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ELECTROMAGNETIC AND WEAK INTERACTIONS IN FEW-NUCLEON SYSTEMS

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Selected problems in electroweak interactions are reviewed. Processes where exact numerical calculations might provide insight are emphasized.

1. INTRODUCTION

One fundamdental question facing physicists today is that of how we unify the basic forces of nature: gravitational, electromagnetic, strong nuclear, and weak nuclear. Although progress toward an answer has been made, the candidate "Grand Unified Theories" are so far just that, candidate theories. Along the path, nuclear physics has contributed significantly to our overall knowledge of the strong force and is in a position to contribute to our knowledge of the weak force. Another fundamental question concerns our understanding of the structure of nuclei. These multibaryon systems comprise most of the mass and energy of the visible universe. Element synthesis is crucially based upon nuclear structure. The energy of our solar system is produced by nuclei. Interactions of nuclei involve all the forces of nature. Thus, to comprehend our universe, we must understand the structure of nuclear systems. But there exist various levels of understanding. Just as one would not attempt to study liquid argon to learn about QED, one does not expect to extract significant knowledge about QCD from studying the binding of the neutron and proton to form deuterium. Likewise, one does not attempt to calculate the structure of complex crystals starting from first principles; solid state is an important and viable field of physics independent of quantum electrodynamics.

Particle physics seeks an understanding of elementary particle interactions at very high energies (ultra short distances). In contrast, nuclear physics strives to describe the nucleus at energies and interparticle distances corresponding to conditions which one might picture as two bags barely overlapping. Here, in a region that the particle physicist finds difficult to describe quantitatively with asymptotically free theories, the nuclear physicist finds simplification and order in terms of nucleons and meson exchange. However, it is the possibility of speculating about the transition from the remarkably successful picture of the nucleus as a composite system of interacting nucleons to one of a quark soup that intrigues many physicists. But one must first define the limits of validity for the description of nuclear phenomena in terms of physically observable baryons and mesons before evidence for quark degrees of freedom in nuclei can be critically evaluated. Recall two nuclear physics successes of the last decade: 1) the perfection of model calculations based solely upon nucleon degrees of freedom to the point that comparison of results with experimental data revealed the inadequacies of the assumption and demonstrated the undeniable need to expand the model to include meson exchange currents - a new degree of freedom; 2) the perfection of realistic nucleon-nucleon potential model calculations to the extent that a comparison of binding energy estimates with well established experimental results revealed discrepancies that could only be accounted for by the introduction of three-body forces. In each case detailed, precision calculations were required in comparison with numerous experimental data before one could establish that these small but significant effects were genuine. Thus, nuclear physics seeks the appropriate degrees of freedom with which to describe nuclear systems and their interactions. The ultimate test of our intellect will be whether we possess the capability to calculate all of the nuclear phenomena which we have the ability to measure.

It is this goal of understanding all we can measure which gives few-body investigations there special place in physics. Not only can experimentalists perform kinematically complete measurements, but theorists can produce exact calculations. Why the emphasis on exact calculations? First, one can test model theories by direct comparison with data. That is, approximations can be controlled, and disagreement between theory and experiment should imply some physics (not harmonic oscillator space) is missing. Second, one can find insight into novel, qualitative features of structure or reactions. For example, a folding model, two-body equation description of ^{3}H will not yield the infinite binding which exact equations produce for zero range forcies. Similarly, a DWBA calculation of ^{3}H(γ,d)n fails to account for the 40% of the cross section near the peak energy which comes from coupling to the three-body channel. Third, one can generate benchmark solutions with which to test approximate procedures before launching involved studies of heavier nuclei. Unfortunately, much hard work is required to solve the exact equations for $A \geq 3$, especially the scattering problem, which accounts for a dearth of published continuum results. Yet, the intuition and understanding from such endeavors are most rewarding.

Two particularly useful classes of nuclear reactions are those involving electromagnetic and weak probes. Despite the auspicious title provided for my talk, there is not time allotted to provide even a catalog of experiments to be done. My remarks must necessarily be truncated to a rather subjective view of recent developments. (My apologies if your favorite piece of physics has been omitted.) In contrast to some previous speakers, I shall consider the quantum hadrodynamic model of Walecka - the nucleon-plus-meson exchange picture of few-nucleon systems. I will not address that energy and momentum region where quark effects might become visible. I hope thereby to adhere to that area of experiment where exact calculations might contribute significantly to our understanding of nuclear physics.

2. ELECTROMAGNETIC INTERACTIONS

This field of physics covers a wide variety of reactions: photodisintegration, radiative capture, elastic and inelastic electron scattering, etc. Experiments may be kinematically complete or incomplete. The QED interaction operator is reasonably well understood. Elastic electron scattering yields our best picture of the charge density of the nucleus. It was the discrepancy between theory and experiment in the case of thermal $np \to {}^2H\gamma$ that led the push for including meson exchange currents in our description of nuclei.[1]

Let us begin with an examination of the ${}^2H(\gamma,p)n$ reaction for 0° outgoing protons, a topic which drew considerable attention at the Eugene meeting. At low energy, the number of partial waves dominating in the continuum is quite limited. Consequently, one does not lose sight of the physics in summing a large number of multipole matrix elements The interaction between a photon and a proton charge can be represented ($\hbar=c=1$) by[2]

$$H^{e}_{int} = \vec{J}(\vec{r})\cdot\vec{\varepsilon}\ \exp(i\vec{k}\cdot\vec{r})$$

and the interaction of a photon with a nucleon magnetic moment can be represented by

$$H^{m}_{int} = \frac{e\mu}{2M}\ \vec{k}\times\vec{\varepsilon}\cdot\vec{\sigma}\ \exp(i\vec{k}\cdot\vec{r})$$

where $\vec{k}$ is the photon momentum and $\vec{\varepsilon}$ is its polarization; $\vec{J}$ is the nonrelativistic nucleon current operator, $\vec{r}$ is the nucleon center-of-mass position, and $\vec{\sigma}$ is the nucleon spin operator. The current interaction can be separated into electric and magnetic parts, and when working with exact initial and final states of the same Hamiltonian, the "electric" components[2] of the matrix element

$$M_{fi} = \langle f|\int d^3r\ \vec{J}(r)\cdot\vec{\varepsilon}\ \exp(i\vec{k}\cdot\vec{r})|i\rangle$$

can be shown,[3] through the use of current conservation, to be identical to those of the long wave length limit series

$$M_{fi} = (E_f-E_i)\sum_L i^L \langle f|\vec{\varepsilon}\cdot\vec{r}(\vec{k}\cdot\vec{r})^{L-1}/L!|i\rangle .$$

This $\vec{\varepsilon}\cdot\vec{r}$ form of the E1 photodisintegration operator[4] contains all relevant meson exchange corrections. However, it does not include the relativistic component of the dipole operator,[5] which will be seen to be important in the 0° cross section.

The data of Hughes et al.[6] which were confirmed by Gilot et al.[7] appear at first sight to disagree with all reasonable two-nucleon potential models (see Fig. 1). They have drawn considerable theoretical attention.[8] But consider what is happening physically. A photon with polarization perpendicular to the beam ($\vec{k}\cdot\vec{\varepsilon}=0$) strikes a deuteron. Classically the $\vec{E}$ field lies at right angles to the incident wave; it cannot produce a force on the proton along the direction (0°) of the beam defined by $\vec{k}$. Quantum mechanically, the photon brings in L=1, the proton and neutron go off back-to-back in the final state, colinear with the incident beam, and therefore have L=0. Hence the transition is forbidden, unless there is spin involved. In a central force model of the reaction, one finds $d\sigma/d\Omega \sim \sin^2\theta$ for the $\vec{\varepsilon}\cdot\vec{r}$ operator; higher electric multipoles merely add higher powers of $\sin^2\theta$. The reaction is nonzero only because of i) the deuteron D-state, ii) noncentral forces in the np continuum, iii) the relativistic spin dependence of the photodisintegration operator, and iv) meson exchange and other non-Siegert terms in the interaction Hamiltonian. It is (i) and (ii) which lead to the nonzero impulse approximation result shown in Fig. 1. It is (iii), the relativistic spin-orbit contribution to the E1 operator which accounts for most of the discrepancy between the data and that impulse approximation result (see Fig. 2), as was first pointed out by Cambi et al.[9] This $(v/c)^2$ relativistic correction[5] due to the induced electric moment of a moving magnetic moment $(\frac{\vec{v}}{c}\times\vec{\mu}\rightarrow\frac{\hbar\,\vec{p}\times\vec{\sigma}}{4m^2c^2}\,2\mu_V)$ becomes important at 0° because that part of the E1 transition operator which dominates the 90° cross section (and thus the total cross section) vanishes. The 20% correction from this this unambigous term in the operator is the dominant correction; uncertainties in the meson exchange current corrections are of the order of ±6-7%. Thus, we see how relativistic effects can be visible in low energy physics. Before leaving the two-body problem, let me note that there is reported to this conference[10] an interesting preliminary result for a measurement of t_{20}, the tensor polarization of recoil deuterons in $^2H(e,e)^2H$. Such information is needed to separate the monopole and

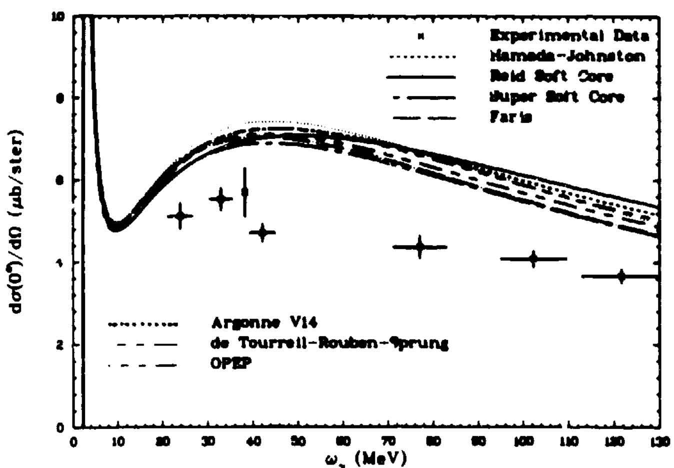

Fig. 1. $^2H(\gamma,p)n$ without spin-orbit; data from Ref. 6 and 7.

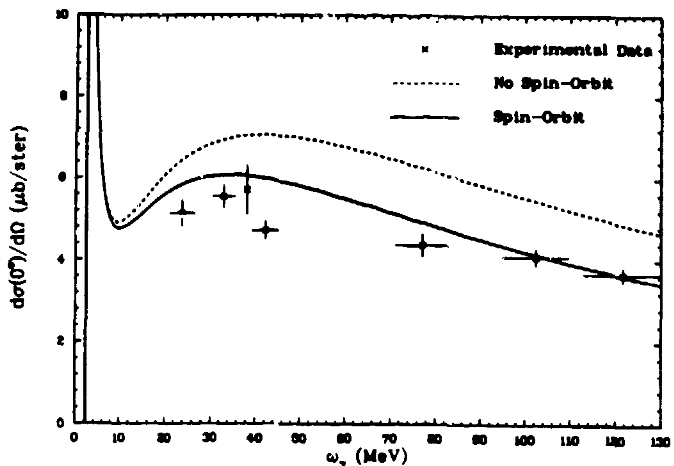

Fig. 2. $^2H(\gamma,p)n$ for SCC model; data from Ref. 6 and 7.

quadrupole charge form factors of the deuteron. In addition, Bohannon and Heller[11] have reported model problem numerical studies for the extension of the soft-photon theorem for bremsstrahlung discussed at the Graz meeting.[12] Finally, Holt et al.[13] have raised a new qeustion concerning deuteron photodisintegration. The neutron polarization in the reaction $^2H(\gamma,n_{pol})H$ was measured at an angle of 90° for $6 \leq E_\gamma \leq 13$ MeV. Disagreement with published theoretical calculations was found. A similar claim[14] has been made for measurement of the cross section asymmetry for deuteron photodisintegration with linearly polarized photons of $80 \leq E_\gamma \leq 600$ MeV for center-of-mass proton angles of 75°-150°.

Let us now turn our attention to the study of elastic electron scattering from ^3H and ^3He. It is this process that yields direct information about the square of the trinucleon ground-state wave function in terms of the charge and magnetic form factors. Recall that the cross section for this simple process can be written as[15]

$$\frac{d\sigma}{d\Omega} = \frac{d\Omega}{d\Omega_{Mott}}\{F_{ch}^2(q^2) + \mu^2\eta^2[1+2(1+\eta^2)\tan^2(\theta/2)\; F_{mag}^2(q^2)\}$$

$$\frac{d\sigma}{d\Omega}_{Mott} = \left(\frac{Z\alpha}{2E}\right)^2 \frac{\cos^2(\theta/2)}{\sin^4(\theta/2)[1+(2E/M)\sin^2(\theta/2)]} ,$$

where $\eta = q/(2M)$, $q = k_e - k_e'$ is the momentum transfer, M is the trinucleon mass, and $\hat{k}_e \cdot \hat{k}_e' = \cos\theta$. The charge form factor $F_{ch}(q^2)$ is defined in impulse approximation by[16]

$$F_{ch}(q^2) = \frac{1}{Ze} \langle\psi|\rho_{ch}(\vec{r},\vec{r}_j)\; \exp(i\vec{q}\cdot\vec{r})|\psi\rangle ,$$

where

$$\rho_{ch}(\vec{r},\vec{r}_j) = \sum_{j=1}^{3} \left[\tfrac{1}{2}(1+\tau_z^j)f_{ch}^p(\vec{r}-\vec{r}_j) + \tfrac{1}{2}(1-\tau_z^j)f_{ch}^n(\vec{r}-\vec{r}_j)\right]$$

and ψ, f_{ch}^p, f_{ch}^n are the trinucleon wave function and charge densities of the proton and neutron respectively. Relativistic corrections of order $(v/c)^2$ include the usual Darwin-Foldy and spin-orbit terms.[5] Meson-exchange-current corrections are of the same order and are intimately connected.[17] The magnetic moment form factor is perhaps more easily described in momentum space

$$F_{mag}(q^2) = \langle\psi|\ \hat{\varepsilon}\cdot\vec{J}\ |\psi\rangle\ ,\ \hat{\varepsilon}\cdot\vec{q} = 0$$

where

$$\vec{J}_{impl} = \vec{J}_{conv} + \vec{J}_{mom}$$

$$\vec{J}_{conv} = \sum_{j=1}^{3} \frac{1}{2M} [\vec{p}_j \exp(i\vec{q}\cdot\vec{r}_j) + \exp(i\vec{q}\cdot\vec{r}_j)p_j]\frac{1}{2}(1+\tau_z^j)f_{ch}^p(q^2)$$

$$\vec{J}_{mom} = \sum_{j=1}^{3} \frac{i}{2M}\ \vec{\sigma}_j\times\vec{q}\ \exp(i\vec{q}\cdot\vec{r}_j)[\frac{1}{2}(1+\tau_z^j)\mu_p f_{mag}^p(q^2) + \frac{1}{2}(1-\tau_z^j)\mu_n f_{mag}^n(q^2)].$$

This operator is of order (v/c) and relativistic corrections are $(v/c)^3$. The isovector meson-exchange-current correction cannot be neglected, being the same order in (v/c) as the impulse current. I wish only to make two points concerning the trinucleon form factors, which have been of intense interest since Collard's original experiment.[18] First, recent measurement[19] of the ^{3}He charge form factor below $q^2 = 4\ fm^{-2}$, when combined with the world's data, indicates that $\langle r_{ch}^2(^3He)\rangle^{1/2} = 1.875 \pm .011$ fm in contrast to that reported by Dunn et al.[20] (The magnetic rms radius is about 1.95 fm.[21]) Work in progress[22] on ^{3}H appears to yield $\langle r_{ch}^2(^3H)\rangle^{1/2}$ somewhat lower than Collard's original value (1.70 fm). An rms radius as small as 1.65 fm would not be inconsistent with point charge radii differences produced in Faddeev calculations (Δr_{ch} $\cong$0.20 fm),[23] because studies of the ^{3}He charge form factor including a Coulomb interaction between protons indicate that the Coulomb repulsion increases Δr_{ch} by a small but not insignificant 0.03 - 0.04 fm.[24] Definitive ^{3}H experiments are needed. Second, the magnetic form factor data are shown in Fig. 3. Theoretical results came tantalizingly close to the data. However, as has been pointed out by Lehman, it is disconcerting to see that the magnetic moments from these calculations do not agree (see Table I).[26]

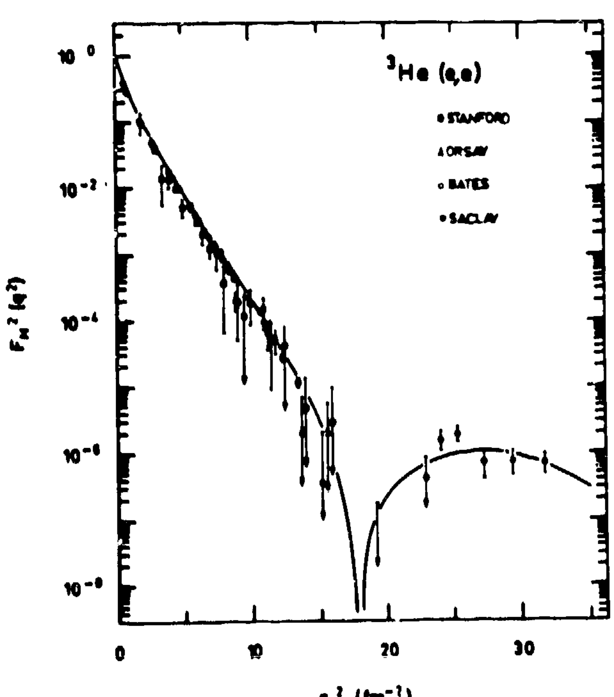

Fig. 3. $F_{mag}^2(q^2)$ for ^{3}He from Ref. 25; curve to guide eye.

In contrast to elastic scattering, inelastic electron scattering, especially coincidence experiments such as ^{3}He(e,e′p)d and ^{3}He(e,e′p)np, yields information about the overlap of the ground-state wave function and the wave function of a nucleon moving freely relative to a deuteron or pair of nucleons in a scattering state. These overlaps define the structure of the $^3H \to nd$, $^3He \to pd^*$ etc. vertices, which can be described in terms of asymptotic normalization constants, momentum distributions, and related quantities.[30] To be be specific we consider the ^{3}He(e,e´p)d experiment of Jans et al.,[31] although there also exist new data by Kozlovsky et al.[32] The general form of the coincidence cross section is

$$\frac{d\Omega}{dE_e d\Omega_e d\Omega_p} = \frac{d\sigma}{d\Omega_{ep}} \; F(E_e,\Omega_e,\Omega_p)\, \tfrac{3}{2}\{|f_0(q)|^2 + 2|f_2(q)|^2\}$$

where $d\sigma/d\Omega_{ep}$ is the half-off-shell ep scattering cross section, $F(E_e,\Omega_e,\Omega_p)$ is a kinematic factor, and $\frac{3}{2}\{\ldots\}$ is the momentum distribution. It is $\{\ldots\}$ which is usually called the spectroscopic factor. A closely related quantity is the fraction of pd component in the trinucleon wave function:

$$P_{pd} = 2\pi \int_0^\infty q^2 dq\, \{|f_0(q)|^2 + |f_2(q)|^2\}$$

The momentum distribution amplitudes $f_0(q)$ and $f_2(q)$ are the ℓ=0,2 components of the overlap of the ground state wave function with the continuum state of a nucleon of momentum $\vec{q}$ moving freely relative to a deuteron:

$$_A\langle nd;\, \vec{q},\, \tfrac{1}{2}m_p\; 1m_d | {}^3H;\, \tfrac{1}{2}m\rangle$$

$$= \sqrt{\tfrac{3}{2}} \sum_{\substack{\ell=0\\ m_\ell}} \; \sum_{\substack{J=1/2,3/2\\ M_J}} \langle \tfrac{1}{2}m_n\; 1m_d | JM_J\rangle\, f_\ell(q) \times \langle \ell m_\ell\; JM_J | \tfrac{1}{2}m\rangle \sqrt{4\pi}\; Y^{[1]}_{\ell m}(\hat{q}),$$

where spin and isospin quantum numbers have been suppressed. These amplitudes are directly related to the asymptotic normalization constants C^1_ℓ of the trinucleon ground state wave function[30,33]

$$\lim_{\rho\to\infty} \Psi(\vec{r},\vec{\rho}) \to C^1_S \sqrt{\frac{\mu}{2\pi}}\, \frac{e^{-\mu\rho}}{\rho} \sqrt{4\pi}\, [[Y^{[0]}(\hat{\rho}) \times \chi^{[\frac{1}{2}]}(1)]^{[\frac{1}{2}]} \times \phi_d^{[1]}(r)]^{[\frac{1}{2}]} \frac{\eta'}{\sqrt{2}}$$

$$- C^1_D \sqrt{\frac{\mu}{2\pi}}\, \frac{e^{-\mu\rho}}{\rho} \left(1 + \frac{3}{\mu\rho} + \frac{3}{\mu^2\rho^2}\right)$$

$$\times \sqrt{4\pi}\, [[Y^{[2]}(\hat{\rho}) \times \chi^{[\frac{1}{2}]}(1)]^{[\frac{3}{2}]} \times \phi_d^{[1]}(\vec{r})]^{[\frac{1}{2}]} \frac{\eta'}{\sqrt{2}}$$

by

$$C^1_\ell = i^\ell\, \{2\pi i\mu\}^{\frac{1}{2}} \lim_{q\to i\mu} (q-i\mu) f_\ell(q)\, \} \,.$$

A question of recent interest is whether one can extrapolate from the measured (q=0) distorted wave quantity[34]

$$D_2 = \lim_{q\to 0} \{-f_2(q)/[q^2 f_0(q)]\}$$

Table I. Breakdown of magnetic moment calculations

	SSC[27]	Paris[28]	RSC[29]
impulse	-1.760	-1.77	-1.826
pair-graph	-0.344	-0.29	-0.563
pion-graph	-0.082	-0.03	-0.202
Δ-graph	-0.144	-0.05*	-0.024

*from coupled-channel calculation.

to the pole position (iμ) where C_S^1 and C_D^1 are defined. That is, if one defines a theoretical distorted wave quantity

$$\tilde{D}_2 = - C_D^1/(\mu^2 C_S^1) ,$$

is $\tilde{D}_2 \cong D_2$? Simple separable model studies indicate that the answer is yes, although not as well as in the case of the deuteron. Separable model results for the $^3H \to nd$ momentum distribution are plotted in Fig. 4 along with data extracted from the $^3He(e,e'pd)$ experiment of Saclay. There is an absolute uncertainty in the extraction of the order of 10-15% due to the assumption of pole dominance and the ambiguity associated with the half-off-shell ep cross section. Within this framework, both the 4% and 7% deuteron D-state models are consistent with experiment for q ≤ 100 MeV/c, the expected range of validity for the pole dominance assumption. Such is also the case for more sophisticated models like the Reid soft core.[31,35] Thus, pole dominance is not a valid assumption at higher momentum transfer. (Incidentally, for the $^3He(e,e'p)np$ reaction[31] where the detected proton does not have a high energy relative to the np pair, neglect of 3-body final state interactions will likely destroy any agreement between theory and experiment.) The inclusive quasielastic cross sections are also most interesting. There are systematic disagreements between theory and data.[36] Time does not permit delving into this subject.

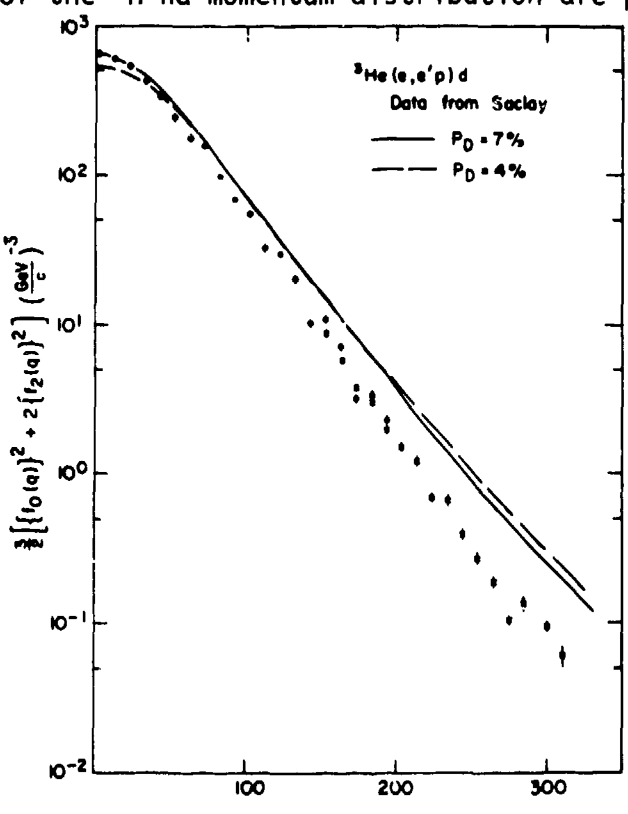

Fig. 4. Momentum distribution for $^3H \to nd$ with date from $^3He(e,e'd)p$.

Before leaving the A=3 isodoublet, let me point out some recent interesting results in the realm of photonuclear physics. In a preprint concerning the $^2H(p,\gamma)^3He$ capture reaction, King et al.[37] have reported measurement of angular distributions from 6.5 to 16 MeV (see Fig. 5). A sensitivity to the D-state components of the ^3He wave function is noted. One caution in any analysis of such data to extract angular distribution coefficients: All higher partial wave contributions should be summed in any analysis because the trinucleons, like the deuteron, are large objects; the multipole series does not converge rapidly and the sum of an infinite number of individually negligibly small terms is not vanishingly small.[40] Skopik et al.[39] have just published an $^3He(e,d)e'p$ measurement which implies that E2 strength near the peak of the $^3He(\gamma,d)p$ cross section is small, less than 2% of the total cross section. A preprint by Torre et al[41] shows reasonable results for magnetic exchange current contributions to the $nd \rightarrow {}^3H\gamma$ thermal neutron capture reaction.[42] In the higher energy region, the question of time reversal invariance in the $^3He\gamma \leftrightarrow pd$ reaction has again come to the forefront. Sober et al.[43] have remeasured at Bates differential cross sections for $^3He(\gamma,d)p$ in the photon energy range of 150-350 MeV for center-of-mass angles of 60° and 90°. The absolute uncertainty for this gas target experiment in which recoil deuterons are detected is quoted as less than 6%. (Preliminary results can be found in Briscoe et al.[44]) These results are significantly higher than those of Saclay and Bonn[45] and lower than those of Caltech and Frascati.[46] The detail balance converted cross sections agree well with the recent TRIUMF data[47] and with new data from the UCLA-Saclay collaboration,[48] although the agreement is poor with older published results.[44] There is <u>no</u> evidence for a violation of time reversal invariance. Finally, interesting Coulomb effects were found in the $^3He(\gamma,2p)n$ reaction for photon energies between 80 and 120 MeV, when the two protons are emitted in close proximity.[49]

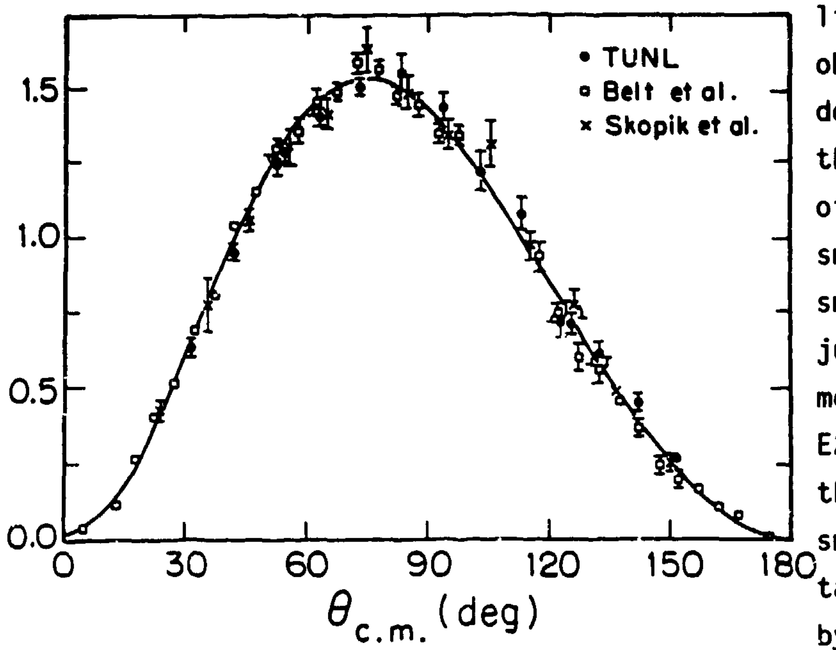

Fig. 5. Angular distribution for $^2H(p,\gamma)^3He$; data from Ref. 37-39.

In the A=4 area, the significant difference between the $^4He(\gamma,p)^3H$ and $^4He(\gamma,n)^3He$ cross sections in the 24-32 MeV photon energy range is the most interesing phenomena. The cross sections are shown in Fig. 6 (solid lines) as they were evaluated by Calarco, Berman, and Donnelly.[50] The shaded bands indicate their estimates of the uncertainties in the individual cross sections. The data points are from Ref. 51-53; these references also contain the data included in the cross section evaluation. It is clear that the cross sections differ substantially below 30 MeV. Because the reaction mechanism is dominated by the E1 ($\Delta S=0$, $\Delta T=1$) transition, the inequality of the cross section implies the existence of strong isospin mixing in the four-nucleon $J^{\pi}=1^{-}$ states. Calarco et al. have interpreted the large deviation of the cross section ratio $R=\sigma(\gamma,p)/\sigma(\gamma,n)$ from a value of 1 in terms of a charge asymmetry in the nuclear force, because continuum calculations published to date predict only small differences in the two cross sections.[50] Other information concerning this energy region is becoming available. Angular distributions for the $^{3}H(p,\gamma)^{4}He$ reaction have been reported by McBroom et al.[54] In addition, Weller et al.[55] have reported a first measurement of polarized neutron capture on ^{3}He at E_n = 9 MeV, which corresponds to a photon energy of 27.3 MeV. The polarized and unpolarized angular distribution data lead Weller et al. to the conclusion that there is little E2 or spin-flip E1 contributing to

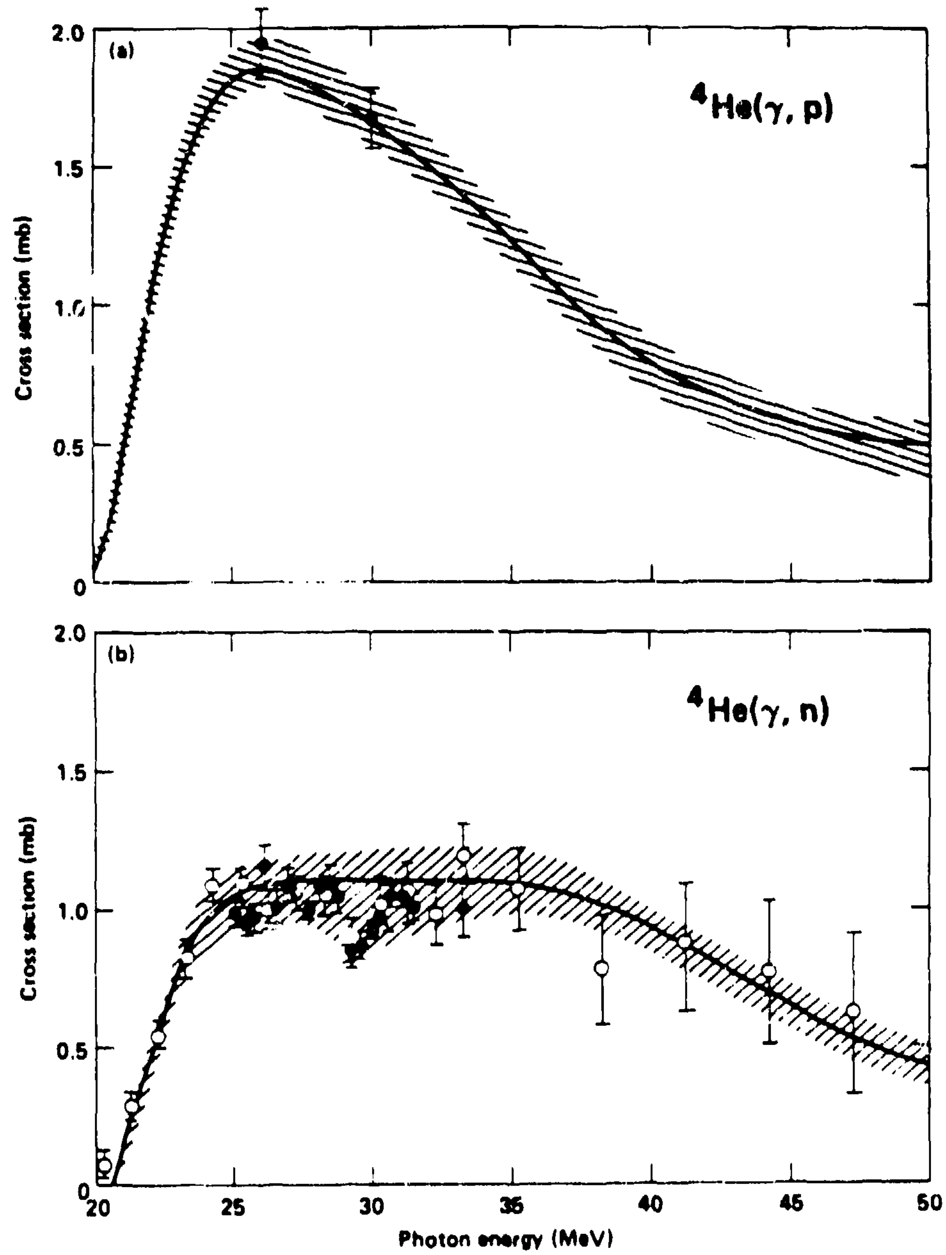

Fig. 6 The $^{4}He(\gamma,p)^{3}H$ and $^{4}He(\gamma,n)^{3}He$ cross section evaluation (solid lines); data in (a) from Ref. 51, open circles in (b) from Ref. 52, closed circles in (b) from Ref. 53.

the cross section.

The photodisintegration of the alpha particle is more complex than that of, say, ^3He where one has only two open channels (pd and ppn).[56] Here one has 5 distinct open channels, and there exist known exicted states of ^4He.[57] However, at the low energies relevant to the ratio puzzle, the dominant E1 transition is saturated by the $^4He(\gamma,n)^3He$ and $^4He(\gamma,p)^3H$ reaction channels.[58] The $^4He(\gamma,d)d$ channel contributes only to even multipoles because of the equal mass and charge of the final-state deuterons, while the multiparticle channels $^4He(\gamma,d)np$ and $^4He(\gamma,n)npp$ do not connect to the T=0 ^4He ground state for any final-state isospin value other than the T=1 of the n^3He and p^3H channels. These multiparticle final states are therefore suppressed relative to two-body final states of the same isospin, just as one sees experimentally and theoretically for the trinucleons.[56] Based upon this knowledge that only 2-body channels are important, a bound-state shell model calculation was used to illustrate the point that, if all three $J^\pi = 1^-$ states (T=1,S=0; T=1,S=1; T=0,S=1) were properly mixed via Coulomb and/or a small charge asymmetry in the NN force, the measured ratio R could be understood.[59] Such a model would appear to be in conflict with the results of Ref. 55. However, recent R-matrix work by Dodder and Hale[60] on fitting of the strong interaction cross sections (elastic scattering, charge exchange, etc.) indicates that Coulomb mixing of the type discussed in Ref. 59 does lead to significant mixing in the $J^\pi=1^-$ levels. Such an R-matrix calculation would be expected to yield a ratio of R>>1.

3. WEAK INTERACTIONS

The unified theory of the electroweak interactions is one of the great achievements of physics. The WGS[61] or Standard Model unifies the weak interactions and electromagnetism in a renormalizable framework. Predictions of weak-neutral-current effects agree with experiment. Despite the notable successes, rigorous testing of the theory lies ahead. It is for this reason that experimentalists must strive for improved μ^- and neutrino facilities. Nuclear targets will play a key role in studies of the structure of the weak interactions, because nuclear selection rules and the variety of available transitions make nuclei excellent filters or analyzers for sorting out components of the weak interaction. Recall that nuclear experiments demonstrated V-A was to be and not S-P-T.

In order to be specific, let me restrict my remarks to neutrino physics. Tests of μ-e universality, induced pseudoscalar coupling, CVC, etc. with muons are of no less importance[62] as are parity nonconservation studies in $\vec{p}p$, $\vec{p}d$ scattering and $np\to d\vec{\gamma}$.[63-65] Even so, there is not time to provide a complete review of the underlying theory. It is assumed that there exists an effective Lagrangian description of the $\nu_e \leftrightarrow e^-$, $\nu_e \leftrightarrow \nu_e$, and $e^- \leftrightarrow e^-$ processes mediated by the γ, charged W, and the neutral Z bosons. The heavy bosons are so massive that those couplings are point-like, and one writes a four-point interaction description: leptonic current times hadronic current. The hadronic currents[66] are of the V-A form $J_\mu = J_\mu + J_\mu^5$ with the charge-changing currents being the raising and lowering parts of the isovector operator $J_\mu^{(\pm)} = J_\mu^{V_1} \pm i J_\mu^{V_2}$. Correspondingly, the electromagnetic current has the isospin structure $J_\mu^\gamma = J_\mu^5 + J_\mu^{V_3}$, and the conserved-vector-current theory (CVC) tells us that the vector part of the charge-changing current is just $J^{(\pm)} = J_\mu^{V_1} \pm i J_\mu^{V_2}$. CVC relates this aspect of the weak and electromagnetic current; this was the first part of the electroweak unification. The Standard Model is, in essence, an extended CVC with the addition of a neutral weak current of the form $J^{(0)} = J_\mu^{V_3} - 2\sin^2\theta_W J_\mu^\gamma$. We believe that the interaction of leptons with the bosons is understood; therefore one is studying the hadronic aspects of the electroweak interaction in nuclear investigations.

Because the momentum transfer is small in conventional processes such as β-decay, e^--capture, and μ^--capture, neutrino studies are valued for their potential to explore the weak interaction form factors over an extended region of momentum transfer q. The Standard Model predicts that the electromagnetic and weak interaction processes are related for all q. There are simple (theoretically) tests of this remarkable concept.[66] Consider (ν_e,ν_e'), $(\bar{\nu}_e,\bar{\nu}_e')$, and (e,e′) scattering from a T=0, $J^\pi=0^+$ nucleus such as ^{4}He (either the elastic scattering or the inelastic scattering to the 20 MeV T=0, $J^\pi=0^+$ first excited state). Because we have T=0, $J_\mu^{(0)} = -2\sin^2\theta_W\, J_\mu^\gamma$; the weak neutral current is pure vector in WSG and is directly proportional to the e.m. current. Thus, there is a direct relation between neutrino scattering and electron scattering. In particular one has

$$d\sigma_{\nu_\ell \nu_\ell'} \equiv d\sigma_{\bar{\nu}_\ell \bar{\nu}_\ell'} = \sin^4\theta_W \, \frac{G^2 q^4}{2\pi^2\alpha^2} \, d\sigma_{ee'}^{ERL} \quad ,$$

where ERL refers to the extreme relativistic limit ($E_e \gg M_e$). This result holds for all q, all θ independent of the nuclear structure. It is a true test of the unification of the electroweak interactions. The neutrino and electron cross sections must be identical if the Standard Model is correct.

I close with cursory mention of weak interaction physics and the deuteron. First a reminder: $\mu^- d \rightarrow \nu n n$ may provide the cleanest measurement of the nn scattering length. Second, parity nonconservation in $\vec{\gamma}$d-np and in $\vec{p}$d elastic scattering yield information about T=1 parts of the weak interaction not available from T=0 $\vec{p}p$ experiments. Third, ν-^2H and $\bar{\nu}$-^2H scattering and reactions are interesting testing grounds of electroweak coupling to more than one nucleon, that is exchange currents. In addition, the elastic scattering is sensitive to axial vector isoscalar coupling which is identically zero in the Standard Model. Donnelly[67] has investigated this in some detail and found that for $E_\nu \cong$ 150 MeV the sensitivity of the cross section to any such nonstandard term can be enhanced by a factor of 10 over the vector coupling. Furthermore, the interference with the vector coupling is destructive for neutrinos and constructive for antineutrinos, providing a clean signal.

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REFERENCES

1. H. A. Bethe and C. Longmire, Phys. Rev. 77 (1950) 647; N. Austern and E. Rost, Phys. Rev. 117 (1960) 1506; A. Cox et al. Nucl. Phys. 74 (1965) 481; G. E. Brown and D. O. Riska, Phys. Lett. 38B (1972) 193; M. Gari and A. H. Huffman, Phys. Rev. C 7 (1973) 944.

2. R. G. Sachs and N. Austern, Phys. Rev. 1 (1951) 705.

3. L. L. Foldy, Phys. Rev. 96 (1953) 178.

4. A. J. F. Siegert, Phys. Rev. 52 (1937) 787.

5. W. A. Barker and F. N. Glover, Phys. Rev. 99 (1955) 317; J. L. Friar, Mesonic vs. Relativistic Effects, in: Mesons in Nuclei, eds. M. Rho and D. H. Wilkinson (North Hollard, Amsterdam, 1979) pp 597-623; J. L. Friar, Nucl. Phys. A353 (1981) 233c.

6. R. J. Hughes et al. Nucl. Phys. A267 (1976) 329.

7. J. F. Gilot et al. Phys. Rev. Lett. 47 (1981) 304.

8. H. Arenhövel and W. Fabian, Nucl. Phys. A282 (1977) 397; E. L. Lomon, Phys. Lett. 68B (1977) 419; M. L. Rustgi et al. Phys. Rev. C 20 (1979) 24; M. Gari and B. Sommer, Phys. Rev. Lett. 41 (1978) [illegible]; E. Hadjimichael, Phys. Lett. 85B (1979) 17; W. Jaus and W. S. Woolcock, Nucl. Phys. A365 (1981) 477.

9. A. Cambi et al. Phys. Rev. Lett 48 (1982) 462.

10. M. E. Schulze et al. Measurement of tensor polarization of the recoil deuteron in electron-deuteron elastic scattering, this volume.

11. G. E. Bohannon and L. Heller, Extension of the Soft-Photon Theorem for Bremmstrahlung (to be published).

12. L. Heller, Lecture Notes in Physics 87 (1978) 68.

13. R. J. Holt et al. Phys. Rev. Lett. 50 (1983) 577.

14. V. G. Gorbenko et al. Nucl. Phys. A381 (1982) 330.

15. M. N. Rosenbluth, Phys. Rev. 79 (1950) 615.

16. L. I. Schiff, Phys. Rev. 133 (1964) B802.

17. J. L. Friar, Phys. Rev. C 27 (1983) 2078.

18. H. Collard et al. Phys. Rev. 138 (1965) B57.

19. D. M. Skopik (private communication).

20. P. C. Dunn et al. Phys. Rev. C 15 (1983) 71.

21. J. S. McCarthy et al. Phys. Rev. C 15 (1977) 1396.

22. D. Beck, D. M. Skopik, and W. Turchnitz (private communication).

23. J. A. Tjon et al. Phys. Rev. Lett. 25 (1970) 540; G. Gignoux and A. Laverne, Phys. Rev. Lett. 29 (1972) 436; G. L. Payne et al. Phys. Rev. C 22 (1980) 823.

24. G. L. Payne et al. Phys. Rev. C 22 (1980) 832; J. L. Friar et al. Phys. Rev. C 24 (1981) 665.

25. J. M. Cavedon et al. Phys. Rev. Lett. 49 (1982) 986; B. Frois, Experiments on few nucleon systems with low and medium energy electrons, this volume.

26. D. R. Lehman, Bull. Am. Phys. Soc. 27 (1982) 694 (and private communication).

27. E. Hadjimichael et al., Phys. Rev. C 27 (1983) 831.

28. Ch. Hajduk et al. Nucl. Phys. A (in print); The elctromagnetic structure of the three-nucleon bound states, this volume.

29. M. A. Maize and Y. E. Kim, Nucl. Phys. A (in print); Meson-exchange currents, current conservation and magnetic form factor of ^{3}He, this volume.

30. B. F. Gibson and D. R. Lehman, Structure of the ^{3}H→n+d(d*) vertexes (to be published).

31. E. Jans et al. Phys. Rev. Lett. 49 (1982) 974.

32. I. V. Kozlovsky et al. Nucl Phys, A368 (1981) 493.

33. J. L. Friar et al. Phys. Rev. C 25 (1982) 1616.

34. L. D. Knutsen et al. Phys. Rev. Lett. 35 (1975) 1570.

35. A. E. L. Dieperink et al. Phys. Lett. 63B (1976) 261.

36. D. R. Lehman, Phys. Rev. C 3 (1971) 1827; H. Meier-Hajduk et al. Nucl. Phys. A395 (1983) 332.

37. S. E. King et al. Effects of the ^{3}He D-state in the ^{2}H(p,γ)^{3}He reaction (to be published).

38. B. D. Belt et al. Phys. Rev. Lett. 24 (1970) 1120.

39. D. M. Skopik et al. Phys. Rev. C 28 (1983) 52.

40. B. F. Gibson and J. S. O'Connell, Phys. Lett. 32B (1970) 331.

41. J. Torre and B. Goulard, Meson exchange currents and radiative thermal neutron capture by the deuteron (to be published).

42. J. S. Merritt et al. Nucl Sci. Eng. 34 (1968) 195; E. T. Jurney et al. Phys. Rev. C 25 (1982) 2810.

43. D. Briscoe et al. Phys. Rev. Lett. 49 (1982) 187.

44. D. I. Sober et al. The two-body photodisintegration of ^{3}He between 150 and 350 MeV (to be published).

45. P. E. Argan et al. Nucl. Phys. A237 (1975) 447; H. J. Gassen et al. Z. Phys. A 303 (1981) 35.

46. C. A. Heusch et al. Phys. Rev. Lett. 37 (1976) 405; P. Picozza et al. Nucl. Phys. A157 (1970) 190.

47. R. Abegg et al. Phys. Lett. 118B (1982) 55.

48. B. H. Silberman et a. (private communication).

49. C. A. Peridier et al. Z. Phys. A 310 (1983) 317.

50. J. R. Calarco et al. Phys Rev. C 27 (1983) 1866.

51. J. R. Calarco et al. (private communication).

52. B. L. Burman et al. Phys. Rev. C 22 (1980) 2273.

53. L. Ward et al. Phys. Rev. C (1981) 317.

54. R. C. McBroom et al. Phys. Rev. C 25 (1982) 1644.

55. H. R. Weller et al. Phys. Rev. C 25 (1982) 2111.

56. B. F. Gibson, Nucl. Phys. A353 (1981) 85c.

57. W. E. Meyerhof and T. A. Tombrello, Nucl. Phys. A109 (1968) 1.

58. A. N. Gorbunov, Proc. P. N. Lebedev Physics Inst. 71 (1974) 1 (Nauka, Moscow; translation: Consultants Bureau, New York).

59. B. F. Gibson, Nucl. Phys. A 195 (1972) 449.

60. G. M. Hale (private communication).

61. S. Weinberg, Phys. Rev. Lett. 19 (1967) 1264 and Phys. Rev. D (1972) 1412; A. Salam and J. C. Ward, Phys. Lett. 13 (1964) 168; S. L. Glashow et al. Phys. Rev. D 2 (1970) 1285.

62. J. D. Walecka, Muon capture reaction (μ^-,ν_μ) with nuclei, in: Proceedings of the Second LAMPF II Workshop, eds. H. Thiessen, T. Bhatia, R. Carlini, and N. Hintz (Los Alamos, LA-9572-C, 1972) pp 440-453; Semileptinic weak interactions in nuclei, in: Muon Physics II, eds. V. Hughes and C. Wu (Academic Press, New York, 1975) pp 113ff.

63. E. M. Henley, Annu. Rev. Nucl. Sci. 19 (1969) 367; E. Fischback and D. Tadic, Phys. Rept. 6 (1973) 124; M. Gari, ibid 6 (1973) 318; M. Box et al. J. Phys. G 1 (1975) 493.

64. B. Desplanques et al. Ann. Phys. (N. Y.) 124 (1980) 449.

65. J. M. Potter, et al. Phys. Rev. Lett. 33 (1974) 1307; B. Balzer et al. Phys. Rev. Lett. 44 (1980) 699; N. Lockyer et al. Phys. Rev. Lett. 45 (1980) 1821; V. M. Lobashov et al. Nucl. Phys. A197 (1972) 241 (and private communication); J. F. Cavaignec et al. Phys. Lett. 67B (1977) 148.

66. J. D. Walecka, Neutrino Interactions with nuclei, in: Proceedings of the Second LAMPF II Workshop, eds. H. Thiessen, T. Bhatia, R. Carlini, and N. Hintz (Loz Alamos, LA-9572-C, 1982) pp 560-583; Weak interactions with nuclei, in: Proceedings of the Third LAMPF II Workshop, eds. H. Thiessen and T. Bhatia (to be published).

67. T. W. Donnelly, Highlights of nuclear physics with neutrinos, in: Proceedings of the Los Alamos Neutrino Workshop, eds. F. Boehm and G. J. Stephenson, Jr. (Los Alamos, LA-9358-C, 1981). pp 11-32; Intermediate energy elastic neutrino scattering from nuclei, ibid pp 75-95.