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HYDROGEN FUSION-ENERGY REACTIONS

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Abstract At the Los Alamos Ion Beam Facility we have installed a low-energy fusion cross section (LEFCS) apparatus specifically designed to measure cross sections to high accuracy for the various fusion-energy reactions among the hydrogen isotopes in the bombarding-energy range 10 to 120 keV. To date, we have completed and published our study of the D(t,α)n reaction, have finished data-taking for the D(d,p)T and D(d,^{3}He)n reactions, and have nearly finished data-taking for the T(t,α)nn reaction. Here we describe the LEFCS facility, present final and preliminary results for these reactions, and compare them with R-matrix calculations.

INTRODUCTION

Recent evaluations[1] of basic fusion-energy reactions have indicated the possibility of large systematic errors in some of the earlier measurements and stressed the need for accurate remeasurements of the cross sections for most of these reactions. In particular, it seemed[1] that beam-energy uncertainties caused by the use of foil-contained gas targets could have been a source of significant error at these energies below the Coulomb barrier where the reaction cross sections change very rapidly with incident energy.

In view of this situation, we developed, installed, and thoroughly tested a low-energy fusion cross section (LEFCS) apparatus for determining the cross sections for nuclear reactions among the hydrogen isotopes at low energy. These cross sections are important in the design of the first magnetic- and inertial-confinement fusion reactors that will eventually provide sufficient energy for commercial use. These reactors are expected to operate in the temperature range $kT = 1$-30 keV, which corresponds to laboratory bombarding energies having a large overlap with our experimental range of 10-120 keV.

We have completed[2] our study of the D(t,α)n reaction, are in the data analysis phase of our study[3] of the D(d,p)T and D(d,^{3}He)n reactions, and are nearly completed with the data-taking for the T(t,α)nn reaction. Final and preliminary results are presented here.

EXPERIMENTAL PROCEDURE AND APPARATUS

The experiments are performed by accelerating negatively charged D or T ions through a windowless, cryogenically pumped, flowing gas target of D_2 or T_2 and into a beam calorimeter. The target density is measured and the calorimeter is checked by using particle beams of several MeV energy from the Tandem Van de Graaff at the Los Alamos Ion Beam Facility. A calibrated resistor stack is used to determine the LEFCS accelerator voltage, and thus the beam energy, to high precision. The charged-particle reaction products are detected in silicon, surface-barrier detectors.

The LEFCS system consists of the following major features: (1) A highly stable, accurately calibrated dual-polarity, 120-keV accelerating system incorporating a duoplasmatron ion source that can be operated in either a positive-ion or negative-ion mode. We normally employ negative ions in order to eliminate undesired molecular species from the beam. (2) A cryogenically pumped, continuous-flow windowless gas target containing reaction-product ports at six angles. The windowless feature allows the beam energy in the reaction region of the target to be determined accurately. To date, the target has been operated with deuterium and tritium gas at flow rates (about 5 std-cc/min) such that the incident beam loses less than a few hundred eV in the target. (3) A beam calorimeter to measure the beam power independent of its charge state and hence to deduce the incident beam flux. The beam-collecting cup is compensated to remain at ambient temperature both when the beam is on and off, thereby reducing the possibility of heat leaks. The power calibration is accurate to 0.1% over a range of 10 to 800 mW. (4) The use of accelerated particles from the tandem Van de Graaff to calibrate the target density to 1 to 2% accuracy. (5) Accurate determination of the accelerating voltage using a resistive divider whose calibration is traceable to the National Bureau of Standards. (6) Tritium handling capability for both the beam and target. Further details are presented in Refs. 2, 4, and 5.

HYDROGEN FUSION-ENERGY REACTIONS

D(t,α)n REACTION

We measured the cross section for the D(t,α)n reaction at 17 triton bombarding energies from 12.5 to 117 keV (equivalent deutron bombarding energies from 8.3 to 78.1 keV). Over this energy range the cross section spans four orders of magnitude, and the reaction is dominated by s-wave capture (isotropic angular distribution) into a $3/2^+$ state in ^{5}He. When comparing measurements of charged-particle cross sections below the Coulomb barrier with other experiments or calculations, it is more informative to use the so called astrophysical S function[6] rather than the rapidly varying cross section itself. Basically, S is obtained from the cross section σ by factoring out the energy dependences of the de Broglie wavelength and the Coulomb penetrability in the incident channel. For d + t we have

$$S = 0.59962\ \sigma\ E_d \exp[1.40411\ E_d^{-1/2}]\ , \qquad (1)$$

where E_d is the deutron bombarding energy in MeV, σ is the cross section in b, and S is expressed in units of MeV b.

In Figure 1 we compare our data with some[7] of the other data in the literature. The LEFCS data are accurate to 1.4% absolute over most of the energy range, with the error rising to 4.8% at the lowest energy. These errors are at least a factor of three smaller than those of previous work. It is seen that S displays the typical bell shape appropriate to a reaction that proceeds through an isolated resonance state. The dashed curve shows the result of a single level R-matrix fit to a data base up to 250 keV that included selected data from the literature as well as the LEFCS results.

In Figure 2 we show the S-function results of several evaluations[8-12] for the t + d reaction at deutron bombarding energies below 20 keV. LA79 is Hale's[8,9] evaluation (up to 8 MeV) prior to the LEFCS results, and LA84 is his most recent evaluation, which includes the LEFCS data. We consider the LA84 evaluation to be presently the most accurate representation of the D(t,α)n cross section, although Greene's[10] work does not seem unreasonable. Clearly the Duane[12] evaluation is to be avoided, and Howerton's[11] shows an odd behavior that we tentatively ascribe to interpolation difficulties, although, on the average, it does give reasonable values. A similar such comparison, but in terms of reactivities up to a plasma temperature kT of 20 keV, is given in Ref. 2. The reader should consult Ref. 2 for further details on the LEFCS D(t,α)n measurement.

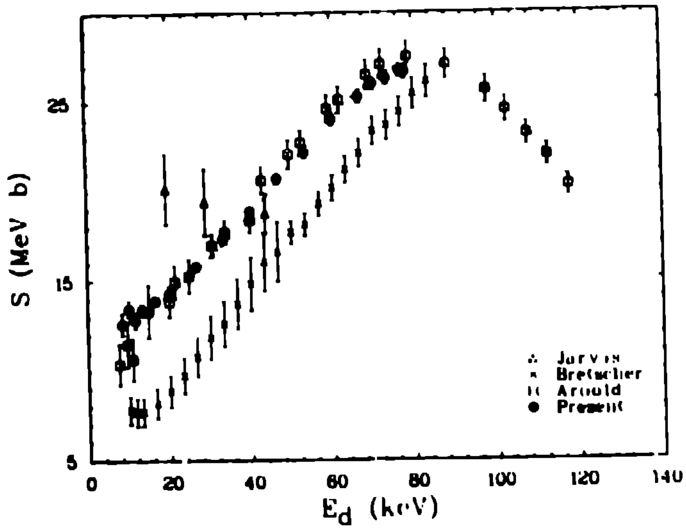


FIGURE 1 The S function, Eq. (1), vs equivalent deuteron bombarding energy for the D(t,α)n reaction. Shown are the present data and those of Ref. 7. Note the suppressed zero. Total errors are indicated. The curve is the result of a single-level R-matrix fit.

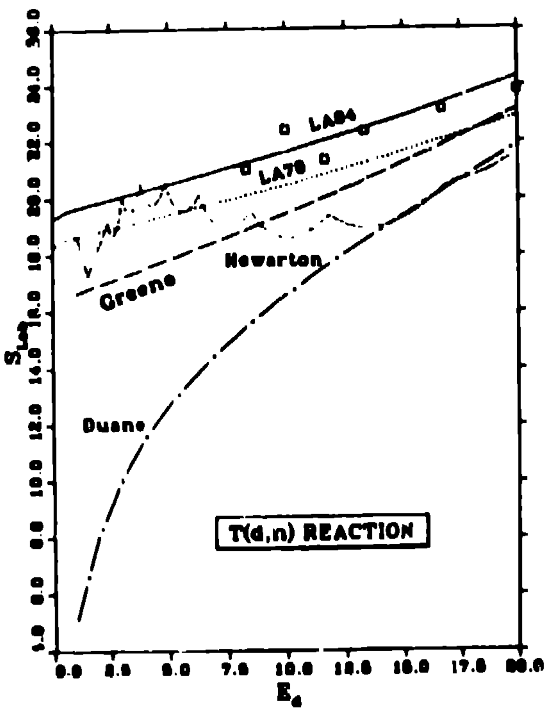


FIGURE 2 Evaluated S functions for the low-energy region of the T(d,n) reaction. E_d is the deuteron bombarding energy in keV, and S_{Lab} is computed by dropping the term 0.59962 in Eq. (1). The solid curve, LA84, shows a recent unpublished evaluation of Hale that includes the LEFCS data (squares). The dashed curve, LA79, is from Refs. 8 and 9. We thank G. M. Hale for furnishing this figure.

D(d,p)T AND D(d,^{3}He)n REACTIONS

By simultaneously detecting p,t and ^{3}He, we measured the differential cross sections for the D(d,p)T and D(d,^{3}He)n reactions at 11 deuteron bombarding energies from 20 to 117 keV. A preliminary extraction of the cross sections from the raw data has been performed, and a few small corrections have yet to be made. In this report we indicate absolute errors of 3%, although when the final error analysis is carried out, we expect most of the data to be more accurate than that.

A remarkable difference between these reactions and the d + t reaction is the large angular anisotropy present in the d + d differential cross sections $\sigma(\theta)$, even at these low energies (see Figure 3). We have therefore fitted our preliminary values for $\sigma(\theta)$ to the form $a + b\cos^2\theta$, assuming s and p waves predominate. From past work[13] it is known that d waves begin to manifest themselves at the higher energies in our range, and therefore in our final analysis we will add a $\cos^4\theta$ term to the fitting function. From our fits to $\sigma(\theta)$ we can derive the integrated cross section σ and convert these to an S function via

$$S = 0.5\, E_d\, \sigma \exp[44.4021\, E_d^{-1/2}] \quad , \qquad (2)$$

where E_d is in keV, σ is in b, and S is expressed in units of keV b. These results are shown in Figure 4. It is seen that over most of our energy range the cross section for the n^3He branch is larger than that for the pt branch, but decreases more rapidly with decreasing energy than does the cross section for the pt branch. In Figures 5 and 6, we compare the LEFCS data with representative sets from the literature.[13] The curves are from a unified, mass-4, R-matrix analysis[8,9] that did not include the LEFCS results. It is seen that there is a relatively small systematic difference between the LEFCS data and the R-matrix

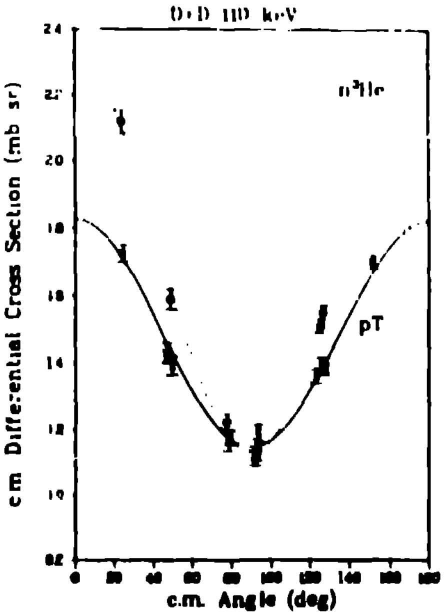
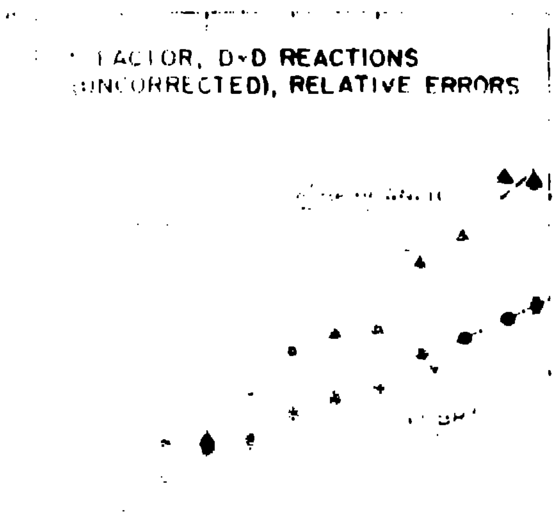


FIGURE 3 The c.m. differential cross section for both branches of the d + d reaction at a deuteron bombarding energy of 110 keV. Note the suppressed zero. The curves represent least squares fits to the data. The displayed errors are statistical only.



[illegible] The S function from Eq. ( ) for both branches of the d + d reaction [illegible]

[illegible] than that of [illegible]

(as can also be seen in Figure 3). In evaluating the anisotropies, the results of Theus et al. perhaps should be given the greatest weight, since they measured $\sigma(\theta)$ at more angles than was done for the LEFCS data, thereby obtaining smaller errors for the anisotropies. We should stress, however, that the absolute cross sections from LEFCS will be the most accurate yet measured.

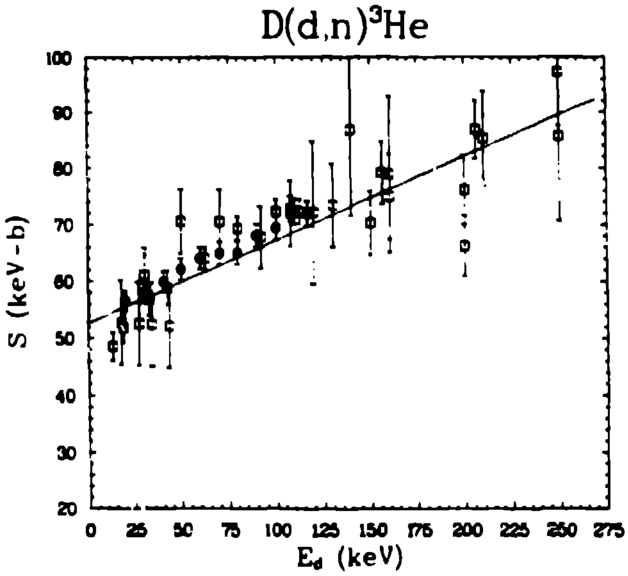


FIGURE 6 The S function for the $D(d,n)^3He$ reaction. See the caption to Figure 5.

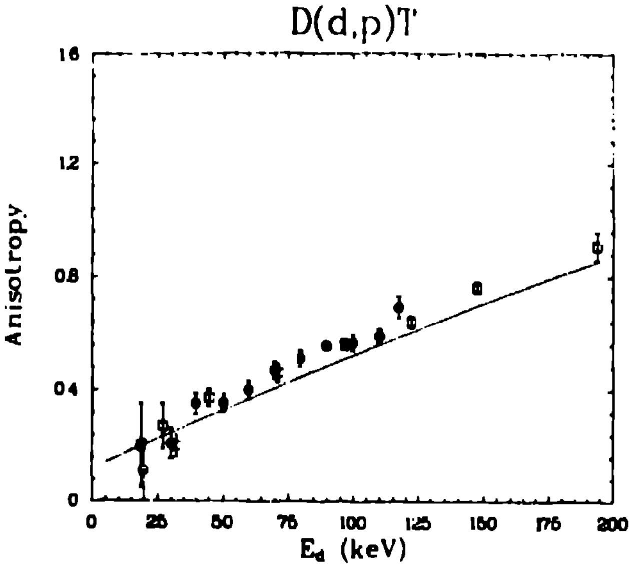


FIGURE 7 The angular anisotropy vs deuteron bombarding energy for the D(d,p)T reaction. The solid circles are the LEFCS data, and the squares are the data of Theus, et al. (Ref. 13). The curve is from a unified, mass-4, R-matrix analysis (Refs. 8 and 9).

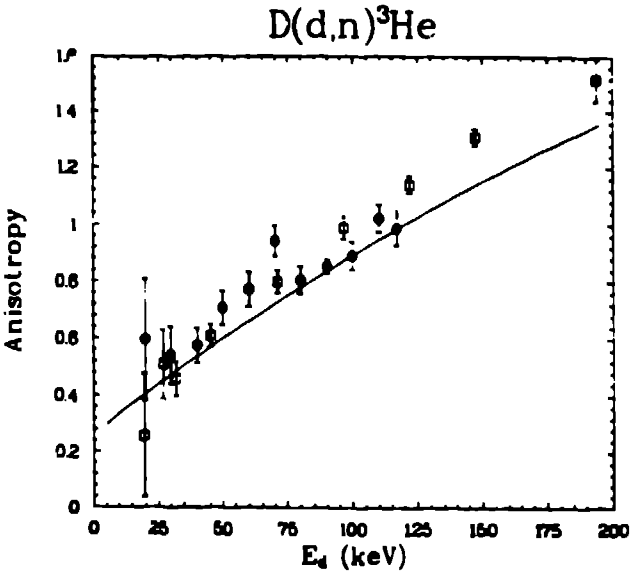


FIGURE 8 The angular anisotropy for the D(d,n)3He reaction. See the caption to Figure 7.

T(t,α)nn REACTION

We have nearly completed measuring the cross section for the T(t,α)nn reaction and have so far obtained data at triton bombarding energies of 115, 105, 90, 75, 60, 45, and 30 keV. Two major complications presented by this reaction are the flowing of tritium in our windowless gas target and the fact that the detected α particles emerge from the reaction with a continuum of energies. This latter effect makes background determination more of a problem than for reactions where the yield is contained in a narrow peak. The background is caused mainly by neutron interactions in the detectors, and to aid in its determination we have covered one of the two 45° detectors with a Ta absorber thick enough to stop the charged particles, but thin enough not to appreciably affect the neutron spectrum. In Figure 9 we show a comparison of the spectra from the two 45° detectors at 115 keV triton bombarding energy. The large peak near the top of the α continuum arises from only a 0.5% deuterium impurity in our tritium target gas. The large peak in the low channels near the electronic cutoff is from tritium decay activity. We have derived preliminary cross sections from the measured spectra through the following procedure: (1) We calibrate the tritium target density by accelerating deuterons, measuring the T(d,α)n yield, and using our previously measured cross sections for that reaction. (2) We interpolate across the D(t,α)n peak. (3) We extrapolate the

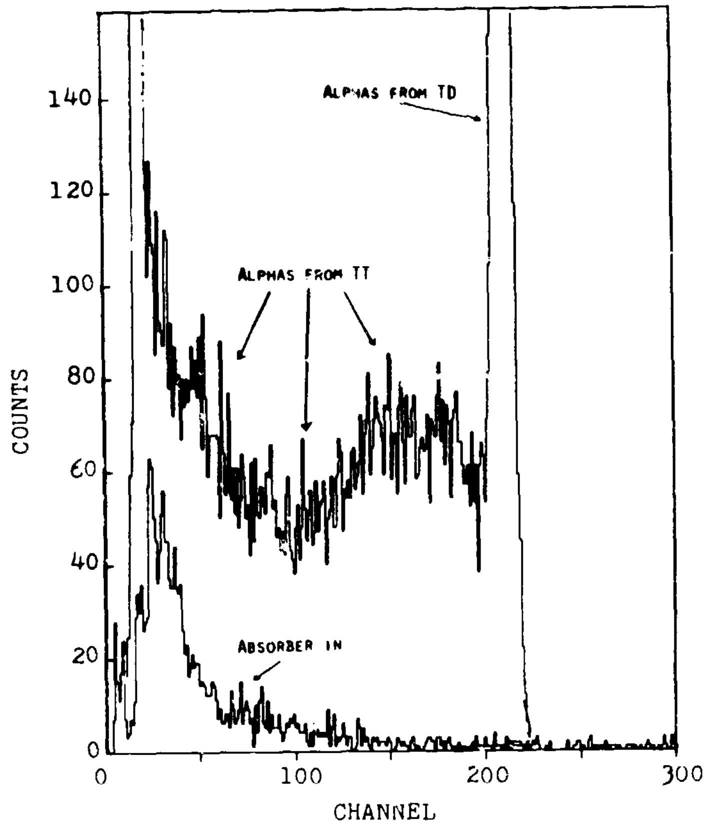


FIGURE 9 Alpha-particle spectrum at 45° (lab) from the $T(t,\alpha)nn$ reaction at 115 keV triton bombarding energy. The neutron background is indicated by the spectrum obtained with an absorber in place that prevented the alpha particles from entering the detector. Channel 200 corresponds to about 4 MeV deposited in the detector.

$T(t,\alpha)n$ spectrum to zero energy. (4) We subtract the neutron-produced background. (5) We integrate the yield over lab solid angle. In the future we will develop a reaction model to aid in the cross section extraction. With such a model we may be able to predict reliably the associated neutron spectrum from t + t. Even without the model, we estimate we can extract cross sections to better than 5% at most energies. In Figure 10 we show the results of the preliminary σ extraction, converted to the S function

$$S = 0.5\ E_t\ \sigma\ \exp[54.3378\ E_t^{-1/2}] \quad , \qquad (3)$$

where E_t is in keV, σ is in b, and S is in keV b. At present, we assign errors of 5% to the LEFCS data. Our data seem to agree best with the data of Serov et al.[14] and confirm Hale's[8,9] analysis quite well. We disagree with Greene's analysis,[10] which was evidently influenced by the Govorov data.[15] Also shown in Figure 10 are the data of Agnew et al.[16]. In the near future we will obtain a small amount of tritium having a deuterium impurity 100 times less than that of our present supply. With this we will

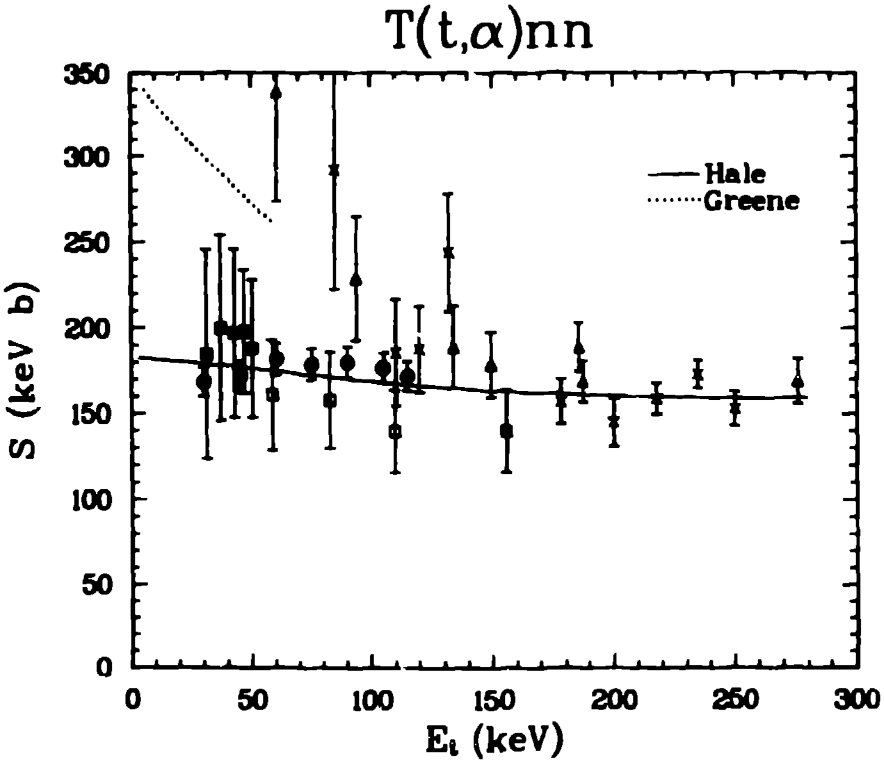


FIGURE 10 The S function of Eq. (3) vs triton bombarding energy for the T(t,α)nn reaction. The solid circles are the preliminary LEFCS data shown with 5% errors. The squares are data of Ref. 14, the triangles are data of Ref. 15, and the crosses are data of Ref. 16. The solid curve is from an R-matrix analysis (Refs. 8 and 9), and the dashed curve is from Greene's evaluation (Ref. 10).

be able, at one or two energies, to investigate more carefully the high-energy end of the alpha spectrum in the region of the nn final state interaction.

CONCLUSION

With the LEFCS system we have demonstrated the ability to measure cross sections for the basic fusion reactions in the low-energy region to unprecedented accuracy. These data can greatly aid evaluations, such as R-matrix analyses, in producing highly reliable fusion energy data. After completion of the t + t measurements we plan to attempt measurements of some gamma-ray reactions, such as D(t,γ)^{5}He, which may be useful as burn diagnostics. We will also look at the feasibility of studying another charged particle reaction of interest, D(^{3}He,p)^{4}He.

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