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The Three-Body Force in the Three-Nucleon System

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Abstract

A brief summary of the deliberations of the Symposium, as prepared immediately after for remarks at the Spring Meeting of the American Physical Society, is given.

Introduction

The traditional approach to nuclear physics, which is formulated in terms of nuclear Hamiltonians that are nonrelativistic, employ pairwise (two-body) forces, and ignore subnuclear degrees of freedom, has been rather successful in describing properties of nuclear ground states as well as scattering and reactions. The implication is that forces depending upon the simultaneous coordinates and quantum numbers of three nucleons (three-body forces) are relatively unimportant. Their small size hinders the observation of three-body force effects in many-body systems. Therefore, the trinucleon system plays an extremely important role in the investigation of three-body force effects, because we can calculate numerically accurate solutions for nonrelativistic Hamiltonians.

Trinucleon bound-state and continuum investigations provide nontrivial tests of the traditional model. There is no guarantee that nucleon-nucleon (NN) forces alone can account for trinucleon observables. Indeed, systematic investigation of low-energy properties, such as the size and energy scales of the ^3H and ^3He bound states and zero-energy scattering of nucleons from deuterons, has revealed the inadequacy of the pairwise force assumption in a nonrelativistic Hamiltonian model. For example, realistic two-body force models underbind the triton by the order of 1 MeV, generate a theoretical rms charge radius which is too large by some 10%, and lead to a neutron-deuteron spin-doublet scattering length which is too large by about a factor of 2. The existence of measurable three-body force (3BF) effects is one possible explanation for these shortcomings of the traditional approach. Our purpose at this Symposium was to examine closely the possibility of identifying experiments which might isolate three-body force effects and theoretical developments which are needed to support such an experimental program.

However, it should be clearly stated in the beginning that evaluating evidence for a three-body force in nuclei is something like seeking two-body short-range correlations. A 3BF in one language may be meson or quark degrees of freedom in another. The bound-state properties and long wavelength workshops worked with well defined questions. In the nucleons-only Hamiltonian picture in which all other

degrees of freedom have been "frozen out," is there evidence for the need for a 3BF to account for the available experimental data? Are there experiments and/or calculations to be done which might reveal such a necessity? Once one pushes the energy above pion production threshold, it is difficult to freeze out the meson degrees of freedom. Therefore, the intermediate-energy workshop was more concerned with the question of whether we can understand the meson degrees of freedom which lead to three-body forces as they become active and of undeniable importance. In that energy region one must study the nuclear force problem including those added degrees of freedom and use the knowledge gained to construct theoretically sound models of currents, etc. The short-range workshop had a wider variety of questions to examine. Because quarks are confined, it is simple to formulate the question of whether quark antisymmetrization leads to measurable 3BF effects. Theoretically, they must appear in the model when one freezes out the quark degrees of freedom to obtain a Hamiltonian in terms of physically observable nucleon degrees of freedom. Likewise, a proper relativistic Hamiltonian treatment of the three-nucleon problem will generate automatically three-nucleon forces. Are these genuine 3BF effects large enough to be experimentally observable?

Three-Nucleon Force Models

One wishes to investigate a nuclear Hamiltonian model in which nonrelativistic nucleons interact and subnuclear degrees of freedom have been suppressed. Thus, one begins with

$$H = \sum_i (t_i + V_i) + \sum_{i < j} V_{ij} + \sum_{i < j < k} V_{ijk} + \dots$$

where the original ansatz is that V_{ijk} and higher order terms can be neglected. (The atomic three-electron force of Primakoff and Holstein is an example of a 3BF which is undeniably present but immeasurably small.) In practice, as Pandharipande pointed out, one finds that the truncation of H to terms of the complexity of V_{ij} and less leads to 1) an underbinding of the triton and the alpha particle and 2) a model of infinite nuclear matter which has an incorrect binding energy per nucleon and an improper saturation density. This deficiency of the two-body force assumption has led to a threefold approach to modeling the three-body force:

- 1 Two-pion-exchange ($\pi\pi$) potential,
- 2 NN- Δ coupled-channels model,
- 3 Phenomenological parametrization.

Diagrammatically, one can write an expansion as in Fig. 1. In the $\pi\pi$ potential approach, McKellar and Coon have utilized a "model-independent" parametrization of the off-shell πN amplitudes based upon the low-energy theorems -- the Weinberg, Adler, and Cheng-Dashen off-shell points determine the πN amplitudes. These amplitudes are used to construct the 3BF potential represented by the first two diagrams -- the second diagram being the iterated one-pion-exchange graph.

Robilotta and coworkers attack this problem from a chiral Lagrangian point of view, but their model does not necessarily respect the above off-shell constraints. The short-range properties of the two models are different, but the calculations of Payne and coworkers appear to establish that the strong short-range repulsion of the nucleon-nucleon (NN) force makes the difference between the two $\pi\pi$ exchange models insignificant in calculations of trinucleon properties.

In the coupled-channels NN- Δ model of Sauer and Hajduk, the Hilbert space requires the inclusion of the 3rd graph in Fig. 1 -- the dispersion diagram. The NN data above pion production threshold are used to fix the model parameters, and the trinucleon properties below that threshold are then calculated. The model encompasses the first nonnucleonic degree of freedom to become active in the baryon sector. The model of Lee is similar in philosophy.

The phenomenological approach of Pandharipande and coworkers proceeds by fitting parameters of theoretically motivated forms to the triton binding energy and properties of nuclear matter. The 3BF plays an important role in obtaining correct saturation properties. The open question is then whether the model works for the alpha particle and other nuclei.

My comments based upon discussions during the Symposium are:

1. The πp and pp terms must be added to the $\pi\pi$ approach. (The momentum space formulation does exist.)
2. The 4th graph in Fig. 1 (N- Δ interaction) and other terms need to be added in the NN- Δ approach. (Pandharipande estimates the contribution to the nonnegligible.)
3. The phenomenological approach can only be tested outside the purview of this Symposium. Good $A=4$ calculations are needed.
4. The πN vertex cutoff Λ as taken from πN data (the Goldberger-Treiman relation) is 700-800 MeV. This disagrees dramatically with NN force models

Fig. 1. Diagrammatic expansion of multipion exchange contributions to the three-nucleon force.

(e.g. the Bonn models) which use 1.2-1.5 GeV and quark models which estimate 500 MeV. Using πN data directly to obtain Λ would appear to have some justification.

5. The phenomenological approach is based upon the fact that there exists no ab initio theoretical model of the NN force. One does the best one can in formulating the long-range part and parameterizes one's short-range ignorance.

The conclusions that followed from the discussions were:

1. Enormous progress has been made in our effort to include 3BF models in the calculation of trinucleon bound-state properties and low-energy nucleon-nucleon scattering; quantitatively reliable results have been obtained.
2. The differences among the various approaches have been defined.
3. The aspects of 3BF models which affect physical observables have yet to be clearly identified.
4. Quantitative 3BF models based upon quark degrees of freedom or relativistic effects do not yet exist.

Bound States

The nonrelativistic three-body force models are the most fully developed. Three-nucleon force models can be directly used in this traditional testing ground for nucleon-nucleon force models and meson-exchange currents. Exact equation (which means that approximations are controlled and that next-order corrections can be calculated) numerical solutions exist. Binding energies are good to better than 50 keV.

Two-body force calculations with realistic forces show

1. $B(^3H) \cong 7.5$ MeV (vs. 8.48 MeV experimentally);
2. $\langle r^2 \rangle$ is correspondingly 10% too large;
3. $E_{\text{Coulomb}} \cong 0.64$ MeV $< B(^3H) - B(^3He) = 0.76$ MeV;
4. Asymptotic normalization ratio $C_2/C_0 \neq$ experiment;
5. Electromagnetic form factors F_{ch} and $F_{\text{mag}} \neq$ experiment.

In examining the charge form factor F_{ch} , the representation of the data would be improved if the 3BF were attractive in the isosceles triangle configuration and repulsive in the collinear configuration. This would reduce $\psi(\vec{r}, \vec{\rho})$ for $\vec{\rho} = 0$, where $\vec{\rho}$ is the coordinate of the 3rd nucleon relative to the interacting pair. This is illustrated in Fig. 2, where the Fourier transform of the ^3He point nucleon F_{ch} is plotted as ρ_{exp} along with theoretical charge densities for the Reid-Soft-core (RSC) potential model. (Note that, as Friar points out, less than 1% of the charge density would be needed to fill the "hole" in ^3He . The models are unlikely to be valid at the 1% level.) Nonetheless, we present in Fig. 3 model calculations of F_{ch} by the Hannover group compared with data compiled by Frois that illustrate the "failure" of the nonrelativistic NN force models.

Fig. 2. Fourier transform of the ^3He point nucleon charge form factor (ρ_{exp}) compared with theoretical charge densities for the RSC potential model.

Fig. 3. Charge form factor calculations by the Hannover group compared with data compiled by Frois.

Table I

Triton binding energy (in MeV) as a function of the number of 3-body channels included in the calculation for the Reid-soft-core (RSC) and Argonne V_{14} (AV14) NN force models and the Tucson-Melbourne (TM) and Brazilian (BR) 3BF models. $\Lambda = 5.8\mu$ for all 3BF calculations.

N	RSC	RSC/TM	RSC/BR	AV14	AV14/BR
5	7.02	7.55	7.66	7.44	8.32
9	7.21	8.33	8.77	7.57	9.27
18	7.23	8.93	8.71	7.57	9.06
34	7.3 ^F	8.86	8.89	7.67	9.22

Adding a 3BF of the Tucson-Melbourne (TM) type does have an effect:

1. $\Delta B(^3\text{H}) \cong 1.5$ MeV (too much);
2. $\langle r^2 \rangle$ becomes too small;
3. E_{Coulomb} is changed little (charge-symmetry breaking does exist);
4. C_2/C_0 is improved;
5. F_{ch} increases by 50% in the region of the second maximum, but a factor of 3 is needed.

The TM 3BF overbinds (see Table I) but, as noted above, the πp and pp terms must still be added to the calculation. Clearly one can adjust Λ (the πN vertex cutoff) to obtain a value of the triton binding which agrees with experiment, as was pointed out by Payne and by Sasakawa. (The neutron-deuteron spin-doublet scattering length $^2a_{\text{nd}}$ is also brought into agreement with experiment, as was discussed by Chen.) The rms radii are then in reasonable agreement (see Fig. 4) with the experimentally extracted values reported by Martino (see Table II). However the form factor problem remains. This is illustrated in Fig. 5, where a comparison of results for the Tucson-Melbourne, Brazilian (BR), and Urbana-Argonne(UA) 3BF models are plotted along with the results for the the RSC model alone. The effect on the charge density is shown in Fig. 6. Introduction of a 3BF does lead to a "hole" in the

Table II

RMS radii (in fm) as determined by the Saclay analysis reported by Martino.

	charge	magnetic
^3He	1.93 (3)	1.93 (7)
^3H	1.81 (5)	1.80 (3)

Fig. 4. Theoretical values of the rms charge radii plotted versus the trinucleon binding energy as reported by Payne. The data are from a Saclay analysis.

charge density, but the density does not match Sick's Fourier transform of the charge form factor. (All densities in Fig. 6 are normalized to an integral of 1; the 3BF densities are pulled in due to the increase in binding energy.)

Conclusions which can be drawn from the bound-state workshop include:

1. First-order perturbation theory is inadequate for treating the 3BF. Second-order changes in the wave function are significant.
2. There is a large enhancement of the P-state component induced by the presence of a 3BF. (The 3BF contains gradient operators.)
3. At least 34 three-body channels must be included to obtain convergence. This means that one must include all NN force partial waves with $J \leq 4$ and both odd and even parity.
4. $\Delta B({}^3\text{H}) \cong 1.5$ MeV for the $\pi\pi$ models with a value of $\Lambda = 5.8\mu$ as determined by the Goldberger-Trieman relation. $B({}^3\text{H})$ is sensitive to the choice of, but not so much to the short-range properties of, the specific 3BF model used.

Fig. 5. The ^3He charge form factor calculated for the RSC potential model with and without a three-body force (TM, BR, and UA).

Fig. 6. Charge densities for the calculations shown in Fig. 5.

5. The NN-NA dispersion diagram is large and repulsive in the Hannover model, such that most of the attraction from the $\pi\pi$ exchange is canceled. This is a real effect arising from the nonstatic nature of the model. However, the N-A interaction is missing from the Hilbert space, which should cancel much of the repulsive contribution to $\Delta B(^3\text{H})$.
6. E_{Coulomb} and $\langle r^2 \rangle$ correlate strongly with the trinucleon binding.
7. The form-factor data are exquisite. The large- q data remain a mystery, although it is not clear that the nonrelativistic models being discussed are relevant. They are unlikely to be valid at the $\frac{1}{2}\%$ level, which is all the charge needed to fill Sick's "hole" in the Fourier transform of the ^3He form factor.

Further points of interest from the bound state workshop include:

1. As shown in Fig. 7, a calculation of the EMC effect for ^3He using Sasakawa's wave function yields a shape that compares favorably with the ^4He data from SLAC. Also, Wiringa stated that an analysis of the EMC effect in ^3He and ^4He in terms of the excess pion content of Ψ indicates that the EMC effect in ^4He should be about twice that of ^3He .
2. Sasakawa showed (see Fig. 8) that a y-scaling plot for $^3\text{He}(e, e')$ is not fitted by an NN force generated wave function and that including a 3BF does improve the fit. However, the improvement could be due just to increased binding and not dynamics.

Fig. 7. Calculation of the EMC effect for ^3He using Sasakawa's wave function compared with data for ^4He from SLAC.

Fig. 8. A calculation of y -scaling using Sasakawa's wave functions. The subscripts label the cut-off Λ in the three-body force.

3. Coester showed that the Lorentz invariance required in a relativistic formulation of a trinucleon calculation automatically introduces a 3BF, but the effect appears to be small compared to $\pi\pi$ 3BF effects.
4. The constituent quark model of ${}^3\text{H}$ (9 quarks in 3 nucleons) requires an antisymmetrization of the quarks which again automatically leads to a 3BF when viewed in a three-nucleon picture. The resulting 3BF effects in the triton energy appear to be small if the bag size is reasonable.

Long-Wavelength Continuum

The overlap in physics and interest between this Workshop and the bound-state Workshop was significant. The sizeable induced P-state in the ${}^3\text{H}$ wave function may

be a good clue as to where to look in this energy region for 3BF effects -- vector polarization. On the other hand, as noted by Redish, 3BF effects in the continuum problem may be suppressed because the volume in which all three nucleons are close together is small compared to the volume of the total interaction region.

It was clear from the discussion that exact, three-body formalism calculations are needed. The multiple-scattering series converges slowly, at best, below 100 MeV. Realistic NN input is required before the results of three-body calculations will be accepted by the community for small, quantitative effects. Higher partial waves must be included in any theoretical investigation.

There exists a wealth of data, much of it proton-deuteron. As Brandenburg summarized the situation, "In what must have been Nature's finest finesse, we were given the Coulomb interaction between protons, which entices experimentalists to measure proton-deuteron scattering and theorists to calculate neutron-deuteron scattering." The bad news is that we are still unable to treat the Coulomb problem well enough to do precision analysis of the beautiful p-d data. The good news is that the n-d data are now of precision comparable to that obtained in p-d scattering. This is illustrated in Fig. 9 from Tornow, where A_y is shown for both p-d (Grüebler, et al.) and n-d (TUNL) measurements. The question is, how can the physics be extracted? What observables might be sensitive to a 3BF?

The answers to these questions are not trivial. They depend upon the vigorous pursuit of theoretical calculations which are long and tedious as well as expensive in terms of manpower and computer time. At present there are only 4-5 groups in the world capable of such calculations. (Younger theorists with experience in these areas are being lost due to the lack of available positions.) On the experimental side, disagreement among some elastic-scattering data sets must be cleared up: A_y at 40 MeV is an example. The NN data must be improved. For example, ϵ_1 in the 3S_1 - 3D_1 channel is still not well determined -- $\vec{L}$ -p measurements are required. The $\delta_{\ell=1}$ amplitudes must be precisely known -- the 3BF has a p-wave character.

Experimental areas which were deemed to hold promise for exposing three-body force effects include:

1. Vector properties of elastic n-d scattering should be investigated further. Calculations by Koike show a sensitivity to $\delta_{\ell=1}$, and the 3BF induces large P-state components into the 3H wave function. In Fig. 10 one sees a definite disagreement between the p-d it_{11} data and calculation including only an NN force
2. Breakup experiments and calculations should explore the "star" and "collinear" geometries above 30 MeV. Analyzing power $\vec{n}$ -d data offer hope of exposing 3BF effects. Here 2% data are possible.
3. Sick pointed out that T_{20} in $\vec{n}d+^3He$ is sensitive to the D-state of the triton and therefore to the separate contributions of the isosceles triangle and collinear configurations in the ground-state wave function.

Fig. 9. Comparison of A_y for p-d and n-d from Tornow.

4. O'Connell proposed an interesting $^3\text{He}(\gamma, pp)n$ measurement in a geometry such that
 - a) there is no E1 transition and therefore no one-body operator (no dipole moment);
 - b) there is no M1 transition and therefore no two-body operator (no isovector MEC);
 - c) thus a 3-body current (hence 3BF) is required for a nonzero cross section.

Fig. 10. Comparison of p-d it_{11} data and an n-d calculation by Koike as reported by Brandenburg.

Intermediate Energy

The energy region in which meson production occurs is exciting because one can investigate those degrees of freedom which are important in generating a three-body force. It is here that one seeks a fundamental understanding of the degrees of freedom that make up the intermediate-range 3BF in terms of physically observed pions. Experiments at this energy investigate these degrees of freedom as they become active. Therefore, experiments such as those which measure T_{20} and it_{11} in nd scattering are of fundamental importance.

An important goal of electronuclear studies is the development of a consistent picture of the electromagnetic currents. A given potential in the Hamiltonian implies a certain form of the currents and vice versa. Experiments such as $^2H(e, e'p)$ and $^2H(\gamma, p)$ are called for to calibrate our modeling of the two-body currents. Then, experiments such as $^3H(e, e'N)$ and $^3He(e, e'p)$ are needed to test the adequacy of the models. Other experiments of interest in this endeavor include $^3He(\gamma, 2p)n$ and $^3He(\vec{e}, e'\vec{d})p$.

On the theoretical side, continuum calculations which treat properly final-state interactions are of prime importance for the analysis of $^3\text{He}(e,e')$ data. In addition, improved calculations are needed for guidance in planning coincidence measurements to test the two-body currents being used.

Short-Range Region

Because this area of research covers the future at machines which do not yet exist (except for SLAC), the short-term goals are difficult to define. Serious model efforts on the scale of the present Faddeev calculations (or larger) will be required. QCD model efforts to understand the nuclear 3BF obviously imply that much work must be done on the nucleon and nucleon-nucleon problems, because the three-nucleon problem becomes a 9 quark problem.

The antisymmetrization of three 3-quark bags obviously leads to three-body forces, when ^3He and ^3H are treated in terms of 3-quark nucleon clusters. Maltman reported estimates showing that these 3BF effects may be smaller than the $\pi\pi$ exchange effects. The dichotomy of the nucleon-meson models and quark models is difficult to define, as is illustrated in Fig. 11. A three-body force diagram due to the exchange of quarks among three-quark clusters can easily be distorted to look like the exchange of two pions in the hadron picture. The difficulty at present in our pursuit of the quark picture is that we must push QCD to a semi-quantitative description of the NN force before we can hope to explain the nuclear 3BF.

Experiments of interest to those of us working in the short-wavelength region include EMC on ^3He , Drell-Yan for proton-deuteron scattering, the ^3H form factor at high momentum transfer (a single-arm experiment for SLAC), $^3\text{He}(e,e'N)$ in the quasielastic region, and $^3\text{He}(e,e'2N)$.

Fig. 11. Comparison of a three-body force term in terms of three-quark clusters and quark-gluon exchange with a three-baryon description and pion exchange.

Concluding Remarks

Physics progresses in cycles. At present the experimentalists have leaped over our computational resources and are ahead of the theorists. This has not always been so.

We have taken giant strides in the last three to five years in our efforts to understand three-body forces in nuclear physics. (An indication of the interest in the topic is given by the fact that the organizers originally hoped for 60 participants and 120 came.) Unfortunately, we have reached only the end of the beginning of the investigation. However, that guarantees that much exciting research lies ahead!