Total Neutron Cross Section of Deuterium below 1000 keV*

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Total neutron cross sections of deuterium have been measured from less than 1 keV to 1000 keV. We also performed a three-body calculation of n-D total scattering cross sections, using separable potentials. The theoretical and experimental results show good agreement. A marked increase in cross section is observed for decreasing energy below 300 keV. We discuss the implications of the results with respect to discrepancies in previously measured n-D scattering lengths.

Total neutron cross-section measurements on deuterium provide a sensitive test of nuclear three-body calculations. However, nearly no experimental data exist above thermal and below 500 keV neutron energy. On the other hand, the various experimental results at thermal energies are not completely consistent with each other, and lead to important discrepancies in the n-D scattering lengths. The current experimental situation is summarized in Table I, in which the thermal cross section and quartet and doublet scattering lengths are shown. Set-A values are obtained from the recent total–cross-section and coherent-scattering-length measurements of Dilge, Koester, and Nistler,[1] and are in agreement with older measurements.[2,3] The A' values were obtained by van Oers and Seagrave[4] from an analysis of measurements of the spin incoherent cross section by Gissler[5] and the coherent scattering length by Bartolini, Donaldson, and Groves.[6] Set A' is in basic agreement with the n-D cross-section evaluations by Seagrave,[7] and Horsley and Stewart,[8] who obtain thermal cross sections close to those of set A' by requiring the existing higher-energy data to extrapolate smoothly down to thermal energies.

TABLE I. Zero-energy n-D scattering parameters.

Set	a_2 (fm)	a_4 (fm)	α_{free} (b)
A^{a}	0.65± 0.04	6.35± 0.02	3.390± 0.012
A'^{b}	0.15± 0.05	6.13± 0.04	3.15 ± 0.04

[a] Ref. 1.
[b] Refs. 4 and 7.

From a theoretical standpoint,[9,10] the a_2 of set A is preferred. However, in view of the sensitivity of the $\frac{1}{2}^+$ state to the nuclear interaction and the uncertainties associated with the interaction, a choice between the A and A' values for a_2 based upon theory cannot be regarded as reliable. A discrepancy also exists between the A' values for a_4 and theoretical predictions which favor a_4 greater than or approximately equal to 6.3 fm.[11] A quartet scattering length of 6.3 fm gives a total cross section of at least 3.3 b, which is in better agreement with direct measurements of this quantity[1-3] than with the predictions of the set A' (see Table I).

The basic experimental setup and procedure is as follows: The electron beam from the Rensselaer LINAC strikes a water-cooled tantalum target producing a white source of neutrons. These neutrons are then scattered by a polyethylene moderator *cum* scatterer. This scatterer acts as the neutron source for the experiment. The tantalum target is placed so as not to be directly visible to the detector.

The collimated beam of neutrons passes through the deuterium sample located at approximately 10 m from the source. The sample consists of a 2.5-in.-diam stainless-steel cylindrical container with 0.050-in.-thick end windows, and is pressurized with 99.8%-purity deuterium gas to

1000 ± 2 lb/in^2 at 0°C. A second identical container was fabricated and evacuated to provide a reference for the cross-section measurement.

The transmitted neutron beam is detected by means of a $^{10}B_4C$ sodium-iodide detector located at 33 m from the neutron source. The data are recorded by means of a PDP-7 on-line computer with 6144 channels available for data. The time of flight is measured by means of a 31.25-nsec digital clock interfaced directly to the computer. The pressurized and evacuated samples are mounted on a computer-controlled sample changer. The two samples are alternately interposed into the neutron beam with a cycle time of approximately 3 min and data for the pressurized sample and the evacuated sample are separately recorded. One then can calculate the total neutron cross section as a function of energy from these two data.

Filters were interposed in the flight path to reduce the effect of the γ flash and to eliminate overlap of neutrons from previous neutron bursts. Notch filters were also placed in the beam to estimate the time-dependent background. These studies showed that there was a considerable amount of time-dependent background in the data, and that it was not possible to subtract this background precisely enough to arrive at results of the desired accuracy.

In an effort to eliminate the effect of this machine-dependent background, two separate measurements were made. In one of these measurements an 8-in.-thick iron filter was additionally placed in the neutron path and a cross-section measurement was carried out. The effect of this filter is to eliminate most of the neutron beam except at specific energies corresponding to deep minima in the iron total cross section, such as at 25 and 82 keV. This greatly reduced the magnitude of the time-dependent background. Furthermore, whatever little background remains can be estimated from the data recorded in between the transmitted peaks since the thick iron filter is essentially black at all energies other than the cross-section valleys. This measurement thus provides a precise measurement of the total cross section at a few energy points corresponding to the iron cross-section minima.

A second measurement made without the iron filter provides a continuous energy measurement. In comparison with the filtered beam results, the magnitude of the cross section was generally low by about 1.5% at very low energies, the difference increasing to about 3% at about 500 keV, and decreasing to about zero at 1000 keV. From these differences a smooth machine-dependent background function is constructed so as to normalize the continuous energy measurement to the precision-point measurements obtained from the iron-filter beam experiment. One then ends up with a final result which is precisely determined at a few points by virtue of the filtered beam measurement and the shape interpolated between those points by the continuous energy measurement.

The magnitude of the cross sections, and thus the errors in magnitude, are tied to the filtered beam result. Two filtered beam experiments were carried out two months apart under somewhat different experimental conditions. The results agreed to within statistics. Results of a third filtered beam run, this time with a carbon sample, agreed within statistics with standard carbon cross sections. Taken together with the considerations previously discussed, it is felt that the error in magnitude is dominated by the statistical errors in the filtered beam results. The experimental results are shown in Fig. 1. Above 1 MeV, the present experimental measurements join smoothly, and agree with the recent measurements of Clement *et al.*,[12] and the evaluations by Seagrave,[7] and Horsley and Stewart.[8] At lower energies, the cross sections increase markedly, and are inconsistent with the evaluations,[7,8] and set A'. However, they are consistent with the thermal measurements in Refs. 1–3 and set A.

Figure 2 shows the results of a simple separable potential three-body calculation of the n-D total scattering cross section. The overall result of this calculation is compared to the experimental data in Fig. 1. The theoretical and experimental results show good agreement. In particular, the marked variation in the lower-energy region is reproduced.

At first thought, we might suppose that a rapid variation in σ_{free} could result from the well-known[4] pole in $K_2 = k \cot\delta_z$ near threshold. However, this variation acts in the wrong direction giving an increasing doublet cross section as E increases. As seen in Fig. 2, the contribution of the doublet state is very small at these energies. The curve shown for the doublet state lies at the center of a band of values obtained from calculations with a number of different separable potentials which give values for E_T in reasonable agreement with experiment and from various parametrizations[4,13] of K_2. Since the doublet con-

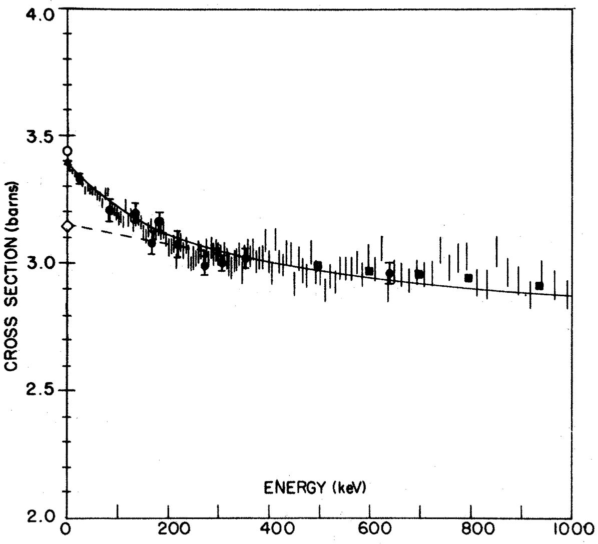

FIG. 1. Total neutron cross sections of deuterium from 0 to 1000 keV. Filled circles, results of the iron-filter experiment as discussed in the text. Filled squares, obtained from Clement *et al.* (Ref. 13). Vertical lines, results of the continuous-energy experiment as discussed in the text. The open circle and solid triangle at zero energy represent the thermal cross section of Fermi and Marshall (Ref. 2) and Dilg, Koester, and Nistler (Ref. 1), respectively. The open diamond is the thermal cross section deduced from the works of Gissler (Ref. 5) and Bartolini, Donaldson, and Groves (Ref. 6). The dashed curve, below 300 keV, is excerpted from the evaluation by Seagrave (Ref. 3). The solid curve is due to the theoretical calculation discussed in the text. The errors shown reflect statistical uncertainties only.

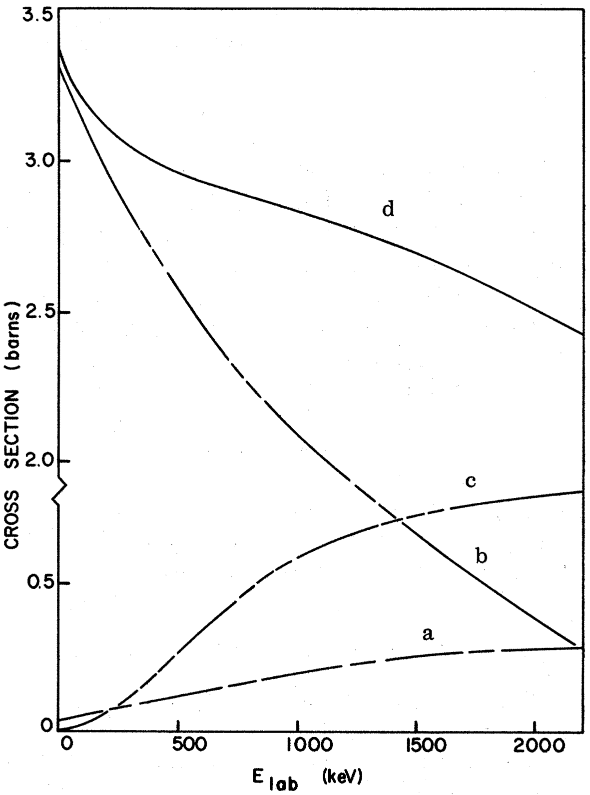

FIG. 2. Neutron-deuteron total cross sections below 2 MeV. Shown are the doublet cross section, all partial waves (curve *a*), the *s*-wave quartet cross section (curve *b*), the quartet cross section for $L>0$ (curve *c*), and the total cross section (curve *d*).

tribution to σ_{free} is very small, the uncertainty in its value has little effect upon the conclusions presented below.

The low-energy behavior of σ_{free} is determined primarily by the quartet state. In Fig. 2 we have shown separately the s-wave and higher partial-wave cross sections. The s-wave cross section is a rapidly decreasing function of energy. However, because of the long-range exchange term[13] in n-D scattering, higher partial waves rapidly become important, and above 0.3 MeV the increase of the higher-l cross section, primarily the p waves, counteracts the decrease of the s-wave cross section to give the comparatively flat result which, as already indicated, agrees quite well with experiment. The rapid decrease in σ_{free} for E between 0.0 and 0.3 MeV results from the rapid drop in the s-wave cross section and the slow increase of the p-wave cross section in this region. Such a phenomenon was already expected by Story.[14] As is to be expected, calculations of the quartet cross section gave essentially identical results for all potentials used. In addition to using central potentials, we calculated the behavior of the s-wave cross section assuming separable tensor potentials, but neglecting those parts of the wave function which have the spectator particle in a D state. The results were the same as for the central potentials. Recent local potential calculations[15] appear also to be in agreement with experiment although the low-energy region has not been thoroughly studied.

Our conclusion then is that theoretical predictions are in good agreement with the total cross-section measurements for $E>0$ and with the Dilg, Koester, and Nistler (set A) value for the zero-energy cross section. In particular, they give a simple explanation for the necessary rapid variation in the cross section below 0.3 MeV. Since the total cross section depends primarily on the quartet scattering, the present results tend to confirm the a_4 of set A. The present results do not specify a_2 because of its very small contribution to the cross section. However, the agreement with Dilg, Koester, and Nistler with respect to $\sigma_{\rm free}$ and a_4 lends confidence to the a_2 of set A.

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Excitation of the Parent Analogs of the ^{58}Ni Giant $M1$ Resonance by the Reaction ^{58}Ni$(t,h)^{58}$Co

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The reaction ^{58}Ni$(t,h)^{58}$Co has been studied at an incident triton energy of 23.5 MeV. Among the low-lying levels are several 1^+ states which are selectively populated. Based on this selectivity and their energy centroid, it is proposed that these states contain an appreciable fraction of the T_0+1 analogs of the giant $M1$ resonance in ^{58}Ni.

The giant dipole resonances are located relatively high in excitation in all even nuclei. The study of the locations and strengths of these levels has an important role in nuclear physics both because of their intrinsic structure and because of their influence on low-energy transitions through particle-vibration coupling processes.[1] These nuclear modes are of isovector character, and thus for a neutron excess they have two isospin components, namely, T_0+1 and T_0, where $T_0=T_z=(N-Z)/2$. Whereas the isospin character of the $E1$ mode has been studied both theoretically[2] and experimentally,[3] there is at present no information on the location of the T_0+1 component of the $M1$ mode in medium and heavy nuclei. (The locations of the T_0 and T_0+1 $M1$ strengths in light nuclei have been summarized previously.[4]) In fact, information on the $M1$ giant resonance is confined to inelastic-electron scattering[5] and photoneutron studies.[6] In addition, none of the analogs of the giant resonances have previously been observed in the charge-exchange processes.

The present Letter reports the results of a new approach to the study of the T_0+1 component of the $M1$ mode. The charge-exchange reaction ^{58}Ni(t,h) has been used to search for the parent analogs in ^{58}Co of the T_0+1 component of the $M1$