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## BRIEF REPORTS

*Brief Reports are short papers which report on completed research or are addenda to papers previously published in the* **Physical Review**. *A Brief Report may be no longer than $3\frac{1}{2}$ printed pages and must be accompanied by an abstract.*

# Neutron-triton cross sections and scattering lengths obtained from $p$-$^3$He scattering

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An approximately Coulomb-corrected, charge-symmetric $R$-matrix prediction for $n$-$^3$H scattering from analyzing $p$-$^3$He data is described, which deviates at most by 2% from the $n$-$^3$H total cross section. The total cross section, together with a new measurement of the coherent scattering length now allows two possible sets of singlet and triplet scattering lengths $a_s$ and $a_t$. Our analysis agrees well with the new value of the coherent scattering length, and determines the set with $a_s/a_t > 1$ to be the correct one.

After years of relative experimental inactivity for $n$-$^3$H scattering, it was realized in the late 1970s that the existing low-energy measurements were inconsistent. Curves corresponding to the then-accepted values of the zero-energy total cross section,[1] $\sigma_T = 1.3$ b, and the coherent scattering length,[2] $a_c = 3.82$ fm, had no intersection[3] when plotted versus the singlet and triplet scattering lengths $a_s$ and $a_t$, respectively.

A more recent measurement[4] of the total cross section extrapolates to a much higher zero-energy value (1.7 b) than does the previous one, as was supported by a preliminary calculation of the type described below. This value intersected the $a_c$ curve almost tangentially, with the result that $a_s \approx a_t$.[5,6]

Here, we describe a calculation of the $n$-$^3$H total cross section and scattering lengths obtained from $p$-$^3$He $R$-matrix parameters[7] by using charge symmetry plus a simple correction to account for internal Coulomb differences between the $p$-$^3$He and $n$-$^3$H systems. The single parameter involved in this correction is refined to obtain improved agreement with the newer $\sigma_T$ measurement,[4] and then is used to predict the values of $a_c$, $a_s$, and $a_t$ for $n$-$^3$H scattering. These values differ significantly from the expectation that $a_s \approx a_t$.

If nuclear forces were charge symmetric, $n$-$^3$H scattering would be described by the same parameters as $p$-$^3$He scattering, except for Coulomb corrections. $R$-matrix theory provides a natural separation of these corrections into "internal" and "external" parts, depending on whether or not the nucleon and trinucleon are close enough to interact via (strong) nuclear forces. The external Coulomb differences between the $n$-$^3$H and $p$-$^3$He systems are all contained in the masses, shift functions, penetrabilities, and phases for hard-sphere and Coulomb scattering. The internal Coulomb differences lead to small, but important, corrections in the $R$-matrix parameters themselves.

Let the $R$ matrix describing $p$-$^3$He scattering for some state of total angular momentum and parity $J^\pi$ at total center-of-mass energy $\varepsilon$ be given by

$$R_p = \sum_\lambda \frac{\gamma_\lambda \tilde{\gamma}_\lambda}{\varepsilon_\lambda - \varepsilon} ,$$

in terms of the reduced-width amplitude vectors $\gamma_\lambda$ and eigenenergies $\varepsilon_\lambda$. The corresponding $n$-$^3$H $R$ matrix (for the same radii and boundary conditions) then is given by

$$R_n = \sum_{\lambda'\lambda} \gamma_{\lambda'} A_{\lambda'\lambda}(\varepsilon) \tilde{\gamma}_\lambda ,$$

where the inverse level matrix has elements

$$(A^{-1})_{\lambda'\lambda} = (\varepsilon_\lambda - \varepsilon)\delta_{\lambda'\lambda} + (\lambda'|\Delta V_c|\lambda) ,$$

in which $\Delta V_c$ is the difference in the Coulomb potentials between the $p$-$^3$He and $n$-$^3$H systems in the internal region. The evaluation of the matrix elements $(\lambda'|\Delta V_c|\lambda)$ requires knowing the eigenfunctions $|\lambda)$ everywhere in the internal region, but the $p$-$^3$He $R$-matrix analysis determines their values (essentially the $\gamma_\lambda$'s) only on the surface which encloses this region. Nevertheless, one can make simple assumptions about $\Delta V_c$ and explore the nature of the internal correction without having a detailed knowledge of the states $|\lambda)$.

The simplest choice is to take $\Delta V_c$ equal to a constant, which we define to be $-\Delta E_c$. Then, because the states $|\lambda)$ are orthonormal, the $n$-$^3$H $R$ matrix becomes

$$R_n=\sum_\lambda \frac{\gamma_\lambda \tilde{\gamma}_\lambda}{\varepsilon_\lambda-\Delta E_c-\varepsilon} ,$$

where one expects $\Delta E_c$ to be approximately equal to the Coulomb energy of a uniformly charged sphere, namely,

$$\Delta E_c \simeq \tfrac{3}{5} Z(Z-1)e^2/a \simeq 1 \text{ MeV} ,$$

with $Z$ (=3) the charge and $a$ the radius of the $p$-$^3$He sphere. This was the simple model used to obtain the prediction for the $n$-$^3$H total cross section shown in Fig. 9 of Ref. 4.

Using the parameters from the somewhat better $p$-$^3$He fit of Ref. 7, and adjusting the Coulomb energy shift to $\Delta E_c=0.86\pm0.04$ MeV to give a better description in the resonant peak near 3 MeV, we obtain the $n$-$^3$H total cross section shown in Fig. 1. This prediction agrees better than before[4] with very low-energy values of the cross section, but now is too shallow (by ~2%) in the minimum near 500 keV. The value of the peak cross section in the resonance is more sensitive than is its position to changes in $\Delta E_c$. As $\Delta E_c$ increases, the peak cross section increases, while values at low energies and in the minimum decrease. The drop in the calculated cross section as the neutron energy increases from zero is due to a decrease in $(\sin\delta_0)/ka$ from unity, caused both by the deviation of the $s$-wave phase shifts $\delta_0$ from their "hard-sphere" values $(-ka)$, and by the decrease in $(\sin x)/x$ as $x$ increases.

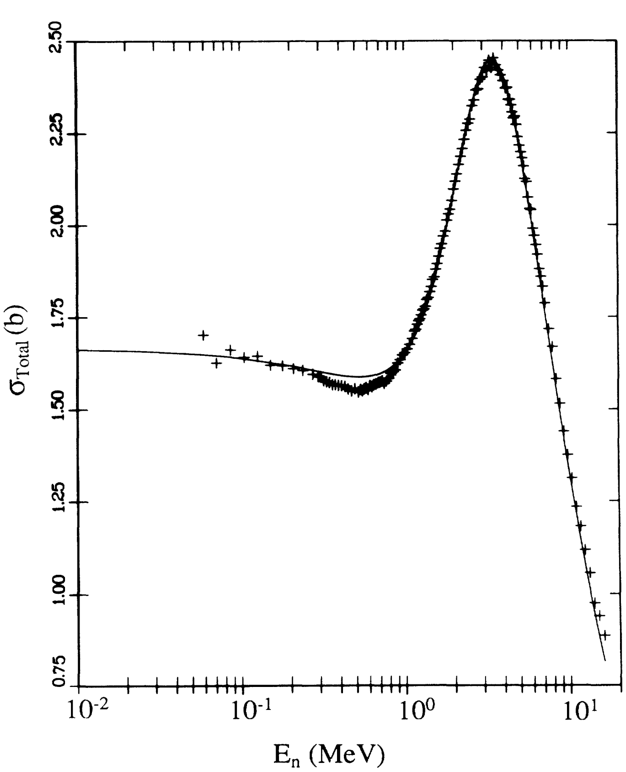

FIG. 1. Prediction for the $n$-$^3$H total cross section obtained from Coulomb-corrected $p$-$^3$He $R$-matrix parameters, compared with the data of Ref. 4. The experimental errors are generally no larger than the plotting symbols.

From the $s$-wave $p$-$^3$He $R$-matrix parameters of Ref. 7, with the $\varepsilon_\lambda$'s shifted by $\Delta E_c=0.86$ MeV, as given in Table I, we obtain for the singlet and triplet scattering lengths

$$a_s=4.453\pm0.100 \text{ fm} ,$$

and

$$a_t=3.325\pm0.016 \text{ fm} ,$$

leading to the value for the coherent scattering length

$$a_c=3.607\pm0.017 \text{ fm} .$$

Judging from the variation in these numbers from the previous, almost equivalent $p$-$^3$He fit,[8] the value of the coherent scattering length is much better determined than is the ratio $a_s/a_t=1.34\pm0.10$. This is not unexpected, since for $p$-$^3$He scattering, the Coulomb amplitude interferes with the coherent nuclear amplitude.

The values of the scattering lengths above do not agree with earlier published values of $a_c=3.82\pm0.07$ fm (Ref. 6) and $a_s \sim a_t \sim 3.70\pm0.10$ fm (Refs. 5 and 6). However, Rauch *et al.*[9] remeasured the coherent scattering length and obtained $a_c=3.59\pm0.02$ fm, in strong contradiction to the previous value.[6] The new measurement plus the zero-energy total cross-section value of $1.70\pm0.03$ b (Ref. 4) implies two sets of scattering lengths: $a_s=4.98\pm0.29$ fm, $a_t=3.13\pm0.11$ fm and $a_s=2.20\pm0.31$ fm, $a_t=4.05\pm0.09$ fm. The coherent scattering length and the first of these sets of spin-dependent scattering lengths, which yields $a_s/a_t=1.59\pm0.15$, are consistent with our values.

Considering the simplicity of the internal Coulomb correction, it is not suprising that we find a residual discrepancy between the calculated and measured values of $\sigma_T$ of as much as 2%. Therefore, we cannot use the discrepancy as evidence of charge asymmetry. The better description of the $n$-$^3$H total cross section obtained with $\Delta E_c$ somewhat smaller than the uniformly charged-sphere value is reasonable if some radial dependence is included in the internucleon correlation functions.

Of course, an even smaller value of $\Delta E_c$ would agree better with the extrapolated zero-energy scattering cross section, but the calculation would then be significantly lower at the peak and higher in the minima than the mea-

TABLE I. $R$-matrix parameters for the $l=0$ $n$-$^3$H states with channel radius $a=4.9$ fm and boundary condition $b=0$.

| $J^\pi$ | $0^+$ | | $1^+$ |
|---|---|---|---|
| $\varepsilon_\lambda$ (MeV) | −29.037 | 24.175 | 14.936 |
| $\gamma_\lambda$ (MeV$^{1/2}$) | 3.844 | 3.811 | 2.195 |

surements. This may indicate the need for additional low-energy dependence in the charge-symmetric $R$-matrix description of $n$-$^3$H and $p$-$^3$He scattering that is not evident from analyzing the $p$-$^3$He data alone at energies above 1 MeV.

Our scattering-length calculation and Rauch's later experimental value[9] of $a_c$ indicate much stronger spin dependence than had previously been thought. This stronger spin dependence implies an *incoherent* cross section $\geq 30$ mb, which is more than an order of magnitude larger than that inferred from the recommended values of Ref. 5, and offers the possibility of measuring the incoherent cross section directly. (In fact, from the data of Refs. 4 and 9 alone, one predicts an incoherent cross section of 80±35 mb.)

There may be a theoretical basis for expecting the ratio $a_s/a_t$ to be substantially greater than unity. Deuteron-exchange contributions that are known to be important in both $p$-$^3$He and $n$-$^3$H scattering[10,11] enhance the singlet scattering length. The same qualitative result follows from a model of the triton as a proton bound to a singlet dineutron, taking into account the effect of the more attractive triplet $n$-$p$ force on the predominantly repulsive neutron-dineutron $s$-wave interaction. The most recent microscopic four-body calculation of Kharchenko and Levashev[12] gives $a_s/a_t = 1.20$.

In all, the simple Coulomb-corrected, charge-independent $R$-matrix calculation provides a remarkably good unified description of the pure isospin-1 reactions of the four-nucleon system. We urge the performance of a measurement of the incoherent cross section as an additional experimental check of this description.

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[1] V. D. Vertebny, M. F. Vlasov, A. L. Kirliyuk, V. V. Koloty, M. V. Pasechnik, and V. A. Stephanenko, Izv. Akad. Nauk SSSR, Ser. Fiz. **31**, 349 (1967) [Bull. Acad. Sci. USSR, Phys. Ser. **31**, 334 (1967)].

[2] R. E. Donaldson, W. Bartolini, and H. Otsuki, Phys. Rev. C **5**, 1952 (1972).

[3] H. Rauch, in *Few Body Systems and Nuclear Forces, I,* Vol. 82 of *Lecture Notes in Physics,* edited by H. Zingl, M. Haftel, and H. Zankel (Springer, Berlin, 1978), p. 289.

[4] T. W. Phillips, B. L. Berman, and J. D. Seagrave, Phys. Rev. C **22**, 384 (1980).

[5] J. D. Seagrave, B. L. Berman, and T. W. Phillips, Phys. Lett. **91B**, 200 (1980).

[6] S. Hammerschmied, H. Rauch, H. Clerc, and U. Kischko, Z. Phys. A **302**, 323 (1981).

[7] G. M. Hale, D. C. Dodder, J. J. Devaney, and K. Witte (unpublished); complete set of $R$-matrix parameters available from one of the authors (G.M.H.).

[8] G. M. Hale and D. C. Dodder, in *Few Body Systems and Nuclear Forces II,* Vol. 87 of *Lecture Notes in Physics,* edited by H. Zingl, M. Haftel, and H. Zankel (Springer, Berlin, 1978), p. 523.

[9] H. Rauch, D. Tuppinger, H. Wölwitsch, and T. Wroblewski, Phys. Lett. **165B**, 39 (1985).

[10] M. Bolsterli and G. Hale, Phys. Rev. Lett. **28**, 1285 (1972).

[11] M. P. Locher and T. Mizutani, Phys. Rep. **46**, 43 (1978).

[12] V. F. Kharchenko and V. P. Levashev, Nucl. Phys. **A343**, 249 (1980).