \sigma_{-1} &= \sigma_{-1}(2) + \sigma_{-1}(3) \\ &= \sigma_{-1}(\frac{1}{2}) + \sigma_{-1}(\frac{3}{2}) , \end{aligned}$$

it is clear that this data exceed the limit set by electron scattering. The recent data of Berman et al¹⁵ on the three-body breakup extrapolate to $\sigma_{-1}(3) \approx 1.0 \text{ mb}$, which is less than the limit for $\sigma_{-1}(\frac{3}{2})$. Because $\sigma_{-1}(3)$ must contain all of $\sigma_{-1}(\frac{3}{2})$, one would like a somewhat larger experimental value for $\sigma_{-1}(3)$. On the other hand, one would like a smaller value for $\sigma_{-1}(2)$ than 1.34 mb, since it is unlikely that $\sigma_{-1}(2)$ contains all of $\sigma_{-1}(\frac{1}{2})$. Such would seem to be the case if the smaller normalization for the peak two-body cross section to be discussed later is found to hold.

Theoretically, Barbour and Phillips¹⁶ have predicted in a Faddeev calculation with separable potentials that some 15% to 20% of $\sigma_{-1}(3)$ should come from $\sigma_{-1}(\frac{1}{2})$. On the basis of the data, this would appear to be an overestimate by a factor of 2 or so.

ANGULAR DISTRIBUTIONS FOR ${}^3\text{He} + \gamma \rightarrow p + d$

Some of the most precise angular distribution data in the field of photonuclear physics has been published for the $p(d,\gamma){}^3\text{He}$ reaction.¹⁷ The statistical accuracy and the angular range of the data provide a critical test of the multipole fits predicted by any theory. What I wish to point out here is that for data of this quality one cannot simply cut off the multipole expansion at

$$b^2(1 + \beta \cos \theta + \gamma \cos^2 \theta)$$

and expect to obtain precision estimates

of γ that are meaningful theoretically. One must follow the methods of analysis required for strong interactions and include the higher partial waves, at least in Born approximation.

In Fig. 4 is shown the data of Ref. 17 for $E_\gamma = 12.1$ MeV along with a fit produced in a zero range calculation:¹⁸ the

Fig. 4. Angular distribution data for the $p + d$ breakup of ^3He at an energy $E_\gamma = 12.1$ MeV; the curve is a sum of all transitions from the S state of ^3He to a plane wave final state of $p + d$.

curve corresponds to electric transitions from the S component of the bound state to all partial waves of a plane wave final state. The γ extracted from the data was $0.16 \pm .05$. The theoretical γ (obtained by expanding exact expressions for the angular distribution) is 0.09. Despite the difference in the values for γ , the theoretical fit is as good as the empirical one because the entire multipole series was summed. The reason for this evidently surprising difference in γ is clear; the expansion has not converged in three terms. Major contributions to the radial integrals in the higher partial waves ($l > 1$) come from the asymptotic region of the wave functions. (This region lies beyond the range of nuclear forces, so that a plane wave approximation to the final state is adequate.) The two-body separation energy is not large, such that the bound state wave function extends

well beyond the rms radius and gives finite contributions to the integrals. Just as $(1+x)^{-1}$ is not well approximated by $1 - x + x^2$ if one is determining the coefficient of x^2 (say for $x = 0.2$), one cannot determine γ properly by truncating the multipole expansion.¹⁹ The point to be emphasized here is that, if the experimental γ is to be interpreted properly theoretically, then it must be extracted in an analysis that includes the

Fig. 5. Angular distribution data for the $p+d$ capture reaction corresponding to $E_\gamma = 109$ MeV. The solid dots are from O'Fallon et al and the other data are from Didelez et al, Ref. 21.

effects of the neglected terms of the multipole sum, at least in a plane wave approximation.

The data of Ref. 17 are clearly not the only angular distribution data available. Other such data in the low energy region can be found in the papers of Ref. 14 and 20. There would appear to be little evidence for abnormal structure in β

for $E_\gamma < 40$ MeV. It seems to be a smooth function of energy as theory would predict.

At higher energies ($E_\gamma > 40$ MeV) the angular distribution appears to exhibit a broad structure at the back angles.²¹ Data corresponding to $E_\gamma = 109$ MeV are shown in Fig. 5 along with a plane wave multipole fit generated by Gibson and O'Connell,²² in which spin-flip and D-state transitions were included. The broad structure at back angles has not been reproduced. This feature of the data is most pronounced in the work of O'Fallon et al near an energy of 80 MeV and appears to have vanished by 140 MeV.

$d\sigma/dE_\gamma$ FOR THE TWO-BODY BREAKUP

The two-body photodisintegration energy spectrum has proved to be somewhat of an enigma. Basically an electric dipole transition from a spatially symmetric S component of the ground state to a nucleon-deuteron p-wave final state, this reaction has provided much excitement over the past few years as various controversies have waxed and waned. First, there was the disagreement between the 90° differential cross section measurements²³ and the total cross section measurement²⁴ as to the correct normalization of the peak cross section. Early theoretical estimates,²⁵ which treated the final state in a plane wave approximation with no deuteron distortion, tended to agree with the smaller, 90° data normalization. Faddeev theory was then utilized to estimate the cross section in terms of a simple separable-potential model; a 25% increase in the theoretical cross section was obtained.²⁶ Thus, the normalization of the total cross section measurement became favored, and new experiments tended to agree with the higher value.²⁷ At about the same time apparent structure developed in the cross section below $E_\gamma = 30$ MeV. This structure was difficult to understand theoretically, and the problem disappeared when the structure vanished upon remeasurement. But just as the structure question was being resolved, the normalization question arose again: a new p-d capture experiment was reported,²⁸ which agrees with the magnitude of the old 90° data, and a contribution to this conference reports a cross section measurement that also supports this normalization.²⁹ In addition, Hendry and Phillips³⁰ have asserted that they believe the separable model may yield too large a cross section. However, the

Fig. 6. Comparison of 90° differential cross section measurements: x Berman, et al; + Stewart, et al; o Belt, et al; ■ Halbert, et al; ● Shin, et al.

Fig. 7. Comparison of total cross section measurements: — Fetisov, et al; o Belt, et al; ■ Halbert, et al; ● Shin, et al.

latest results from the National Bureau of Standards³¹ would seem to support the higher peak cross section value and are in

excellent agreement with a separable-potential calculation.³²

Let us examine the low energy data. Shown in Fig. 6 is a reasonable sample of the 90° data available through the middle of last year. Clearly the magnitude of the peak cross section clusters about two different values. One wonders how a number of different experiments (capture, photon, and electron) can factor so neatly into two different groups. It should be noted from this figure that all of the experiments tend to agree above 25 MeV. In Fig. 7 we see a similar collection of data for the total cross section measurement. The agreement as a function of time with the old total cross section data (shown as a histogram) is apparent. The value of 64 mb reported from the recent capture measurement²⁸ would fall slightly below the data shown in the figure ($E_\gamma = 16$ MeV).

A sample of the unpublished data from Glasgow³³ for the photodisintegration reaction is shown in Fig. 8. The curve refers to a separable-potential model calculation³² that agrees reasonably well with the data in Fig. 7. It is shown here for orientation purposes. Note the following: 1) agreement with the data above 20 MeV is quite good--recall that all the 90° experiments shown in Fig. 6 appeared to be consistent beyond 25 MeV; 2) the calculation badly overestimates the data in the region of the peak cross section. In contrast to this, we can see in Fig. 9 the data from the Bureau of Standards³¹ compared to the same theoretical calculation. Here agreement with the data from the peak cross section energy to above 20 MeV is clearly evident.

Although a theorist should always be wary of making remarks about experimental data, it would appear that there is some difficulty in counting the deuterons from the two-body breakup reaction below 20 MeV. All of the experiments are in reasonable agreement as to the magnitude of the cross section above $E_\gamma = 20$ MeV. Since it becomes more difficult to get the deuteron out of the target as the deuteron energy becomes smaller, it would seem that the experimental problems become greatest in the low energy region (around the peak cross section). Conversations with Bill Dodge³⁴ indicate that, at least in the experiments done at the National Bureau of Standards, very thin-walled targets must be employed if an accurate measurement of the low energy deuterons is to be made.

Fig. 8. Comparison of the 90° differential cross section data of Ref. 33 with the separable-potential model calculation of Ref. 32.

Fig. 9. Comparison of the 90° differential cross section data of Ref. 31 with the separable-potential model calculation of Ref. 32.

What does theory have to say? The shape of the energy spectrum is apparently well accounted for by the separable-potential model results. The cross section is governed almost entirely by the bound state energy, independent of the singlet and triplet potential assumption. This is illustrated in Fig. 10, where we plot spectra corresponding to: 1) a completely consistent model in which the same singlet and triplet potentials (s-wave only) are used to generate the bound state and scattering state, 2) the same model as (1) except that the bound state energy is artificially adjusted to the experimental value after the momentum dependence of the bound state has been determined, 3) the same bound state as described in (2) but with different potential parameterization in the scattering state. It is clear that models (2) and (3) give roughly the same energy spectra; they have the same binding energy in the bound state and therefore similar asymptotic behavior. From the sum rules we know that two bound state wave functions having the same rms radii will produce about the same total cross section integral. Thus, differences in the final state interactions can only shift the energy dependence of the spectra

Fig. 10. Comparison of theoretical calculations of the 90° differential cross section: 1) consistent model using the same potentials for the bound state and scattering state, 2) same model as (1) but with the binding energy adjusted to the experimental value after the bound state was generated, 3) same bound state as (2) with different potentials used to generate the scattering state.

Fig. 11. Comparison of the available high energy photodisintegration data at 90° , courtesy C. Schuhl.

slightly, as is illustrated in Fig. 10. (On the other hand, the binding energy of the bound state can change the peak cross section by a large fraction.) The contention that the separable-potential model overestimates the cross section³⁰ can only be checked by means of a realistic local potential calculation. However, on the basis of the available data, it would not appear that the normalization could be off by more than 10%.

The photodisintegration data for higher energies are also interesting to examine. Besides the interesting feature in the angular distribution discussed previously, there is a change of slope in the energy spectrum above 100 MeV. In Fig. 11 is shown a comparison of the high energy data available.³⁵ The SACLAY data have just been obtained using a bremsstrahlung beam incident on a liquid ^3He target; both the proton and the deuteron were detected to reduce background. Note that on a log scale the data appear to exhibit one slope below 100 MeV and a different slope above 100 MeV. Although there is some spread in the data at the higher energies, the distinct change of slope is clear. This structure of the cross section should make for interesting speculation by theorists for some time to come; it should be noted that a similar character is found for the two-body spectrum in the case of ^4He as opposed to the broad resonance structure

Fig. 12. Comparison of the three-body total cross section data: Gorbunov et al.²⁴; Gerstenberg et al.²⁵; Berman, et al.³⁶.

that occurs in the deuteron photodisintegration spectrum between 100 and 400 MeV.

THREE-BODY PHOTODISINTEGRATION

The photodisintegration reaction leading to the three-nucleon final state has not been extremely popular because of its difficulty. The most recent data is that of Berman et al.³⁶ It is shown in Fig. 12, along with the earlier measurements of Gorbunov et al.²⁴ and Gerstenberg and O'Connell.³⁷ There appears to be reasonable evidence for structure of some nature in the cross section when the data of Ref. 36 are examined along with the fore-aft asymmetry measurement of the same experiment. However, the structure would necessarily have to be relatively narrow. Theoretically any structure of such a narrow nature is hard to produce. This can be seen by looking at Lehman's formulation of the amplitude for the three-body breakup reaction diagrammatically as in Fig. 13, where X is the amplitude for the off-shell N - d scattering process and B represents the Born amplitude for the reaction.³⁸ Since X is apparently smooth

and the three-body final state reaction apparently contains little $T = \frac{1}{2}$ amplitude, it is difficult to produce much narrow structure in the theoretical cross section. In a recent review by O'Connell,³⁹ it was pointed out that over the years various sharp structure features have appeared in the trinucleon photodisintegration cross section data and that usually these features go away after a careful remeasurement and searches in alternate reactions. In light of the fate of the structure in the two-body final-state reaction, one can only hope that the structure in the three-body final-state reaction will either be confirmed or denied by other experiments before theorists spend years trying to reproduce it in model calculations.

WEAK INTERACTIONS

Many of you are aware of the close connection between the weak and electromagnetic interactions. Both share the same advantages as probes of nuclear structure. Therefore, let us look briefly at what we have to look forward to in

Fig. 13. A diagrammatic formulation of the three-body photodisintegration amplitude in terms of the Born amplitude for the breakup reaction and the off-shell N - d scattering amplitude.

the near future. Because useful neutrino beams, such as the one being constructed at LAMPF, are some distance into the future, let us concentrate on the μ -capture reaction.

It should be noted that the one-body operators governing the two different processes are very similar. Instead of the familiar charge, current, and magnetic moment operators of the electromagnetic interaction

$$\begin{aligned} & \frac{1}{2}(1 + \tau_i^z) \exp(i\vec{q} \cdot \vec{r}_i) \\ & \frac{1}{2}(1 + \tau_i^z) \vec{p}_i \exp(i\vec{q} \cdot \vec{r}_i) \\ & \mu \frac{1}{2}(1 + \tau_i^z) \vec{\sigma}_i \times \vec{q} \exp(i\vec{q} \cdot \vec{r}_i) , \end{aligned}$$

we have the weak vector operators which differ from the above in that $\frac{1}{2}(1 + \tau^z)$ is replaced by τ^- (which transforms a proton into a neutron), axial vector operators

$$\begin{aligned} & F_A \tau_i^- \vec{\sigma}_i \cdot \vec{p}_i \exp(i\vec{q} \cdot \vec{r}_i) \\ & F_A \tau_i^- \vec{\sigma}_i \times \vec{q} \exp(i\vec{q} \cdot \vec{r}_i) , \end{aligned}$$

and the pseudoscalar operator

$$F_p \tau_i^- \vec{\sigma}_i \cdot \vec{q} \exp(i\vec{q} \cdot \vec{r}_i)$$

The point to be recognized is that, except for the differences in the coupling constants and the isospin changing operator τ^- , these are the familiar operators whose matrix elements are measured in inelastic electron scattering. And, as one might expect, the electric dipole transition part of the μ -capture rate (spin averaged) for

$$\mu^- + A(Z, T) \rightarrow A^*(Z-1, T+1) + \nu_\mu$$

can be related to the bremsstrahlung weighted photonuclear sum rule for transitions to the $T + 1$ giant resonance⁴⁰

$$\gamma + A(Z, T) \rightarrow A^*(Z, T+1) .$$

For the trinucleon system there appear to be two very interesting reactions:

$$\begin{aligned} \mu^- + {}^3\text{He} &\rightarrow {}^3\text{H} + \nu_\mu \\ \mu^- + {}^3\text{H} &\rightarrow {}^3\text{n} + \nu_\mu . \end{aligned}$$

In the ground state to ground state reaction (the super-allowed transition) one can easily test coupling constants, etc. But more interesting is the possibility of using the hyperfine transition rate (${}^3\text{He}$ has spin $\frac{1}{2}$ as does the μ , so that capture can occur from both $J = 0$ and $J = 1$ states) to determine the D-state probability of the ground state wave function. The lower transition dominates and proceeds primarily through the S-state component of the wave function, whereas the upper transition is sensitive to the % D-state admixture.⁴¹

In the three-neutron final state reaction we, of course, have the possibility of looking directly for three-neutron resonances, which we cannot do by electron scattering or photodisintegration. The neutrino will have an energy spectrum extending to approximately 65 MeV [$E_{\text{max}} = 2/3(m_\mu - B_3)$], so that the nuclear physics in the matrix elements can be tested over a broad range of momenta. Calculations can easily be performed in analogy with photodisintegration calculations if one uses the formulation indicated in Fig 13; only the Born amplitude need be altered.

Although the weak interactions are more closely associated with intermediate energy physics, those working in classical photonuclear (low energy) physics should become aware of and maintain an active interest in weak interaction developments. The dichotomy between the two fields is not great, if it exists at all.

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