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NUCLEAR REACTIONS AMONG THE HYDROGEN ISOTOPES AT LOW ENERGIES

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Summary

The low-energy fusion cross-section (LEFCS) apparatus installed at the Los Alamos Van de Graaff facility has been used to measure the cross sections for the important fusion-energy reaction D(t,α)n over the triton bombarding energy range of 12.5 to 117 keV. This corresponds to an equivalent deuteron bombarding energy range of 8.3 to 78.1 keV and to a D+T plasma temperature (kT) range of 0.7 to 18.8 keV. Over most of the energy range the cross sections are accurate to 1.4%, with the error rising to 4.8% at the lowest energy. A data base was constructed for deuteron bombarding energies up to about 250 keV that included our data and four other data sets.[1-4] This data base can be fitted quite well with a single-level ($3/2^+$) resonance formula in the R-matrix formalism. Work is currently in progress on the D(d,p)T and D(d,^{3}He)n reactions, with studies of D(t,γ) and T(t,α)nn planned for the future.

Introduction

At the Los Alamos Van de Graaff Facility,[5] we have developed and installed an apparatus[6-8] (LEFCS) for the study of nuclear reactions[9] that are fundamental to the implementation of energy production through controlled thermonuclear processes. The bombarding energies for these studies are in the range 10 to 120 keV, and considerable effort has been expended to reduce systematic errors to an overall level of a few percent. Initially we are investigating reactions among the hydrogen isotopes: (1) we have completed measurements on the D(t,α)n reactions; (2) we are currently working on the D(d,p)T and D(d,^{3}He)n reactions, and; (3) we plan to study D(t,γ) and T(t,α)nn in the immediate future.

The experiments are performed by accelerating negatively charged H, D, or T ions through a windowless, cryogenically pumped, gas target and into a beam calorimeter. The target density is measured and the calorimeter calibration is checked by using particle beams of several MeV energy from the Los Alamos Tandem Van de Graaff. A calibrated resistor stack is used to determine the LEFCS beam energy to high precision. This energy has been checked to somewhat less accuracy by a time-of-flight method using a pulsed laser to produce a burst of neutral atoms by photodetachment of the negative ions.

Figure 1 shows a schematic diagram of the LEFCS system.

Apparatus

Ion Source and Accelerator

A 120-kV, dual polarity ion source and accelerating system were built to specifications by the General Ionex Corporation. The ion source is a standard duoplasmatron with a 30 kV extraction lens and a crossed field analyzer. In order to eliminate the production of unwanted molecular species, such as HD^+ when attempting to produce a pure T^+ beam, we have normally operated the source in its negative-ion, direct extraction configuration, thereby producing 40- to 50 μA beams of H^-, D^-, and T^-. Our tests have established that the accelerating voltage is stable to one part in 10^4 (FWHM) up to 100 kV, and then the instability rises from 10 V at 100 kV to 25 V at 120 kV. The absolute voltage is measured to better than one part in 10^4 with a resistor stack (Spellman Model HVD-200) whose calibration is traceable to the National Bureau of Standards.

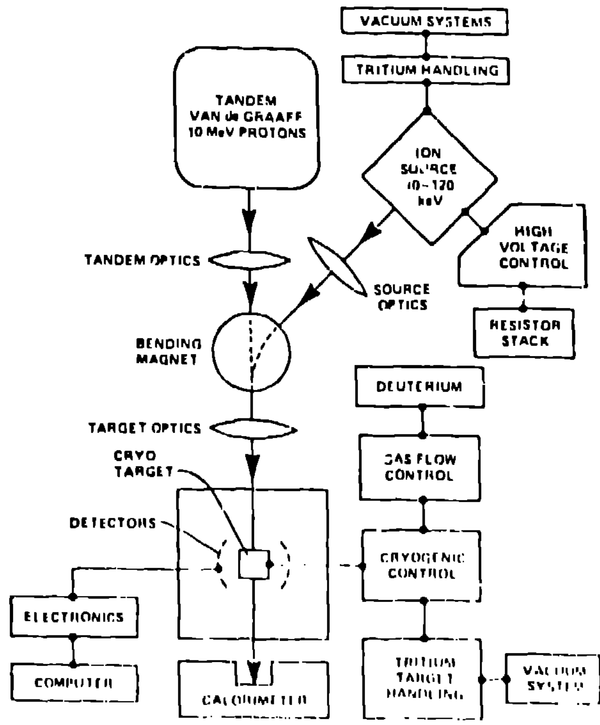

Fig. 1. Schematic diagram of the Los Alamos Low Energy Fusion Cross Section Facility (LEFCS).

Target and Detection System

Figure 2 illustrates the gas target and detector arrangement. To keep systematic errors arising from beam energy uncertainties at a low level, there are no gas-confining foils in the beam path. Instead, the target gas (usually D_2) flows out through the beam ports and is frozen onto surfaces kept at 4 K by a liquid-He dewar. The remaining few percent is pumped by a 500-ℓ/s turbomolecular pump. The D_2 gas in the target is at a temperature of 10 [illegible] K and flows at a rate of 5 atm-cc/min. These operating conditions yield a target density of about [illegible] D atoms/cm^3 (a pressure of about 8 mTorr and an areal density of about 0.01 μg/cm^2). In the D(t,α)n experiments, this density causes the total energy loss in the target to be in the range 70 to 190 eV, which again keeps errors arising from beam energy uncertainties at a low level. The target density was determined to [illegible] by scattering 10 MeV protons from the deuterium gas and using the known scattering cross section, which we had measured to 0.8% in a separate experiment. Note in Fig. 1 that either the low energy beam or the beam from the Los Alamos Tandem Van de Graaff can be directed through the target. The target temperature and gas flow rate can be reset with high reproducibility and remain quite constant over extended periods of time. In the calibration runs, we determined how the target density changes with variation of the flow and temperature about their usual values.

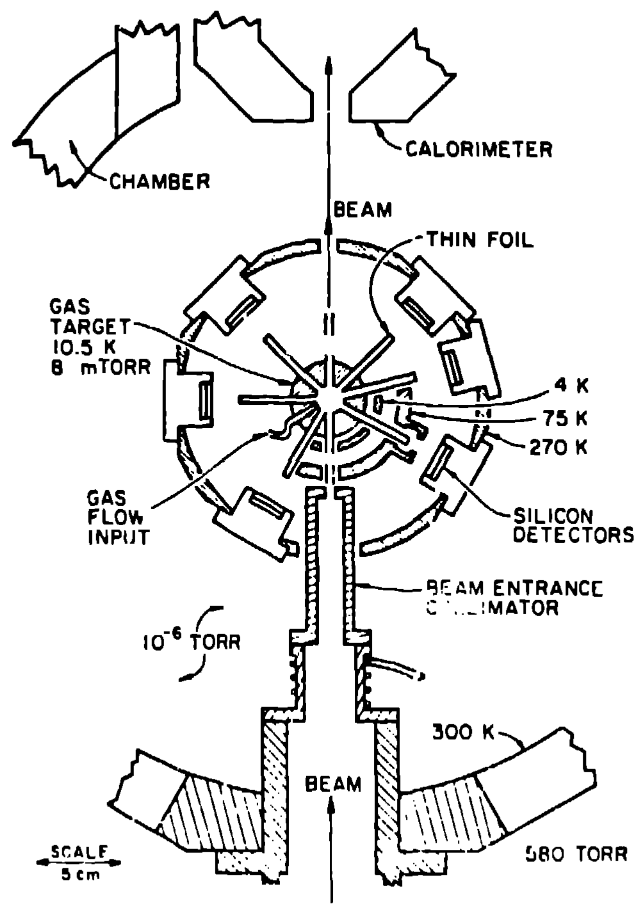

Fig. 2 LEFCS gas target and detector system. Only a portion of the 4-K and 75-K cylindrical surfaces are shown.

The reaction particles leave the target volume through six tubes capped on their outer ends by 30-μg/cm², stretched polypropylene foils.[10] The reaction volumes are defined by 2-mm-wide, vertical slits in a stainless steel ring positioned near the inner ends of the tubes and by 2-mm-diam apertures near the outer ends of the tubes. This arrangement defines six nominal reaction angles of 45°L, 45°R, 75°R, 90°L, 120°R, and 150°L, where L and R indicate left and right of the incident beam (as viewed in Fig. 2), gives a geometry factor of about 40×10^{-9} cm sr at each angle, and has an angular acceptance in the reaction plane of 3.2° (FWHM) at each angle.

On emerging from the target and passing through the polypropylene foils, the reaction products impinge upon 50 μm thick, silicon, surface barrier detectors, and if they are energetic enough to pass through such a detector, they then enter similar detectors of 500 μm thickness. For the D(t,α)n experiment, only the 50 μm detectors were connected to the data acquisition system, as they readily stop the approximately 4 MeV α particles from that reaction. Both sets of detectors were so connected for the density calibration experiments.

Beam Calorimeter

Because the low energy beam undergoes significant charge exchange in the target, we have chosen to determine the beam intensity by calorimetric means. The details of the calorimeter are given in a contributed paper[11] to this conference. In brief, the collecting cup is biased cold by a thermoelectric cooling circuit and warmed back up to ambient temperature by power furnished by a heating transistor. Thus in the no-beam steady state, the heat furnished to the cup by the heating transistor is balanced by the constant heat withdrawn from the cup by the cooling circuit, and the cup is then at the same temperature as its surroundings, thereby reducing heat leaks. The heating-transistor power is measured accurately and regulated by an electronic circuit. When the beam is on, the power to the heating transistor is automatically decreased just enough to again bring the cup to ambient temperature. Thus, the decrease in power to the heating transistor is a measure of the beam power. The calorimeter electronics integrates this beam power over the run duration to yield the total energy furnished by the beam, independent of the beam's charge state. Knowledge of the beam energy per particle as it enters the calorimeter then allows us to calculate the beam flux. The calorimeter was calibrated by using the known heat output of a precision resistor embedded in the cup. This calibration was checked by using a 3-MeV-proton beam from the Van de Graaff and comparing the calorimetrically determined beam flux with that determined simultaneously by charge collection. The calibration is accurate to 0.08% over a power range of 10 to 800 mW.

Laser Time-of-Flight System

We have been working on a time-of-flight apparatus that can be mounted at the beam exit port of the scattering chamber in place of the calorimeter. The intention is to be able to check the beam energy as obtained from the calibrated resistor stack and to study the energy loss in the gas target and beam energy spreads. The method consists in measuring the flight time of a packet of neutral beam atoms produced by exposing the negative component in the beam to a fast pulse of 1-μm radiation from a Nd·YAG laser. Most of our studies to date have been with a 20- or 40-keV-triton beam. Shifts in beam energy of a few tens of eV are readily observed with the system; however, we have not yet obtained sufficient stability and reproducibility to make accurate absolute energy measurements; for example, we have been able to check the beam energy to an accuracy of only 50 to 100 eV at 20 keV.

The D(t,α)n Experiment

Procedure

After the cryogenics, electronics, and D_2 target gas flow had stabilized and the triton beam had been properly focussed through the target, the beam was intercepted just after passing through the bending magnet (Fig. 1), and the beam off power level of the calorimeter was measured. The beam was then allowed to pass through the target, and a data run of 10- to 90 min duration was carried out, depending on the counting rate. At the end of the run, the beam off power level of the calorimeter was again determined. Every 24 hours the 4 K pumping surfaces would be warmed, the accumulated D_2 pumped away, and the liquid He dewar refilled. Data were obtained at 16 triton bombarding energies from 12.5 to 117 keV, and at least two data runs were made, not always contiguously, at each energy. At the lowest energy, ten runs were made resulting in an accumulated beam flux of 60 particle mC. Throughout the course of data taking we employed beam currents from 1.4 to 4 μA and beam powers from 20 to 120 mW. The data were recorded and important parameters were monitored with the aid of the MODCOMP IV/25 on line computer system and data acquisition program Z at the Los Alamos Van de Graaff Facility. In particular, the target temperature and D_2 flow rate were read and recorded every 12 sec by the computer.

TABLE I. SIGNIFICANT ERROR CONTRIBUTIONS. $T(d,n)^4He$

SCALE ERROR = 1.3%	FROM 9 SOURCES, LARGELY FROM THE D(P,P)D CALIBRATION; THE OTHER 8 SOURCES RARELY ABOVE 0.1%			
RELATIVE ERROR:	FROM 7 SOURCES; ONLY COUNTING STATISTICS (Y) AND BEAM INTENSITY (CALORIMETER, C_D) ABOVE 0.3%			

E_D (keV)	Y (%)	C_D (%)	TOTAL RELATIVE (%)	TOTAL ABSOLUTE (%)
8.3	4.5	0.5	4.6	4.8
10.0	2.3	0.5	2.3	2.7
13.3	1.7	0.5	1.7	2.1
16.7	0.7	0.4	0.9	1.5
20.0 – 12 PTS – 78.1	0.4	0.12	0.5	1.4%

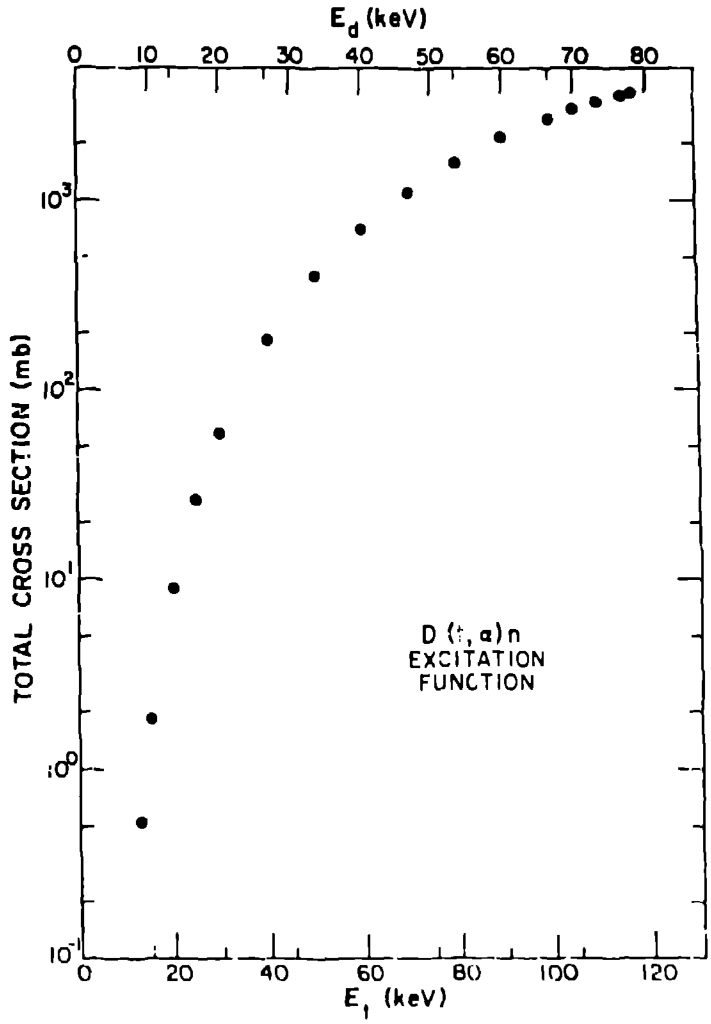

Fig. 3 Integrated (total) cross section for the $D(t,\alpha)n$ reaction vs triton (E_t) or equivalent deuteron (E_d) bombarding energy as measured in the present work. The unlabelled ticks on the cross-section scale are "2" and "5".

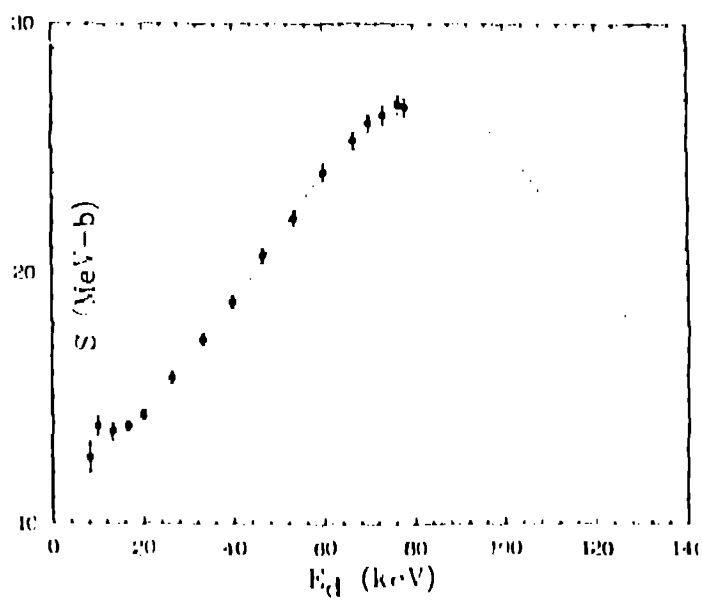

Fig. 4 The S function vs equivalent deuteron bombarding energy for the present $D(t,\alpha)n$ data. Total errors are shown. Note the suppressed zero. The curve is the result of the single level fit discussed in the text.

Error Contributions

The care we have taken with respect to the beam energy has resulted in very small uncertainties in the mean beam energy at the center of the gas target (the reaction energy); namely, 6 eV at 12.5 keV rising to 16 eV at 117 keV. The energy spread in the reaction energy is 17 eV at 12.5 keV rising to 35 eV at 117 keV. The relative errors in the integrated cross sections vary from 0.5% at the high energies to 4.6% at the lowest energy. In addition, there is an overall scale error of 1.3%. Table I summarizes the significant error contributions, note that the equivalent deuteron bombarding energy is given instead of the triton energy.

Results

The relative detection efficiencies of the six detectors (Fig. 2) are known to 1%, and to this level of accuracy we find that the c.m. differential cross section for the $D(t,\alpha)n$ reaction is independent of angle, indicating the dominance of the s-wave interaction in the dt channel. This fact also simplifies the calculation of the integrated cross section; we simply compute the average c.m. differential cross section from the six measured values and multiply by 4π. Figure 3 is a semilog plot of the integrated cross section vs bombarding energy. The cross section has been measured over a range of four orders of magnitude, ranging from 4.74 b down to 0.525 mb. This lowest value corresponds to a differential cross section of 41.8 μb/sr, which is not extremely low by some standards; however, it must be remembered that here we use a very thin target, about 0.01 μg/cm². A form of the data more useful for comparison purposes is shown in Fig. 4. There we plot the astrophysical S function, defined by

$$S = \sigma E \exp\left(1.08727 E^{-1/2}\right) ,$$

where σ is the cross section in b, E is the c.m. energy in the dt channel in MeV, and S is expressed in units of MeV b. This definition factors out from σ the energy dependence of λ^2 and the Coulomb penetrabili-

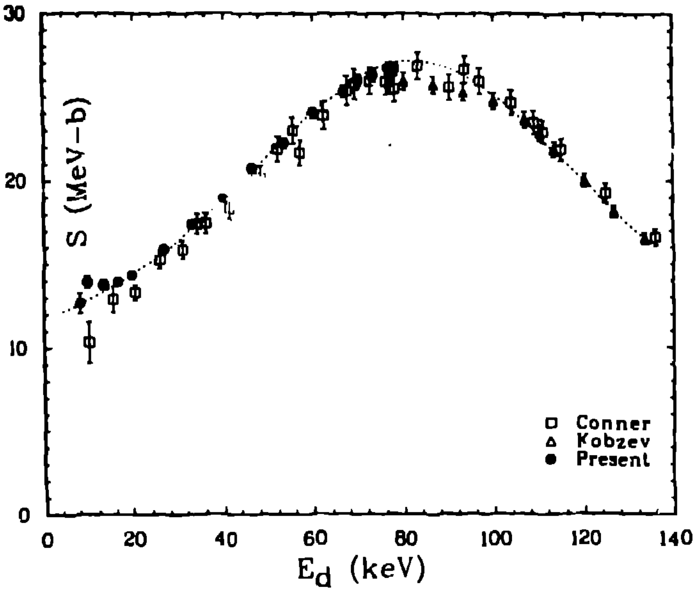

Fig. 5 The S function vs deuteron bombarding energy for the D(t,α)n reaction. Shown are the present data and those of Refs. 1 and 4. Total errors are shown. The curve is the result of the single-level fit discussed in the text.

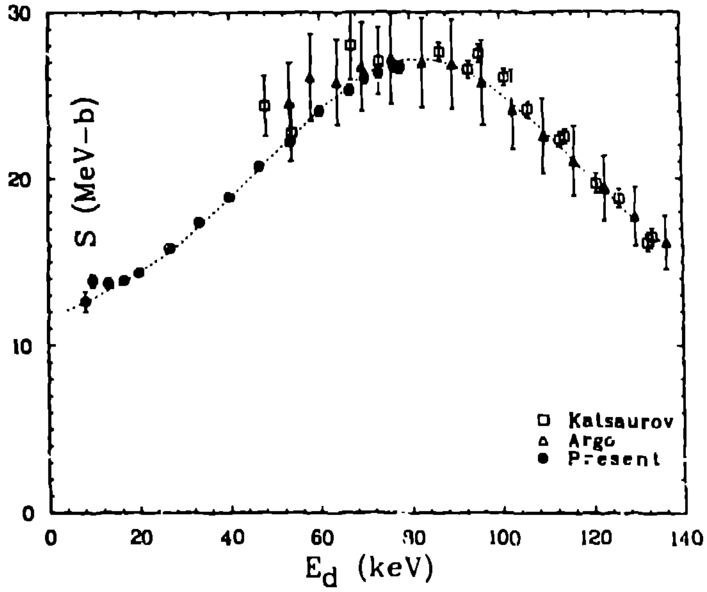

Fig. 6 The S function vs deuteron bombarding energy for the D(t,α)n reaction. Shown are the present data and those of Refs. 3 and 13. Total errors are shown. The curve is the result of the single-level fit discussed in the text.

ity in the incident channel, thereby relegating to S an energy dependence more nearly resulting from explicitly nuclear effects. Figures 5 to 7 show our S function compared with previous results from the literature.[1-4, 12-14] In Figs. 4 to 7, we have chosen to display S vs the deuteron bombarding energy, and the dashed curve in each figure is a single-level fit to be discussed below.

Single-Level Fit to D(t,α)n

R-matrix theory[15] has been extremely useful in describing reactions among light nuclei and has, in particular, been used to help understand reactions important to fusion energy.[16] Although a current R-matrix analysis of the mass-5 system[16,17] has covered the energy range up to about 10 MeV deuteron bombarding energy and has used a multilevel approach, it might be expected that a single level approach would be valid up to a few hundred keV because of the dominance of the $3/2^+$ resonance in this energy region. Therefore, we have constructed a data base for deuteron energies up to about 250 keV using our data and those of Refs. 1 to 4 and have performed a single-level fit to this data base in the R-matrix formalism. A good fit was achieved with a χ^2 per datum of 1.39 for 176 data points and 4 fitting parameters. This fit is shown as a dashed curve in Figs. 4 to 7. Thus we see that the variation with energy of the cross section is well reproduced theoretically through the energy dependences of the R matrix and of the Coulomb functions as expressed in the penetrabilities and level shifts.[15] There is, however, one unsatisfactory aspect of this single level fit; namely, the intrinsic strength of the $3/2^+$ level in ^5He, as expressed for example by the product of the reduced widths for the entrance and exit channels, is given to be several times larger than both that from a single-particle estimate and that from a multilevel fit.[16,17] This problem is being investigated.

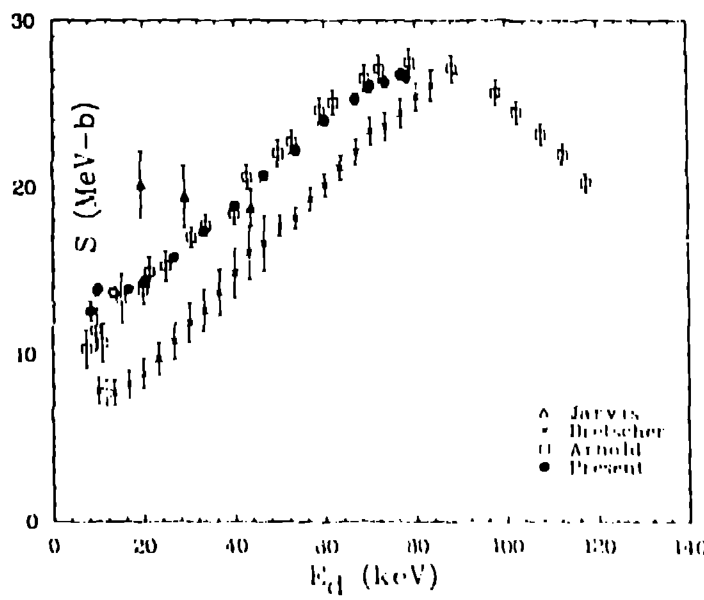

Fig. 7. The S function vs deuteron bombarding energy for the D(t,α)n reaction. Shown are the present data, those of Refs. 12 and 14, and a portion of those of Ref. 2. Total errors are shown. The curve is the result of the single level fit discussed in the text.

Discussion

In Fig. 4, the eye is irresistably drawn to the low energy datum that lies about two standard deviations above the curve. No such structure is expected in that energy region, and we have been unable to discover any experimental difficulties; therefore, at present, we ascribe that structure to statistical fluctuation.

In Figs. 5 to 7, we compare our data with previous work.[1-4,12-14] Our results appear to be in reasonably good agreement with the data of Conner[1] (Fig. 5) and Arnold[2] (Fig. 7), although some systematic differences can be noted. The measurements of Bretcher[12] and Jarvis[14] (Fig. 7) are in marked disagreement with the present experiment, and although the data of Katsaurov[3] and Argo[13] (Fig. 6) do not have a large overlap with our energy range, they do seem on the average to lie somewhat higher than our values. The data of Kobzev[4] (Fig. 5) do not overlap in energy with ours, but do lie below the smooth trend that would be indicated by our measurements. It is seen that the main value of our data lies in their significantly smaller (usually by at least a factor of 3) errors than those of previous work.

The previous R-matrix analysis of the mass-5 system[16] gives cross-section predictions that are about 7% below our measurements. A reanalysis is underway[17] in which the present results are included in the data base. We are also attempting to understand the anomalous $3/2^+$ strength that we obtained from our single-level fit.

Future Work Using the LEFCS Facility

We are presently making measurements for the $D(d,p)T$ and $D(d,{}^3He)n$ reactions, and will soon be studying other charged particle reactions such as $T(t,\alpha)nn$ and $D({}^3He,\alpha)p$. Recently the idea has been propounded to use the rarely produced, but energetic, gamma rays from some of these few-body reactions to diagnose the operation of fusion-energy devices. Many of the cross sections for producing such gamma rays are very poorly known, and the LEFCS facility could be very useful in making such measurements. We hope to initiate such a program by first studying the $D(t,\gamma)$ reaction.

Acknowledgments

Many people have contributed to the development of the LEFCS facility. R. Martinez has been especially valuable for his continuing design, construction, and assembly efforts since the project's inception. G. G. Ohlsen and F. D. Correll made major contributions during the early stages of this work, and W. G. Sondheim and L. J. Morrison also contributed during the early phases. R. Hiebert's development and construction of the calorimeter control circuit and J. W. Toevs's later advice on its operation were invaluable. The cooperation of the staff at the Los Alamos Van de Graaff Facility has contributed greatly to the success of this project; we especially thank B. Roybal, D. Schmitt, J. Hunt, D. McMillan, T. Gibson, J. Rose, and R. Poore. We thank G. M. Hale for discussions on the theoretical aspects of this work. P. J. Spellman and his collaborators at Sandia Laboratory calibrated our HV resistor stack and digital voltmeters. This work was supported by the U. S. Department of Energy under Contract W-7405-ENG-36.

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