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Measurements of the Neutron–Proton and Neutron–Carbon Total Cross Sections at Electron–Volt Energies

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We have measured the neutron–proton total cross section in hydrogen gas and the neutron–carbon total cross section in pyrolytic graphite between 0.3-and 400-eV laboratory energy. After subtracting the capture cross section and molecular binding effects, we find 20.37±0.02 b for the free neutron–proton scattering cross section and 4.7534±0.0045 b for the free neutron–carbon cross section. The effects of these measurements and those of L. Koester on the singlet and triplet *n–p* scattering lengths and effective ranges are discussed.

We undertook this work to check on the 1949 measurement of the neutron–proton incoherent cross section by Melkonian,[1] whose data dominates our present knowledge of low-energy neutron–proton scattering. The precision of σ_0 strongly affects the precision of the *n–p* singlet and triplet scattering lengths and in turn the effective ranges. We used a time-of-flight method of energy selection.

Figure 1 shows an assembly of the four most recent theoretical treatments of the *n–p* cross section in hydrogen gas vs neutron lab energy. Below 0.819 eV, vibrational transitions in the molecule are not excited, but rotational transitions are excited. Messiah's semiclassical treatment[2] agrees with Brimberg's quantum-mechanical treatment[3] below 0.8 eV and above 0.3 eV. Vibrational transitions may occur above 0.819 eV. Brimberg did not calculate the vibrational excitations, but Messiah did, with the results showing a secondary rise in cross section. Messiah's calculations show a rapid approach to the asymptotic form $\sigma=\sigma_0\ (1+2\hbar\omega_0/48E)$, where $\hbar\omega_0$ is the mean vibrational level spacing in the hydrogen molecule. This form was also exhibited by Placzek and was used by Melkonian[1] in his data reduction. Andréason and Thölén[4] applied Brimberg's full quantum-mechanical technique at one energy (1 eV) only to transitions to the first vibrational excited state, finding an $0.058\sigma_0$ increase in cross section compared with Messiah's finding of $0.033\sigma_0$. Their paper incorrectly takes the cross section for excitation of rotational states only as $1.006\sigma_0$ by interpolation on Brimberg's results. In contrast, we read Messiah's figures to obtain $0.980\sigma_0$. The total cross sections in the two cases are $1.064\sigma_0$ and $1.038\sigma_0$, both points appearing in our figures. At higher energies, the *n–p* cross section falls below σ_0. A precise measurement of σ_0 must be in the region where the cross section is most constant with energy.

Figure 2 shows the same curves and points of Fig. 1 plotted against time-of-flight with our data points and an empirically fitted curve added. The fit is made over the first thirty-nine points. There is good agreement with the theory of Messiah and Brimberg where vibrational transitions in the hydrogen molecule are absent or of negligible effect, i.e., at low and high energies. In between, the agreement with Messiah is bad. The agreement with our interpretation of Andréason and Thölén's work is good.

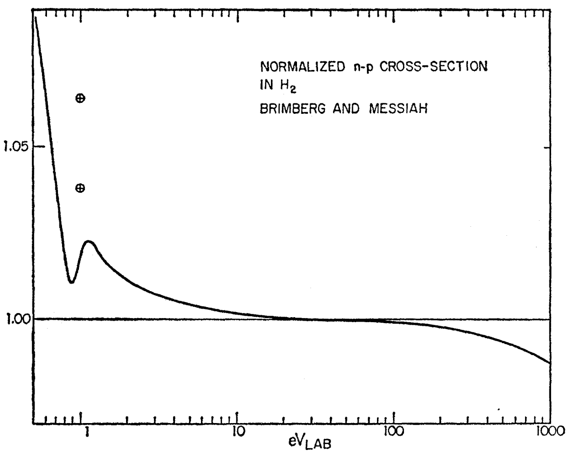

FIG. 1. The cross section for neutrons on molecular hydrogen according to calculations of Messiah normalized to unity at the free *n–p* cross section. The points are calculations of Andréason and Thölén. The upper point they quote directly, the lower point is our reinterpretation.

Pending an improved theory we have restricted our fit to the first eight points of Fig. 2 (9.95 to 359 eV) in order to minimize the vibrational transition effects,

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[1] E. Melkonian, Phys. Rev. **76,** 1744 and 1750 (1949).

[2] A. M. L. Messiah, Phys. Rev. **84,** 204 (1951).

[3] S. Brimberg, "On the Scattering of Slow Neutrons by Hydrogen Molecules," thesis, Royal Institute of Technology, Stockholm (No. 116, 1956). Repro Print AB and Geneva Conference (1958).

[4] S. Andréason and A. Thölén, thesis, Chalmers Institute of Technology, Gothenburg, Sweden (1961).

TABLE I. Table of results.

	This work plus old a_c/a_H	Previous work	Koester's work plus this work
σ_H	20.37 ± 0.02 b	20.36 ± 0.05 b	
σ_c	4.7534 ± 0.0045 b	4.704 ± 0.019 b	
a_c	Corrected for possible C^{13} spin incoherence		Direct
	6.656 ± 0.010 F	6.622 ± 0.017 F	6.656 ± 0.004 F
a_c/a_H		-1.7718 ± 0.0031	-1.7904 ± 0.0006
a_H	-3.657 ± 0.009 F	-3.737 ± 0.011 F	-3.719 ± 0.002 F
a_H	Parahydrogen	-3.80 ± 0.05 F	
	NaH crystal	-3.9 ± 0.1 F	
a_t	5.392 ± 0.006 F	5.399 ± 0.011 F	5.411 ± 0.004 F
a_s	-23.689 ± 0.013 F	-23.680 ± 0.028 F	-23.671 ± 0.012 F
$\rho_t(0, -\epsilon)$	1.724 ± 0.007 F	1.732 ± 0.012 F	1.747 ± 0.004 F
$\rho_s(0, 0)$	2.42 ± 0.09 F	2.48 ± 0.11 F	2.59 ± 0.08 F

using Messiah's asymptotic form with σ_0 and $\hbar\omega_0$ as adjustable parameters. The *n–p* effective range and capture cross section are used for small corrections. The result is entered in the upper left-hand corner of Table I. The carbon cross section was measured in pyrolytic graphite, which is free of overt molecular binding and coherent scattering effects above 0.3 eV. Our result from 0.3 to 200 eV is the second entry in Table I.

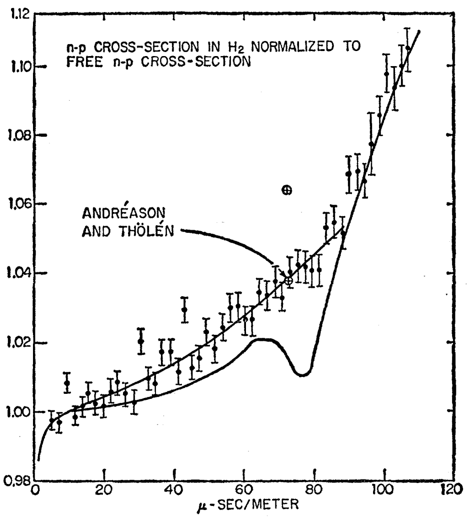

FIG. 2. The *n–p* cross section in hydrogen compared with experimental points.

Using these values and previously measured values of the coherent scattering lengths a_c/a_H we recompute the best values of the singlet and triplet *np* scattering lengths and effective ranges in column 1 of the table. The previous measurements are taken from Wilson[5] and are in column 2 of the table.

Koester[6] has remeasured a_c and a_H separately in a very precise measurement. Our a_c agrees with his. His a_c/a_H is appreciably different from the earlier work. The best values including Koester's work are in column 3 of the table and are recommended for future use.

We have not changed σ_H but have reduced the error; we change σ_c 1% or two standard deviations of the old value. Koester changes a_H/a_c five standard deviations of the old value. The new higher values for a_t and ρ_t are fitted more easily by the potential and boundary condition models. The new higher value of ρ_s (0, 0) is 4.4% lower than the *p–p* effective range.

We hope for an improved understanding of the hydrogen molecular correction which presently prevents a more accurate value of σ_0 which still dominates the error in a_s, a_t, and ρ_t. We also hope for another measurement of a_H to confirm Koester's change. This could be by a parahydrogen cross-section measurement. The error in ρ_s is now dominated by the higher energy data.

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[5] R. Wilson, *The Nucleon-Nucleon Interaction* (Interscience Publishers, Inc., and John Wiley & Sons, Inc., New York, 1962).

[6] L. Koester, Z. Physik **198**, 187 (1967). Koester's derivations of a_s, a_t, and ρ_t are incorrect. We use only his values of a_c and a_H which are correctly derived.