QUARTET n–d SCATTERING LENGTHS

J.L. Friar, D. Hüber

Theoretical Division, Los Alamos National Laboratory
Los Alamos, NM 87545, USA

H. Witała

Institute of Physics, Jagellonian University
Reymonta 4, 30-059 Cracow, Poland

and G.L. Payne

Department of Physics and Astronomy, University of Iowa
Iowa City, IA 52242, USA

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Quartet n–d scattering lengths are calculated using second-generation nucleon-nucleon potential models. These results are compared to the corresponding quantity recently calculated using chiral perturbation theory.

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Solving exact few-body equations offers a possibility to test the present understanding of nuclear forces by direct comparison of theoretical predictions with experimental data. It is the scattering problem which provides the real opportunity to explore in depth the accuracy of our knowledge of the nucleon–nucleon interaction. Neutron–deuteron (n–d) elastic scattering at zero incident energy is the simplest three-nucleon scattering problem. At this energy only the s-wave scattering lengths survive. In the limit of relative n–d momentum $q_0 \to 0$ the eigenphase shift in the total angular momentum $3/2$ state can be written in terms of quartet n–d scattering length a_4 by

$$\delta_4(q_0) \to -a_4 q_0 \,. \tag{1}$$

Accurate calculations of n–d quartet scattering lengths were first performed 10 years ago [1]. This quantity is known to be insensitive to most physics,

such as $\ell > 0$ partial waves of the nucleon–nucleon (NN) potential and three-nucleon forces, because of constraints arising from the Pauli principle. The low (actually, zero) energy of the incoming neutron emphasizes s-waves, while the quartet spin emphasizes $S = 1$ between the two neutrons, which combination is Pauli forbidden. This reaction at zero energy depends only on details of the deuteron s-wave for an accurate calculation.

The potentials of a decade ago (sometimes called "first-generation" potentials) were not particularly accurate fits to the NN data base (or even to the data bases in use when those potentials were constructed). Deuteron properties, such as binding energies and asymptotic normalization constants, had considerable variations. Thus, it is not surprising that three-nucleon properties showed considerable spread due to these indifferent fits, although it was never clear in advance which properties were suspect. One such property was a_4, the n–d quartet scattering length, where values of 6.304 fm and 6.380 fm were obtained [1] for the RSC [2] and AV14 [3] potential models, respectively. Variations of these numbers due to partial-wave limitations or three-nucleon forces are of the order of $10^{-3}a_4$ (or less), which is much smaller than the potential-model difference. Such minimal influence of three-nucleon force effects and higher nucleon–nucleon partial waves is due to the fact that Pauli repulsion for three nucleons in the same spin state keeps the nucleons apart.

Recently, a new class of potentials has been developed (sometimes called "second-generation") that provides greatly improved fits to the NN data base [4, 5]. Only a single calculation [6] of a_4 exists for a single second-generation potential model (AV18) [5], and that result lies between the RSC and AV14 results listed above. Until very recently, no particular motivation existed for revisiting the a_4 calculations.

Chiral perturbation theory [7] (χPT) provides an alternative path (to conventional potentials) for calculating few-nucleon observables. Scattering amplitudes are constructed directly from a field theory, employing one or another scheme of regularization and renormalization. In this fashion the first three-nucleon calculation exploiting chiral perturbation theory was recently performed [8] for the observable a_4. The result, 6.33(10) fm, lies between the RSC and AV14 results quoted above, which motivates this brief update of the theoretical situation.

We have calculated a_4 for a variety of second-generation NN potentials listed in Table I. These include the Nijmegen 93 (N93; nonlocal), the Nijmegen II (N II; partial-wave local), the Reid soft core 93 (RSC93; partial-wave local), the CD-Bonn (CDB; nonlocal), and the Argonne V18 (AV18; local) potentials. The large difference (>1%) seen between the previous (first-generation) potential-model results is not reproduced in our five (second-generation) results, which are within a factor of 2×10^{-3} of each other. We

TABLE I

Quartet *n-d* scattering lengths (a_4, in fm) calculated using potential models and χPT, together with the experimental value.

type	N93 [4]	N II [9]	RSC93 [4]	CDB [10]	AV18 [5]	χPT [8]	Expt. [11]
a_4	6.346	6.343	6.353	6.350	6.339	6.33(10)	6.35(2)

also note the AV18 potential contains an electromagnetic force that must be turned off in momentum-space procedures in order to obtain a result. We have determined using a configuration-space approach [1] that eliminating this force component lowers a_4 by approximately 0.018 fm, which is a very small change. Our result in Table I incorporates the complete force, and is slightly larger than that of Ref. [6]. All (second-generation) theoretical results agree with the experimental value.

The large discrepancy seen for first-generation potentials has vanished. Second-generation potential results are now in close agreement with the χPT result. Although the latter has a relatively large theoretical error bar, that error reflects an estimate of uncalculated higher-order Lagrangian terms. Given that these would roughly correspond to small components of the nuclear potential (which scarcely affect the result), it seems likely that the error is overestimated for this reaction.

In summary, second-generation NN potential calculations of a_4 are in much better agreement with each other, and with chiral perturbation theory, than were older first-generation potential calculations.

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