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Fifty years of the quasi-deuteron model

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A half century ago several physicists used two-nucleon correlations in nuclei to interpret reactions in which a single nucleon has a high momentum: capture of slow negative pions, the high momentum tail on the Fermi distribution, and the high energy photoeffect. I christened this model the 'quasi-deuteron model'. Recently physicists used the quasi-deuteron model for proton-proton pairs produced by fast positive pions, for deuteron knock-out by electrons, and for elastic electron scattering by nuclei at high momentum transfer. The quasi-deuteron model agrees with the relation between measurements of deuteron and trinucleon form factors for momentum transfers from 0.05 to 0.84 $(\mathrm{GeV/c})^2$.

1. Introduction

In this paper I'll spend some time on the early history of the quasi-deuteron model: Heidmann 1948 and 1950, and Levinger 1951. Then I'll comment on calculations on the trinucleon. Then I'll jump to my last student's PhD thesis, Gangopadhyay 1990, and our papers, Gangopadhyay 1992 and 1993. I returned to our work with an addendum, Levinger 2000, prompted by recent measurements of Abbott 2000a, 2000b, on the deuteron monopole form factor.

This paper is somewhere between a memoir and an incomplete review of nucleon correlations in nuclei. For a less incomplete review see Antonov's 1993 book.

Figure 1, from data in Levinger 2000, shows absolute values of form factors as the ordinate (on a logarithmic scale) vs. the squared momentum transfer in $(\mathrm{GeV/c})^2$. The points show the deuteron monopole form factor: squares show earlier work, and diamonds show Abbott's work. The curve shows the trinucleon isoscalar charge form factor, evaluated at 3 $q^2/4$, and then divided by 1.9. I use Amroun's 1992 compilation. Why do we use isoscalar? Why do we use $3q^2/4$? Why do we divided by 1.9? See below.

For the moment postponing these questions, look at Figure 1. We see excellent agreement between the curve and the deuteron points, if we ignore the first two points and the last four points. The form factors vary over a factor of hundreds in the region where curve and points agree. The disagreement at small momentum transfer is explained below; and I'll suggest possible explanations for the disagreement at large momentum transfer.

2. Early history

A half century ago we believed that nuclei were composed of nucleons. We knew that pions could be important; but we didn't know about quarks. (See Carlson 1997 and Sterman

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1997.) We tried to understand certain processes that couldn't happen for free nucleons, or needed high momentum. In 1948 Heidmann studied the production of "stars" by nuclear capture of slow negative pions. Also see Tamor 1950. Correlations are needed: perhaps two-nucleon correlations, or perhaps four-nucleon correlations. Experiments favored the alpha particle model of correlations.

In 1950 Heidmann returned to two-nucleon correlations when he worked with Hans Bethe at Cornell. He used the model to calculate the high momentum tail on the momentum distribution of nucleons in a nucleus, and the resulting cross section for "pick-up" of fast neutrons. He found agreement with experiment.

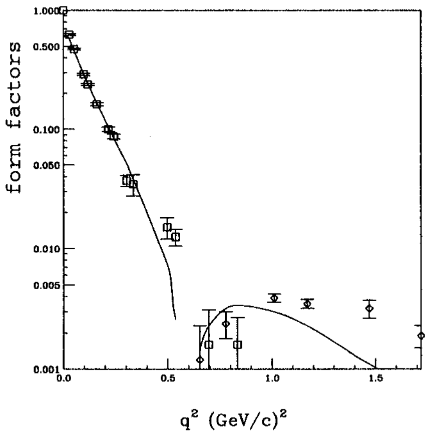

Figure 1. Form factors: squares and diamonds for deuteron–the latter for recent measurements–and curve for trinucleon. See text.

I was also working with Hans Bethe at Cornell where we had a 300 MeV betatron. Bob Wilson wanted to measure Compton scattering by the proton; but hydrogen targets weren't available. So he used the difference between paraffin and graphite targets. But the emission of fast protons from graphite dominated. How could this happen? Hans Bethe suggested that these fast protons came from the carbon photoeffect, with two-nucleon correlations based on Heidmann's model. In my 1951 paper I argued that for the photoeffect (in the electric dipole approximation) we need to consider only neutron-proton correlations: the continuum state of a deuteron. So I used the name "quasi-deuteron" model.

I used the experimental value of the nuclear density, and found that the ratio of the nuclear to the deuteron photoeffect was 8 NZ/A. I also calculated the energy spectrum and angular distribution of high energy protons from carbon, and found agreement with experiment. I proposed experiments on neutron-proton coincidences, measured in 1956 by Wattenberg. Note that Khokhlov independently proposed the quasi-deuteron model in 1952.

Subsequent work by Dedrick in 1955 and Gottfried in 1958 refined the quasi-deuteron model. It remains a heuristic model, like the much better known nuclear shell model, or nuclear collective model. See my 1961 book on the nuclear photoeffect.

3. The trinucleon

A third of a century ago I and some excellent RPI graduate students joined the lively field of calculations on the trinucleon (^{3}H and ^{3}He). I reviewed our and other calculations and experiments in 1974. Given the two-body potential we have several accurate methods to solve the Faddeev equations. At RPI we used both separable approximations and expansions in hyperspherical harmonics.

A tenth of a century ago I finally realized that we now had an example to test the accuracy of the quasi-deuteron model: compare the deuteron and trinucleon wavefunctions. See Gangopadhyay's 1990 RPI thesis, and our 1992 paper. The trinucleon wavefunction depends on two vectors, the Jacobi coordinates **x** and **y**; while the deuteron wavefunction depends only on **y**, the separation of a pair of nucleons. Gangopadhyay showed that for high momentum the trinucleon wavefunction factors to a good approximation to a product of a function depending on **p** and a function of **q**. (These are the momenta conjugate to the Jacobi coordinates.) The proof is simple: see for instance my 1974 eq. (5.18) with a change of notation.

$$w(\mathbf{p},\mathbf{q}) = h(q)g(p)/(E_T - 3q^2/4 - p^2) \tag{1}$$

E_T is the trinucleon energy. For high momentum p, w factors.

Gangopadhyay also tested the accuracy of factorization: it is good to about 10% for small y.

4. Electron scattering from the trinucleon

After Gangopadhyay passed her thesis defense, I was driving in Vermont and thinking about her thesis. I thought "if the trinucleon wavefunction does factor, then the trinucleon form factor for elastic scattering should be proportional to the deuteron form factor. But that can't agree with experiment! How do we get out of this paradox?" When I returned to RPI Gangopadhyay and I looked at the paradox and it disappeared!

Consider the triton in the quasi-deuteron model, and assume that the triton wavefunction z(**x**,**y**) is unchanged by exchange of the two Jacobi coordinates:

$$z(\mathbf{x},\mathbf{y}) = N^{1/2}u(x)u(y) \tag{2}$$

where u is the deuteron wavefunction. See Gangopadhyay 1992 eq (13) in different notation. Now x = $3^{1/2}\, r_3$, and $\mathbf{y} = \mathbf{r}_1 - \mathbf{r}_2$. Using algebra we find (Gangopadhyay eqs. (14) through (18))

$$G_E(3q^2/4) = NG_0(q^2) \tag{3}$$

Here G_E is the trinucleon form factor, G_0 is the deuteron form factor, and N is the number of quasi-deuterons in the trinucleon.

I return to Figure 1. Why do we used the isoscalar charge form factor for the trinucleon? See Gangopadhyay 1993: we want to use the completely symmetric S state of the trinucleon. Why do we use the monopole moment for the deuteron? Because the trinucleon doesn't have a quadrupole moment. And why use N = 1.9 in Figure 1? Gangopadhyay in 1993 gave four other determinations of the value of N. Her thesis gave N = 2.1; Laget's 1989 calculation and the 1991 measurements by Audit each gave N = 1.7; and Kolb's 1991 photoeffect measurements gave N = 2.1 The average value of N I used gives the good fit shown with no adjustable parameters.

My 1951 calculation, if applied to the trinucleon, gives N = 5.3; but since the trinucleon has a much lower density than a heavy nucleus, it should have a smaller value for N. Also, from eq. (1) we don't expect the quasi-deuteron model to hold for small values of q. So the disagreement shown in Figure 1 for the two lowest value of q is as it should be.

5. Recent work

In 1995 Hennings studied the relation between calculated form factors for the deuteron and trinucleon, for a specified potential. He found a relation similar to Gangopadhyay's: $G\_E(a\ q^2 + b)$ is proportional to $G\_0(q^2)$,with a = 0.60 and b = 0.1 $(GeV/c)^2$. (Gangopadhyay and Figure 1 uses a = 0.75 and b = 0.)

Tripp in 1997 measured deuteron knockout from inelastic scattering by ^{3}He. He found that the isotriplet quasi-deuteron gave an unexpectedly large contribution to the reaction.

Carlson, and also Sterner, in 1997 reviewed theory and experiment on elastic scattering at high momentum transfer. They give rules, based on perturbative quantum chromodynamics for quark-counting. The deuteron form factor should be proportional to q^{-10} and the trinucleon form factor to q^{-16}: so they couldn't be proportional. But is the momentum transfer region covered in Figure 1 high enough to use quark counting? It seems likely that the squared momentum transfer should be larger than 10 $(GeV/c)^2$ for quark counting to hold; but perhaps we feel the influence of quark counting above 1 $(GeV/c)^2$. In 2000 I suggested two other explanations for the deviation of data from the curve at high momentum transfer. First, Abbott's measurements have not been confirmed by others. Second, Amroun's trinucleon form factors use an extrapolation to high momentum transfer for the triton.

6. The next decade

Other physicists at this conference also work on two-nucleon correlations: see Grabmayr, Kaptari, Pacati, Ryckebusch, Lehr, and Gaidarov; and also Jones for the region of validity of quark counting.

Does the quasi-deuteron model work for form factors of nuclei with mass number more than 3? Gangopadhyay in 1992 found that it did work for the alpha particle: either $G_4(3q^2/4)$ or $G_4(2q^2/3)$ are proportional to the (then poorly known) deuteron $G_0(q^2)$. In Figure 2 I compare $G_4(2q^2/3)$ with Abbott's data for the deuteron. (With the more accurate deuteron data, our earlier choice of 3/4 doesn't work.) The alpha particle form factor is from Arnold, 1978. I divide by 1.7: i.e., an alpha particle contains 3.4 quasi-deuterons. Again we find excellent agreement for a large range of momentum transfer. But why use 2/3, instead of the value 3/4 justified for the trinucleon by Gangopadhyay?

Quark-counting gives a q^{-22} for the alpha particle form factor; so we would expect more serious disagreement between curve and deuteron data in Figure 2 than we found in Figure

1. Since this does not happen, I now question quark-counting rules as the explanation for the high momentum disagreements shown in the two figures.

In summary, the quasi-deuteron model has had many successes in its first half century. We need to find more successes and also failures in the coming decade. Any model (shell, collective, or quasi-deuteron) has a limited region of validity.

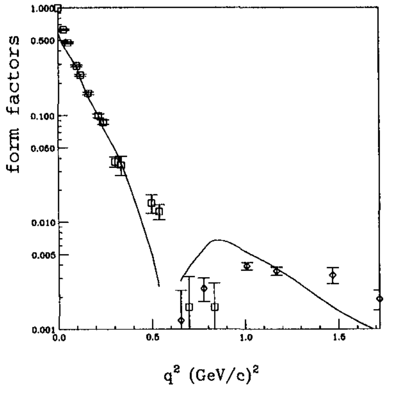

Figure 2. Form factors: deuteron (squares and diamonds) and curve for alpha particle

7. Acknowledgement

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