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LA-UR -87-2037

CONF-870619--1

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LA-UR--87-2037

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TITLE RECENT RESULTS IN THE THEORY OF THE THREE-NUCLEON SYSTEMS

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SUBMITTED TO Proceedings of the "International Conference on the Theory of Few Body and Quark-Hadronic Systems", held at Dubna, USSR, June 16-20, 1987.

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RECENT RESULTS IN THE THEORY OF THE THREE-NUCLEON SYSTEMS

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INTRODUCTION

The few-nucleon problem plays a comparable role in nuclear physics to the few-electron problem in atomic physics. The relative simplicity of treating the interactions of only a few bodies allows us to solve the Schrödinger equation with a much greater degree of accuracy than we can attain for the case of many bodies. Precise measurements and accurate calculational techniques for H-like and He-like ions permit fine details in those atomic spectra (such as the Lamb shift) to be studied. Recently, for example, the Lamb shift in He-like Uranium was measured[1] for the first time. The interpretation of this result relies upon detailed and precise calculations of the energy levels of that system.

While nuclear physics experiments and calculations are rarely as precise as those of atomic physics, considerable progress has been made and continues to be made in our understanding of the few-nucleon systems, which are the testing ground for new ideas and mechanisms in nuclear physics. Much of this progress stems from improved calculational abilities, which has led in turn to consideration of interesting (but relatively small) physical mechanisms contributing to the properties of the trinucleons (and other nuclei). Before treating in detail such phenomena as meson-exchange currents, relativistic corrections, three-body forces, and subnuclear degrees of freedom, one must have control over the basic process of calculating Schrödinger eigenvalues and eigenfunctions. This control seems now to be largely in hand, at least for the trinucleon bound states.

Few-nucleon physics is such a rich and diverse field that only a small subset of topics can be reviewed here. Other results and topics will be stressed by other speakers. I will concentrate on calculational results obtained by the Los Alamos-Iowa Faddeev group[2] (LAFG) and on related calculations. Most of our interest has centered on the ^{3}He and ^{3}H ground states, including the effects of the Coulomb interaction between the two protons in the former. Very recently, a new member of our group (Joe Carlson) has made some exciting progress in treating the alpha particle[3]. I will also discuss zero-energy n-d and p-d scattering and our improved understanding of the scattering lengths for these systems. In addition to detailing results of our calculations I will attempt to provide simple physical pictures for these results, where possible.

CALCULATIONAL TECHNIQUES

A wide variety of calculational techniques exist for solving the Schrödinger equation, including the Raleigh-Ritz variational technique[3-7], the hyperspherical harmonic expansion[8-9], the Green's function Monte Carlo method (GFMC)[7,10], and the Faddeev procedure[11-13]. All of these have been used for the trinucleon bound states and for the α-particle. The august variational technique provides a rigorous upper bound for the energy, but does not generate a wave function whose quality matches that bound. Moreover, it is often not applied in a constructive manner; that is, it is not always clear how to systematically improve the wave function in order to lower the energy. For simple potentials, those without spin and isospin dependence (i.e., identical central forces for all nucleons), this technique can be extremely effective. This remark applies to all of the above mentioned methods[4]. The introduction of spin-dependence in general, and a strong tensor force in particular, can significantly alter the convergence properties of the first three methods, which must be evaluated on a case by case basis. Nevertheless, their implementation for the α-particle is not much more difficult than for the triton, which contrasts strongly with the Faddeev approach.[14]

The GFMC method is an old technique[10] which is enjoying a resurgence[3,7]; it is "exact" in principle within the Monte Carlo sampling errors. The "wave function" generated by this procedure is a random sample of points over the nuclear Hilbert space, which can be viewed as the representation of the exact wave function by a set of δ-functions. The Schrödinger equation in (imaginary) time, τ, is integrated forward with small time steps from an initial sample, and components of excited state wave functions (energy, E_n) decay exponentially with increasing time [$\sim\exp(-(E_n-E_0)\tau)$], leaving only the ground state component with energy E_0. This procedure converges to the lowest energy state of the Hamiltonian irrespective of the symmetry of that state under particle interchange. The general presumption is that (for Fermions) the totally symmetric state, rather than the totally antisymmetric state, lies lowest in energy, because Pauli Principle constraints increase the wave function complexity. By projecting the Monte Carlo distribution of δ-functions on a totally antisymmetric trial function, this problem vanishes "in the mean"; unfortunately this trick does not control the variance, whereby the "noise" in the energy distribution can grow uncontrollably and eventually will swamp the signal as one goes forward in time.

Recently, it has been found that in the A=3 and 4 systems (only), the totally symmetric ground states lie higher in energy than the antisymmetric ones and hence do not hinder the convergence. This unexpected result is simple to understand, if we note that isospin is the degree of freedom which adjusts itself to accommodate the symmetry, because the angular momentum barrier selects the S-waves (and tensor-coupled D-waves) as the dominant partial waves. In the symmetric channels, the $^1S_0$ partial wave has T=0 while $^3S_1$ has T=1, and the dominant long-range OPEP becomes repulsive. Other components of the force also become repulsive. At the present time only the Argonne V_6 potential[15] has been treated (central plus tensor forces, but no spin-orbit interaction or other angular-momentum dependence). Both the triton and α-particle problems have been solved, the former agreeing with the corresponding Faddeev calculations. Incorporation of the spin-orbit force is in progress. This technique has the potential to become the method of choice for solving the few-nucleon bound-state problems.

One of the problems which has faced our field until fairly recently has been the lack of benchmark calculations against which calculational procedures can be compared and checked. This situation has been alleviated by a number of very accurate Faddeev calculations for the triton[16-18]. The latter technique originates in the seminal work of L. D. Faddeev[11], who developed the method whereby scattering boundary conditions for three particles (as originally implemented for local potentials by Malfliet and Tjon[19]) could be properly implemented. It also provides an excellent procedure for solving for the bound states of three nucleons, although the asymptotic boundary conditions are not in doubt in that case (i.e., the wavefunction must vanish). Faddeev's original presentation and most of the subsequent bound state calculations were performed in momentum space[13]. The Sendai group[18] works in a mixed momentum-configuration space representation, while the Grenoble-(Montreal[20]-Leningrad[21]) and Los Alamos-Iowa groups[2] work in configuration space. The latter representation provides a natural way to incorporate[21,22] the pp Coulomb interaction into ^{3}He and ^{4}He.

The Faddeev method is traditionally implemented in a way which takes advantage of the angular momentum barrier for the loosely bound trinucleons. The nucleon-nucleon (NN) force is decomposed into an infinite number of (non-local, partial-wave) channels, each of which is nonvanishing only in a specific NN partial wave (e.g., $^1S_0$). This force is then truncated to a finite number of channels for the interacting pair (coupled to the remaining spectator nucleon) and the Faddeev equation, completely equivalent to the Schrödinger equation, is solved "exactly" for the truncated problem. Higher orbital partial waves are suppressed geometrically by the angular momentum barrier and the procedure converges rapidly. The original calculation[19] used 5 channels (all positive-parity NN partial waves with total angular momentum $J \leq 1$), and has progressed to 18[17] ($J \leq 2$) and recently to 34 channels[16,18] ($J \leq 4$). Contributions[23] to the Argonne[15] V_{14} potential energy are {-13.763, -39.082, -0.377, -0.103, -0.015, -0.0064, -0.0013, -0.0008, -0.0002} MeV for J = 0 → 8, while a kinetic energy of 45.670 MeV leads to a total energy of -7.678 MeV. The point is that one should not compare small-basis Faddeev calculations with other techniques which automatically assume all NN partial waves

TWO-BODY AND THREE-BODY FORCES

Triton calculations have been performed for a number of "realistic" NN interactions: Reid Soft Core[24] (RSC) [-7.36 MeV], the Argonne [15] V_{14} (AV14) [-7.68 MeV], Super Soft Core[25] (C) [-7.53 MeV], de Tourreil-Rouben-Sprung[26] (B) [-7.57 MeV], Paris[27] [-7.64 MeV] and Bonn[28] [-8.33 MeV][29]. All are 34-channel results[16,18], and with the exception of the Bonn result[30,31] are roughly 1 MeV too low. See also Ref. 17 and 31.

The latter potential has 3 significant features which presumably play some role in the increased binding. One feature of uncertain quantitative importance is the fact that the configuration space version of the most recent Bonn potential, like the Paris potential, has momentum-dependent components of the form $(\vec{p}^2, V)$, where $\vec{p}$ is the relative two-body momentum. Such terms were neglected in almost all of the older semiphenomenological potentials, but they arise naturally[32] and are in fact required by special relativity[33]. The second feature is the weaker tensor force in the various Bonn potentials[28] (there are many such potentials with disparate forms and ages). It has been known for several decades that weakening the tensor force increases the triton binding energy. The reason is that although the triton binding is very sensitive to the tensor force, the deuteron is even more so. Consequently, the obvious requirement for any potential that the deuteron have the correct binding energy leads, upon weakening the tensor force, to a significantly enhanced central force, which is more effective in the triton than the deuteron and thus increases the triton binding. Typical (but clearly unphysical) potential models without a tensor force overbind the triton.

The third feature which is salient is the fact that the potentials which are fitted solely to np scattering data are stronger than those fit also to pp data. The T=0 partial waves are determined solely by np data, but charge dependence of the force makes T=1 partial waves differ for the np and pp (or nn) cases; the s-wave scattering lengths prove this.[32] Consequently the $^1S_0$ potential for the AV14 and Bonn potentials, having been fit to np data, are stronger than those fit to pp data. Recently[34] we showed that if the tiny isoquartet (T=3/2) component of the trinucleon wave function produced by this charge dependence has a negligible effect, the appropriate T=1 NN force for use in the triton (assuming charge symmetry) is given simply by $(2V_{pp}/3 + V_{np}/3)$. Qualitatively this results from the 3 NN pairs in the triton being roughly 3/2 T=0 pairs and 3/2 T=1 pairs; there is one nn or pp pair (T=1), while each of the np pairs has a 3/4 T=0 (S=1) and 1/4 T=1 (S=0) weighting. Thus the force for the like particles (nn or pp) comes in with twice the weight of the unlike particles. The amount by which using V_{np} increases the binding over the "2/3-1/3 rule" given above is a model-dependent question, but simple estimates suggest that each "third" of a potential changes the binding energy by roughly 100 keV. Thus, using the 2/3-1/3 rule could reduce binding for np-fitted potentials by as much as .2 MeV and increase the binding for pp-fitted potentials by .1 MeV.

The quantitative reason why the recent Bonn potentials produce significantly more binding is under investigation by several groups[29-30]. One fundamental question must be borne in mind: Are the features of the Bonn potential which produce the additional binding subject to simple experimental verification (i.e., comparison with data), or are they based largely upon theoretical prejudice?

If the triton is underbound by 1/4-1 MeV, what mechanisms could produce the requisite additional binding? Attention has focused on relativistic corrections[35] and three-nucleon forces[33]. These are not necessarily separate categories; it is known that certain components of the most popular three-nucleon force models[36,37] are of order ($1/c^2$). It is worth remembering[16] that the relatively small binding energy of the triton results from the cancellation of large potential and kinetic energies (~50 MeV). Thus 1 MeV in additional binding is only 2 percent of the total potential energy, and relativistic corrections this large would not be unexpected.

What is a three-nucleon force? In any calculation we choose to perform, it is often convenient to "freeze out" certain degrees of freedom. These frozen degrees of freedom (and sometimes other mechanisms) lead to forces which depend on the simultaneous coordinates of three nucleons. A good example, and one which has merited a major amount of attention, is the Δ-mediated force[38], which Professor Sauer will discuss in greater detail. One nucleon can emit a π or ρ meson which polarizes a second nucleon into a Δ; the latter (virtual) state decays and the subsequent decay meson is absorbed by a third nucleon.

The methodology which has directed the development of the Tucson-Melbourne[36] (TM) and Brazilian[37] models of this force is similar to that which led to the Axilrod-Teller three-atom force[39]. The easiest to calculate (and therefore hopefully the most important) three-body forces are the longest-range ones. In atoms that force is the one caused by mutual (virtual) dipole excitations of the electron clouds (analogous to the van der Waals mechanism). In nuclei it is the one generated by exchange of the lightest meson, the pion. Fortunately for us this case is greatly aided by powerful theorems[36] which arise from chiral symmetry and restrict the long-range interaction (low-momentum regime) of the pion with a nucleon. Unfortunately, the short-range behavior is not similarly constrained, nor is the contribution from chiral-symmetry-breaking. The latter problem can be partially resolved by appealing to experiment (i.e., phenomenology). The biggest problem is the uncertain pion-nucleon form factor.

Calculations by the LAFG[16] and Tohoku[18] groups have shown that the TM, Brazilian and Urbana-Argonne[5] (UA) force models produce roughly 1.5 MeV additional energy for a particular choice of the π-N form factor. Unfortunately, the results are extremely sensitive to the range chosen for that form factor. Longer-range choices can generate much less additional binding (less than .25 MeV); the converse is also true. There is no question that three-body forces exist and play a role in the triton. The amount of additional binding, however, is problematical.

The Hajduk-Sauer model[38] has implicit three-nucleon forces, which arise because they do not freeze out the Δ-degrees of freedom. Rather, they incorporate Δ-components into the nuclear wave function. The HS model leads to roughly .25 MeV additional binding. Because the HS and TM models are very different, a detailed comparison has not yet proven possible. Professor Sauer will discuss his model in more detail.

TRINUCLEON OBSERVABLES

Although we have detailed the significant calculational progress which has been made recently, we still have a serious problem resolving the origin of the remaining binding energy in the triton. Different models lead to different results, and this situation will remain until potential models can be ruled out because they disagree in a significant way with data. A further complication is the lack of sufficient high quality NN data which constrain the tensor force. For common potential models this force generates more than half of the triton potential energy. This very difficult experimental problem is now being attacked by a number of groups, and significant progress can be expected in the next few years.

In view of this uncertainty, is there anything one can say about other trinucleon observables, such as the rms (charge) radii, the Coulomb energy of ^3He, and the s- and d-wave asymptotic normalization constants, the N-d scattering lengths, and the electromagnetic form factors of the trinucleons. Fortunately, the answer is (a qualified) yes[40]. Unless our understanding of the trinucleon binding is in serious error, many of these observables depend primarily on the binding energy, rather than on details of how the binding is obtained. This should not be too surprising, since the deuteron is a classic example of a weakly bound system, many of whose properties depend on this weak binding and on the nature of OPEP[41], the longest-range component of the NN force and a dominant element of the NN tensor force. Obviously all realistic force models contain OPEP. One immediate result is that the triton D-state probability should be 3/2 times the corresponding deuteron probability. This relationship works well[40] and results from 3/2 T=0 pairs in the triton.

If we plot the value of an observable versus the triton binding energy, E_B, for a variety of model calculations, the results in many cases show a clear dependence on E_B with little variance or spread. We can adopt the language of electromagnetic interactions (deep inelastic or quasielastic scattering) and say that "scaling" holds for these cases (i.e., there is only a single <u>effective</u> dependent variable). The tracking of the n-d doublet scattering length with E_B (the Phillips[42] line) and the α-particle binding with E_B (Tjon[14] line) are well known examples. Because we have solved many different two-body and two- plus three-body force models, which give a wide range of binding energies, we can use these solutions to investigate scaling of observables. That is, we adopt the philosophy that all of these models are undoubtedly flawed in details, but quantum mechanics and general features of the

NN force may constrain their predictions and give us critical insight. Our many calculations then will form a kind of "theoretical data set."

A good example of this process is the rms charge radius. Schematic trinucleons are depicted below in Figure 1. The protons are shaded. If all NN forces were identical we would have the equilateral configuration in (1a). The rms charge radius is the (mean) distance from the trinucleon center-of-mass (CM) to any one of the protons. Because the pp or nn force is weaker than the np force, the like particles actually lie further from the CM than the remaining unlike particle. Qualitatively, the angle θ in Figure (1b) is greater than 60° and the equilateral configuration (S-state) in (a) becomes isosceles in (b). The deviation of the isosceles from the equilateral configuration is a measure of the mixed symmetry S'-state. The geometry clearly indicates that the charge radius of ^{3}He is greater than that of ^{3}H. This is shown in Figure 2, a "scaling plot" of the rms charge radius $\langle r^2\rangle^{1/2}$ versus E_B for our theoretical data set. A point Coulomb interaction is included in the ^{3}He calculations. The data from a Saclay[43] analysis are in good agreement with the simple fits.

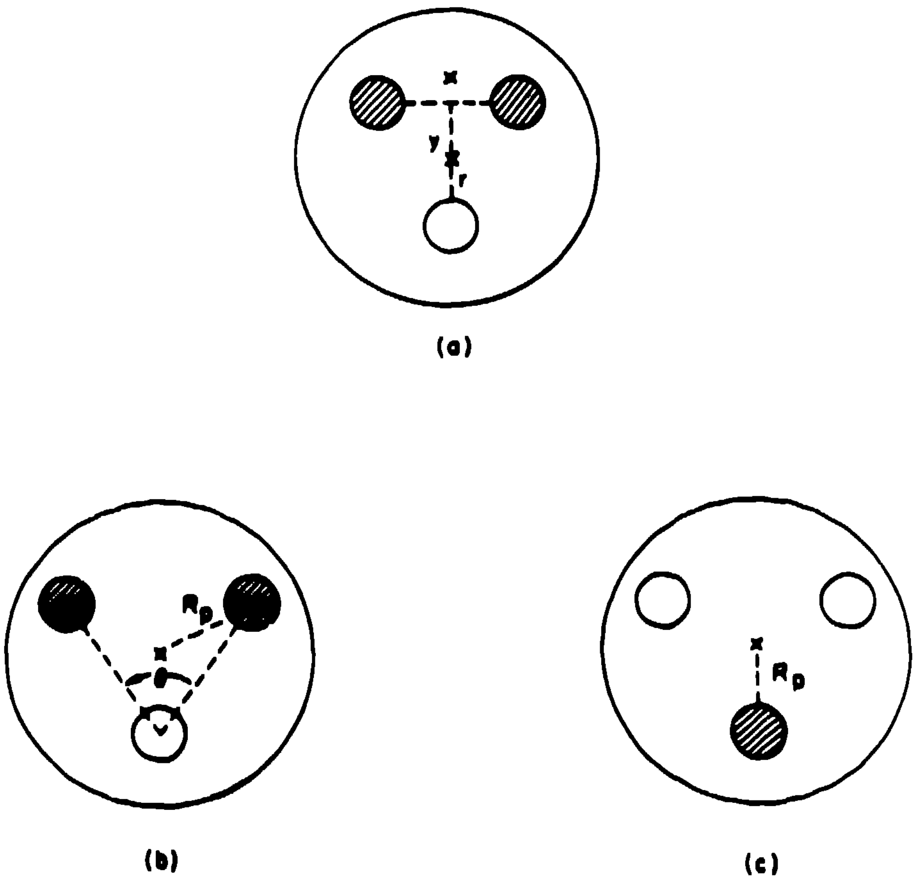

Figure 1. Schematic trinucleons with coordinates.

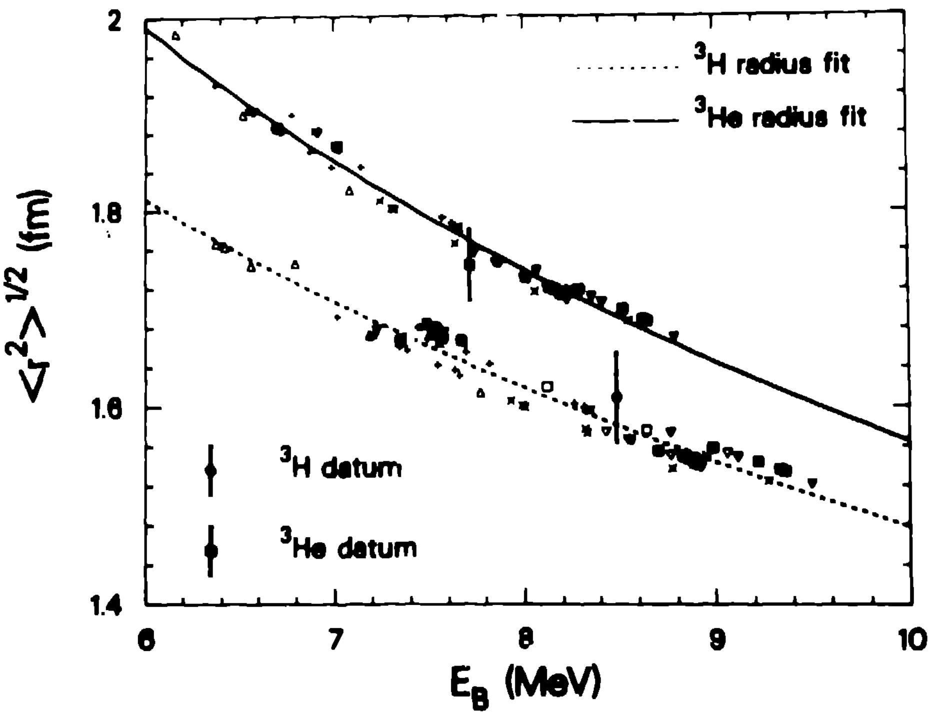

Figure 2. Scaling plot of rms charge radii calculations with fits and data.

The qualitative behavior can be easily understood. The mean-square radius is a matrix element which heavily weights the outer portion of the wavefunction, which schematically behaves as $\exp(-\kappa r)$, with $\kappa \sim (E_B)^{1/2}$. Assuming that the entire wavefunction has this form and performing the quadratures leads to $<r^2>^{1/2} \sim E_B^{-1/2}$. The isoscalar combination of rms radii $[(2<r^2>_{He} + <r^2>_H)/3]^{1/2}$, does indeed vary in this fashion, while the difference component, which is largely determined by the S'-state, decreases more nearly as E_B^{-1}. The latter behavior can be traced to the rapid decrease of the probability of the S'-state, $[P_{S'} \sim E_B^{-2}]$, as a function of binding. This trend has a large spread and does not manifest scaling as clearly as the rms radii.[40] Although not specifically included on our plot, the Bonn result[29] falls on the ^{3}H curve.

The weak pp Coulomb force produces two competing effects[22] on the ^{3}He charge radius. The Coulomb interaction lowers the binding energy and this increases the radius. In addition the asymptotic form of the wavefunction is changed from a Hankel function (exponential) to a Whittaker function, which falls more rapidly at large separations, thus lowering the rms radius. These two effects are seen clearly in Figure 3.

The Coulomb energy of ^{3}He has long been known to be smaller than the 764 keV binding energy difference of ^{3}He and ^{3}H. The first quantitative demonstration of this was given by Fabre de la Ripelle[44] and Friar[45], who derived a simple

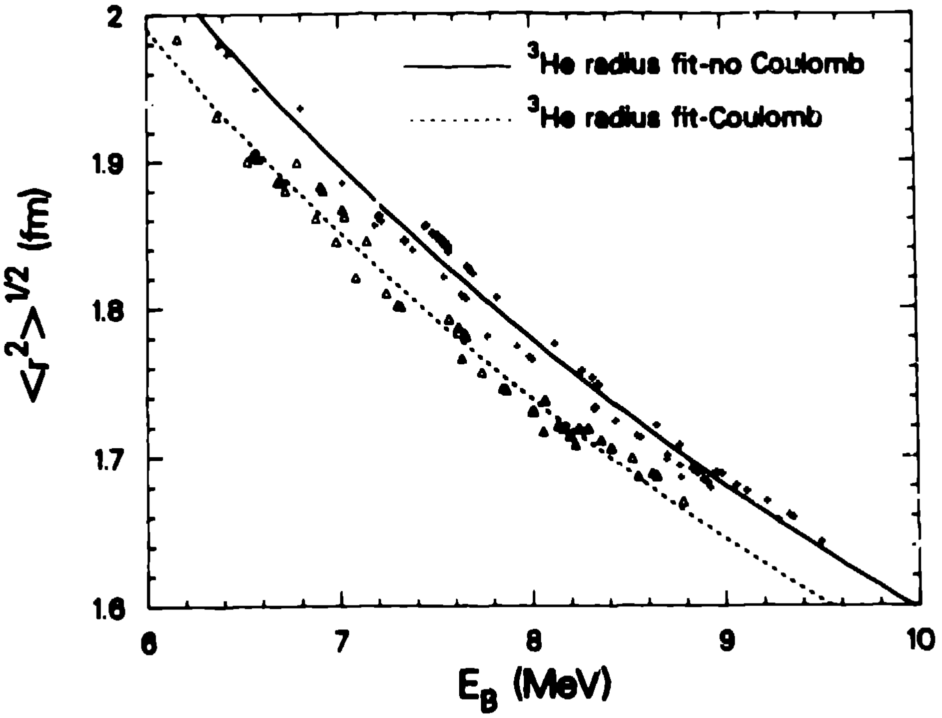

Figure 3. Scaling plot of ^{3}He rms charge radius calculations, with and without a Coulomb interaction.

approximation to the Coulomb energy which allowed experimental electron scattering data to be used to estimate that energy. The simplest version of that formula can be derived from Figure 1. The (point-nucleon) Coulomb potential in Figure (1a) is α/x, where α is the fine structure constant. If the trinucleons are primarily in an equilateral configuration, we can replace x by $\sqrt{3}r$, which in effect replaces the two-body correlation function by the charge density: $E_c = \langle \alpha/x \rangle = (\alpha/\sqrt{3})\int d^3 r \rho_{ch}(r)/r$. This simple approximation can be extended to include mixed-symmetry wave function components and the proton's charge distribution. It can be demonstrated[22] to work at the 1% level by calculating both sides of the relationship. If experimental data are used for ρ_{ch} one finds $E_c = 638 \pm 10$ keV. A scaling plot of E_c versus E_B, taking account of the proton's charge distribution, is shown in Figure 4. It produces $E_c = 652$ keV at $E_B = 8.48$ MeV. The slightly larger number results from the inability of theoretical wave functions to reproduce the inner portion of $\rho_{ch}(r)$, which leads to a small increase in E_c. The additional 100 keV which is needed is due to other direct and indirect charge-symmetry-breaking mechanisms.

Another important set of observables are the asymptotic normalization constants[29,46]. If one stretches the triton until a deuteron is outside the force range of the remaining neutron, the wave function becomes proportional to an exponential ($\sim\exp(-\beta y)$), where y is the relative coordinate of the two systems and β

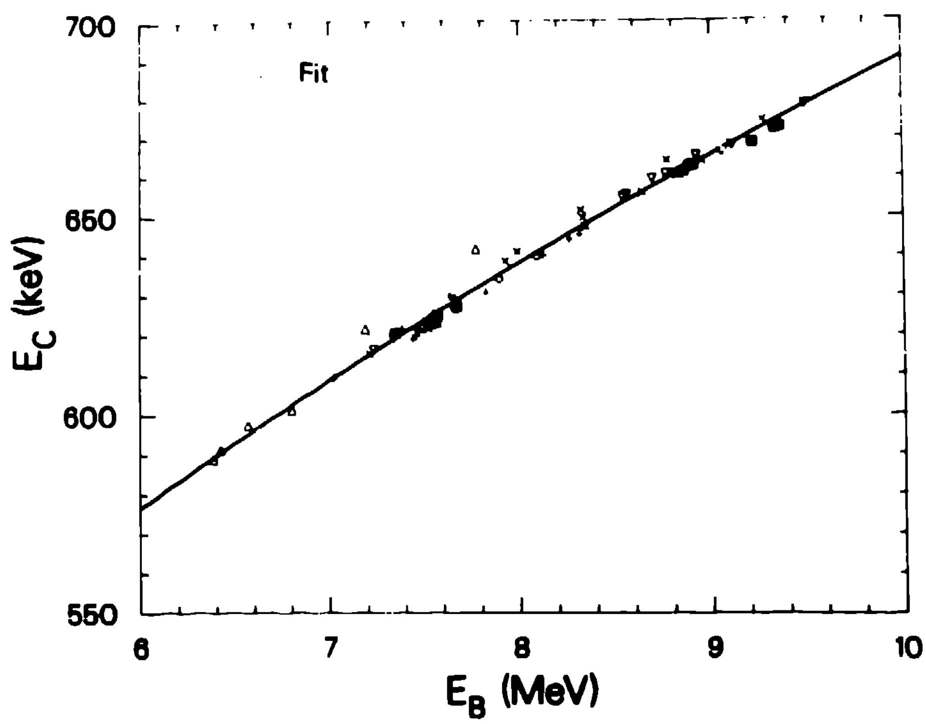

Figure 4. Scaling plot of ^{3}He Coulomb energy.

proportionality constant is the asymptotic normalization. Because of the NN tensor force, there are actually 2 constants, one for s-wave (C_S) and one for d-wave (C_D), and their ratio, $\eta = C_D/C_S$. There has been considerable recent interest in these constants for the analogous deuteron problem/41/. Because the wave number β increases as triton binding increases, the asymptotic wave function becomes steeper and probability decreases in the exterior region. It becomes easier for the asymptotic wave function to match smoothly onto the interior portion if the asymptotic normalization constant increases as the binding increases. Each constant (C_S, C_D and η) increases with energy, as illustrated by η in Figure 5. Both ^{3}H and ^{3}He (with a Coulomb interaction) are shown together with data.

The scattering of a nucleon from a deuteron at very low energies leads to two scattering lengths: doublet (a_2) and quartet (a_4). The latter is not very interesting, being primarily sensitive to the deuteron binding energy. The former, however, reflects the underlying dynamics of the triton, but perhaps in a trivial way/47/. Figure 6 shows the results of n-d and p-d doublet scattering length calculations at Los Alamos/48/ for a variety of realistic and unrealistic two-body and three-body force models, plotted versus the corresponding ^{3}H or ^{3}He binding energy. The n-d case scales according to the "Phillips line" and passes through the datum. The p-d case does not and is controversial because of the existence of

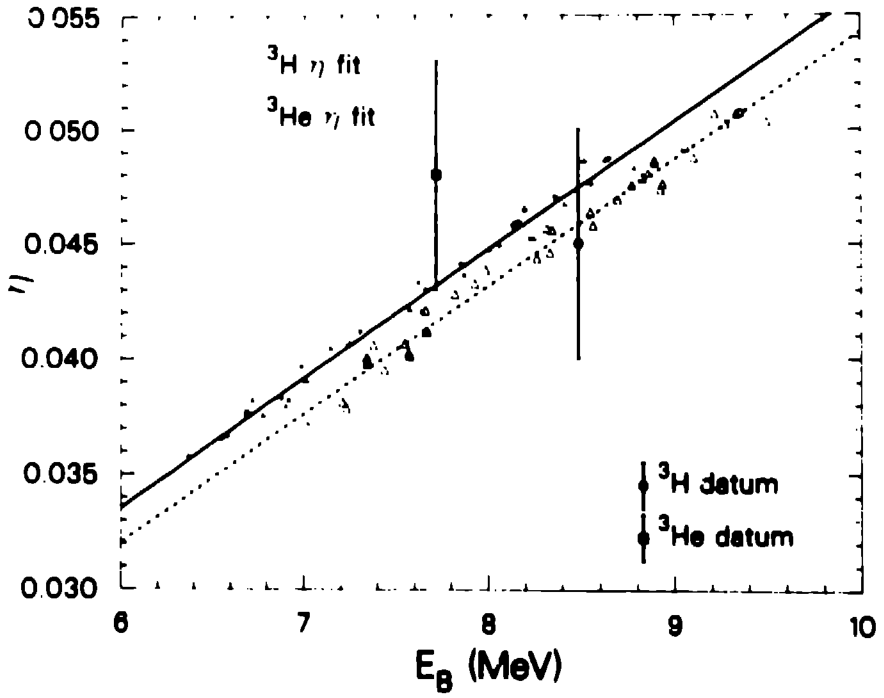

Figure 5. Scaling plot of asymptotic D/S ratio, with fits and data.

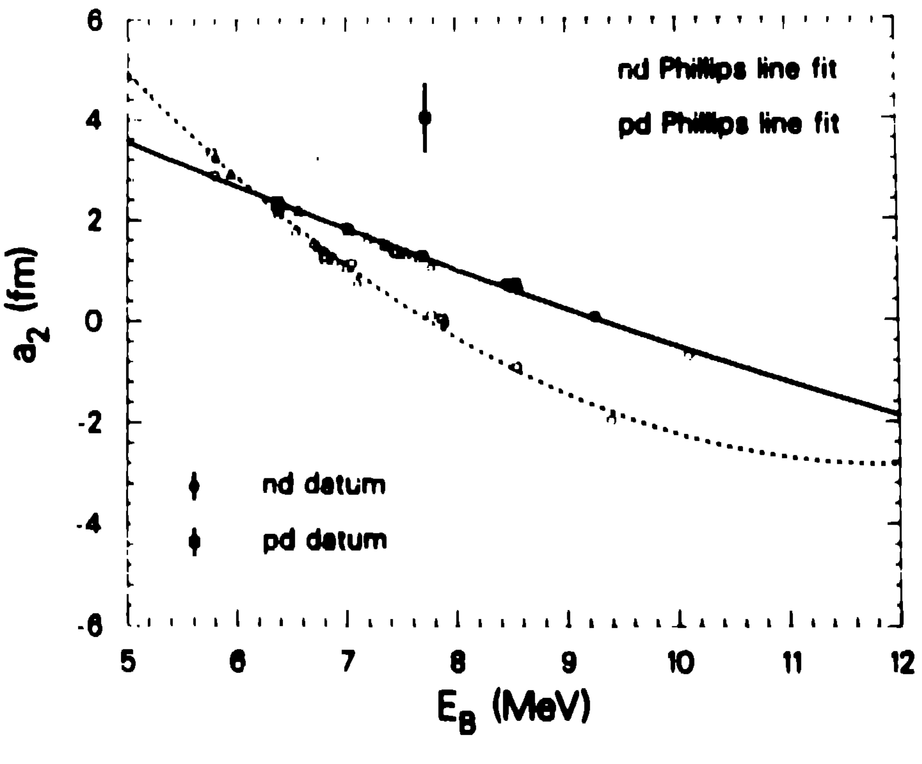

Figure 6. Phillips curve for Nd doublet scattering lengths, with fits and data

extremely weak long-range polarization forces ($-1/r^4 + \ldots$), which nevertheless affect the definition of the scattering length. Recently it has been shown that a proper treatment of these long-range forces, should produce a negligible change in a_2, although some care needs to be exercised[49,50]. There is still an unresolved discrepancy between the results of Refs. 48 and 51, and those of Ref. 52.

Our final topic concerns the charge densities of the trinucleons, ^{3}He and ^{3}H. Our community has long awaited the ^{3}H experiments, recently completed at Saclay[43] and Bates[53]. Figure 7 depicts the point-nucleon ^{3}He charge density calculated[54] for the RSC two-nucleon interaction and different three-body forces (TBF). None of the results reproduce the "hole" in the quasi-experimental data, where the effect of the nucleon's charge form factor has been removed. Figure 8 shows the analogous ^{3}H calculation. The three-nucleon forces show a tendency to produce a hole in the interior of $\rho_{ch}(r)$, but it is inadequate. The hole reflects the failure of the calculations to reproduce the value (and position) of the secondary maximum in the charge form factor. Figure 9 displays the ^{3}H form factors for the same cases, together with data[43]. Among the explanations proposed for this discrepancy are relativistic corrections and meson-exchange currents.

SUMMARY

There has been much progress in our understanding of ^{3}He and ^{3}H recently. Faddeev calculations of high accuracy are now possible for binding energies and other observables. This has led in some cases to both quantitative and qualitative descriptions. We still have an incomplete knowledge of the triton binding at the level of roughly 1 MeV.

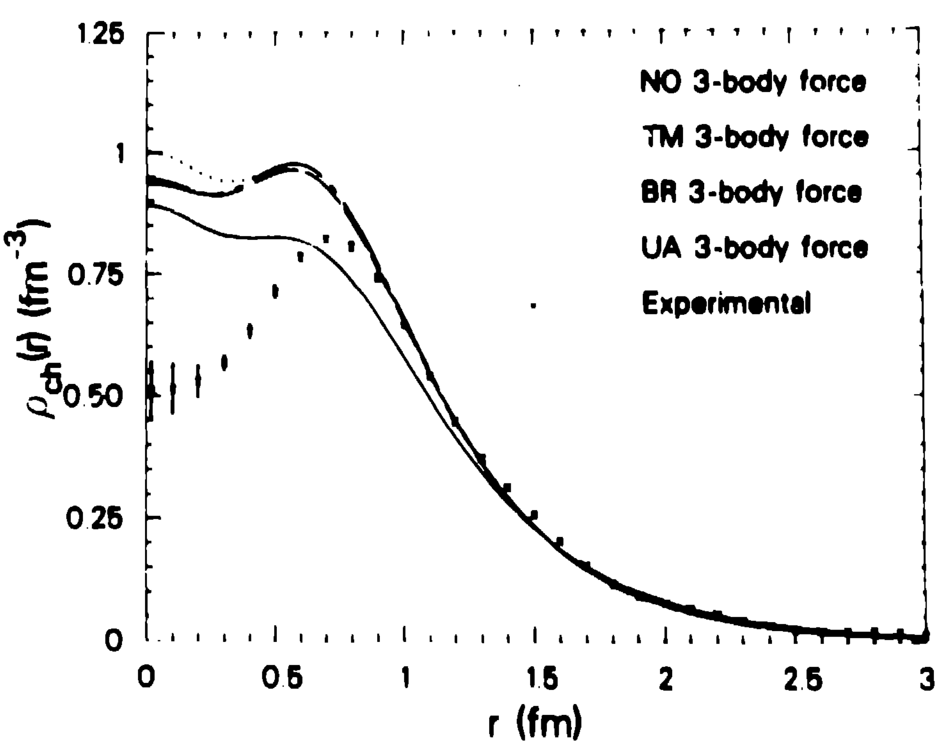

Figure 7. RSC ^{3}He charge densities for various TBF models, with data

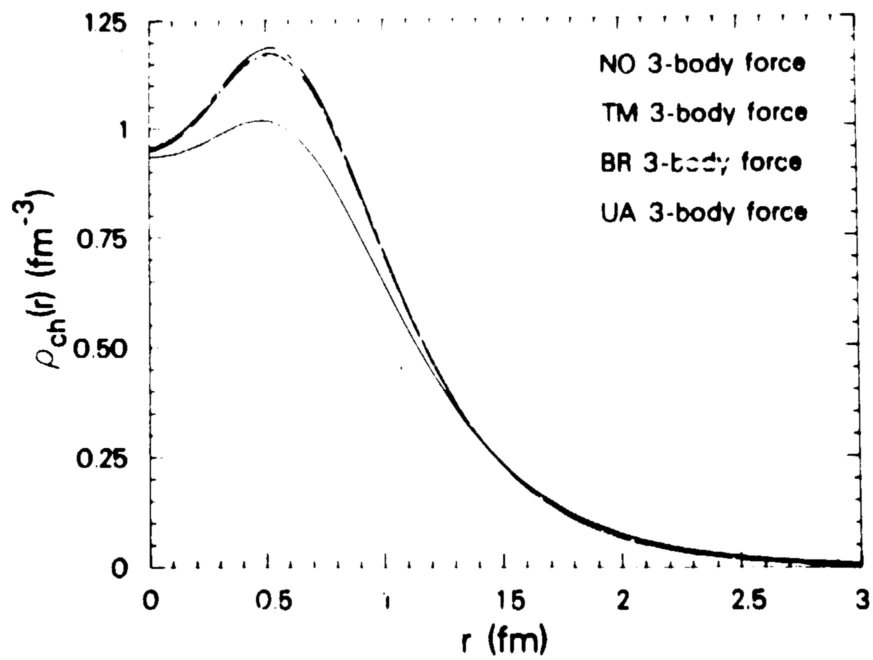

Figure 8. RSC ^3H charge densities for various TBF models.

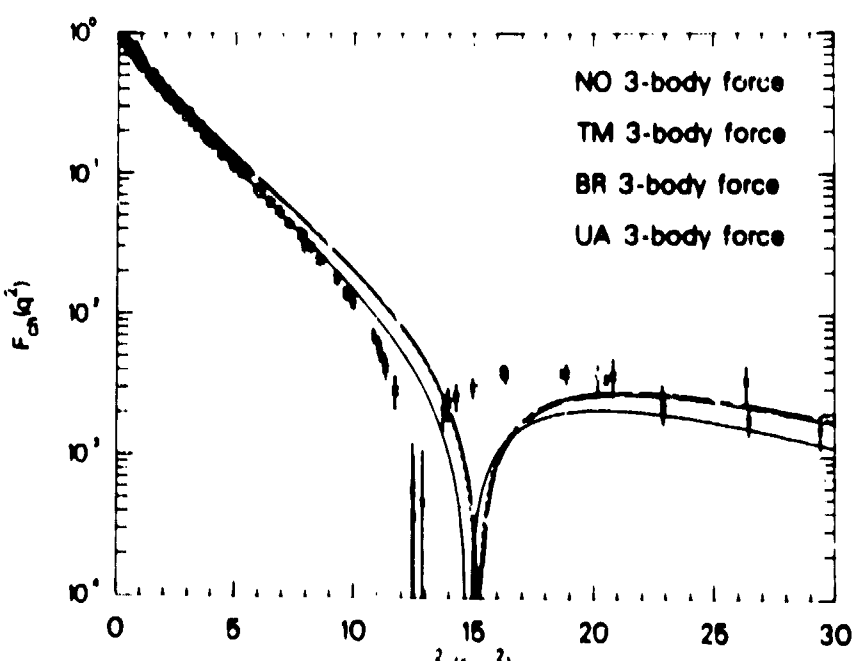

Figure 9. RSC ^3H charge form factors for various TBF models, with data

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