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LOW-ENERGY NUCLEAR REACTIONS WITH HYDROGEN ISOTOPES

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Abstract

Using the Los Alamos Low-Energy Fusion Cross-Section Facility (LEFCS), we have completed the study of the D(t,α)n reaction from E_t = 12.5-117 keV, and now have measured angular distributions of the reactions D(d,p)T and D(d,^{3}He)n from E_d = 20-117 keV. The experimental equipment features a windowless cryogenic target, a precision beam-intensity calorimeter, a 10- to 120-keV accelerator producing negative tritium ions, an accurate target gas-flow and temperature system, and a tritium gas-handling system. Most of the quite anisotropic angular distributions of the D + D reactions have relative errors of about 1% and the integrated cross sections have absolute errors of about 1.3%. Astrophysical S functions extracted from the data and also from a least-squares fit of $a + b\cos^2\theta$ to the data show a curious behavior with energy. The cross sections, which agree with previous but less accurate data, are compared with R-Matrix calculations. We also show preliminary results for alpha-particle spectra of the T(t,α)nn reaction. A feature of this experiment is the flow through our windowless target of 1.5 standard liters of tritium gas per day.

1. Introduction

The Los Alamos program in Low-Energy Fusion Cross Sections (LEFCS) was begun several years ago to improve the accuracy of and clear up discrepancies [1] among measured cross sections for the basic fusion reactions D(t,α)n and T(t,α)nn. The D+D reactions D(d,^{3}He)n and D(d,p)T have no major discrepancies, but have been studied as a check of our system and to improve the accuracy of the existing data. All of these reactions are of interest in the physics of few-body nuclear interactions and will be 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.

Our D(t,α)n experiment is now complete and published [2], and has produced absolute cross sections with 1.4% absolute error over most of the range of 8.3 to 78.1 keV equivalent deuteron bombarding energy. We have now completed data taking for the D+D channels and are in the process of performing the T(t,α)nn experiment.

In this paper we will show samples of raw and analyzed angular distributions of the D+D data, the subsequent integrated cross sections, and a first look at the results of the T(t,α)nn experiment.

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 calibration is checked by using particle beams of several MeV energy from the Tandem Van de Graaff of 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.

2. Apparatus and Experimental Procedure

The experimental equipment and procedures are described in detail in Refs. 2-5, and only an overview and features new to the D+D and T+T experiments will be given here. Figure 1 shows a schematic diagram of the LEFCS system. The design of the experiment has been dominated by the need for accurate knowledge of the bombarding energy, detection of as low a counting rate as possible, and the elimination of as many sources of systematic error as possible. A cryogenic windowless gas target was chosen to avoid energy-loss uncertainty in entrance and exit foils. A temperature of the target chamber (10.5 K for deuterium and 11.2 K for tritium gas) just above the freezing point of the target gas gives the maximum target density compatible with an appropriate energy loss in the target. The resulting gas density is low, approximately 10^{16} nuclei/cm^3. The target gas, after leaving the target, is pumped (frozen) by nearby 4-K surfaces. Accurate control of the target density is maintained by precise control of the continous flow of deuterium or tritium (at 5 standard cc/min) and of the temperature at the reaction volume. Alpha particles, protons, tritons, and ^{3}He particles from the various reactions come out of the cryogenic target region through thin exit foils and are detected by standard surface-barrier solid-state detectors. The product Gn of the geometry factor G and the target density n for deuterium is calibrated using a 10-MeV proton beam from the Van de Graaff; the necessary D(p,p)D accurate cross sections were measured by us in a separate experiment [2] using the Los Alamos precision 30-inch scattering chamber. The Gn product for a tritium gas target was found by using a deuterium beam and normalizing to the D(t,α)n cross section previously measured [2].

Because the low energy beam undergoes a large amount of charge exchange as it passes through the target, we measured the beam intensity with an accurate calorimeter [2,6], having an error of less than 0.5%. An extensive tritium handling system is necessary to be able to use and recover tritium in either the ion source or target. We used roughly one standard liter of tritium in a typical run day when using a tritium target. A negative ion beam was used to avoid unwanted molecular species, and to reduce problems associated with slit-edge scattering. We typically used a very stable beam of 1-5 μA with 99.5% transmission through a 2.4-mm target aperture. The critical beam energy was determined primarily by measuring the accelerator high voltage with a precision resistor stack and then making various small corrections. The resistor stack calibration is traceable to the primary voltage standard at the National Bureau of Standards.

Of the many sources of error considered [2] the relative error of the D+D data is dominated by fluctuations in the target density, counting statistics, and the repeatability of the calorimeter measurement; the latter two error sources were important especially at low energies. The absolute scale error is largely due to the uncertainty of the D(p,p)D calibration cross section (1.2%).

The T+T experiment has the additional complication that there are 3 reaction products, resulting in the strength of the reaction being spread out in a spectrum of alpha energies. In this case neutron background contributes significantly to the relative error. The absolute error is largely due to the uncertainty of the T(d,α)n calibration cross section (1.4%). We expect to obtain a total absolute error in the integrated cross section of 5% or better.

3. The D(d,^{3}He)n and D(d,p)T Reactions

Figure 2 gives an example of the raw data for the D+D interaction. The proton peak is at an energy (about 4 MeV) near to that of the alpha particle of the D(t,α)n reaction [2] and was easily measured accurately. The ^{3}He and triton peak are at or below 1 MeV, and improvements decreasing the electronic noise and neutron background were made before satisfactory results were obtained. The beam stop and various slits were baked to drive off impacted tritium from early runs with a triton beam, eliminating background neutrons from the T(d,n) reaction. A software algorithm was introduced in our data acquisition program to eliminate multiple noise events caused by occasional sparking in our accelerator.

The angular distributions at 110 keV bombarding energy are shown in figure 3. These and the following results are preliminary, waiting for small final corrections. Unlike the D(t,α)n reaction there is a remarkable anisotropy, largest in the neutron branch. We made measurements at 11 bombarding energies from 20-117 keV. Most of the angular distributions have relative errors on the order of 1%, and the resulting integrated cross sections have absolute errors of about 1.5%. The D(d,^{3}He)n integrated cross-section exitation function is shown in figure 4 on a semi-log plot. Seen is the familiar sharp rise due to the coulomb-barrier penetration; but because of this rise it is not very informative to compare our data with other work on such a plot. We prefer instead to present the data as the astrophysical S function [2] which is universally used in the field of nuclear astrophysics and factors out in the incident channel the the energy dependence of the Coulomb barrier and the wavelength of the bombarding particle, leaving in the S function the more specific nuclear effects: $S = 0.5\ E_d\ \sigma\ \exp(44.402\ E^{-1/2})$. Here E_d is given in keV, σ in b, and S in keV b.

Thus, figure 5 presents S(E) for our data. Relative errors are shown. The straight lines are least-squares fits to the data. The E=0 intercepts are S(0)=53.6 (n^3He) and S(0)=55.7 (pt) keV b. Shown in figure 6 are our S-function values compared with a representative selection of data from a number of absolute measurements [7] performed in the period from 1948-1960. As mentioned in the introduction, no discrepancy is resolved, but the accuracy of D(d,^{3}He)n and D(d,p)T cross sections in this energy region has been greatly improved.

Returning to the angular distribution data, we have made a least squares fit using our data to the form $\sigma = a + b \cos^2\theta$. The S and P-wave contributions are represented by a and b respectively. Given in figure 7 are the S- and P-wave S functions for the two channels. The strength a P-wave interaction at this low energy is understandable when one notes that this region of excitation in the compound system (E_x= 24 MeV in ^{4}He), is dominated by negative parity levels helping the P-wave compete in spite of the suppression by the angular momentum barrier. Less well understood are the relative intensities of S_b for the n^3He and pt channels, and the markedly different slopes of S_a for the two channels. The anisotropy coefficients A = b/a of our data agree well with those of Theus, McGarry, and Beach whose definitive study [8] of the relative angular distributions of the D+D reaction channels ranges from 20 to 350 keV.

4. The T(t,α)nn Reaction

Several factors make the T+T experiment considerably more difficult. As mentioned earlier the 3-body alpha particle spectrum makes the neutron background a much more significant source of error. The work done in reducing these effects in the D+D experiment greatly helped. A sample of the raw data spectrum for the sum of four 100-minute runs is shown in figure 8. The large peak in channel 200 (about 4 MeV) are alpha particles from the D(t,α)n reaction, the deuterium being a 0.5% contaminant in the target gas. In the region of channel 20 to 50, noise and neutron background become important.

After suitable subtractions, what is left is an expected [9] double-humped alpha particle spectrum of the T(t,α)nn reaction. Integration over alpha energy and angle (assuming isotropy in the center-of-mass system) gives results shown in figure 9 in which are plotted the energy dependence of the S function from the preliminary data taken to date at E_t = 117, 105, 90, and 75 keV. Our data are shown with 5% error bars. One sees the improvement over previous data [10-12]. Note that the S function is flat (or very nearly so) with energy while the in the D+D case it falls with decreasing energy. How low we will be able to go in energy depends on how rapidly the neutron flux and cross section fall off. We hope to reach 30-40 keV.

5. Future Plans

After finishing the D+D and T+T experiments we hope to attempt a study of the low-intensity, but energetic, gamma rays produced in some of the pertinent few-body reactions as diagnostics of plasma conditions. A measurement of the

$^3He(d,p)^4He$ reaction would be of interest and may be possible at the highest energies we can obtain, 100 to 117 keV.

6. Acknowledgements

Many people have contributed to the development of the LEFCS facility. R. Martinez has been especially valuable for his continuing construction, assembly, and maintainence since the project's inception. R.A. Hardekopf, G.G. Ohlsen, and F.D. Correll made major contributions during the early stages of this work. J.C. Gursky's skill in fabricating the thin exit foils is greatly appreciated. R. Maltrud has been invaluable in obtaining and advising us about the target tritium gas. We thank G.M. Hale and D.C. Dodder for discussions and for their help with their R-matrix code EDA. M.S. Peacock furnished her usual expert assistance during the computational phases. The cooperation of the staff at the Los Alamos Ion Beam Facility has contributed greatly to the success of this project.

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Figure Captions

Fig. 1. Schematic diagram of the Los Alamos low-energy fusion cross section (LEFCS) facility.

Fig. 2. D+D raw data spectrum at 90 keV and 45°. In order of increasing channel (energy) the peaks are ^{3}He, T, and P.

Fig. 3. Example of angular distributions for the D+D reactions at 110 keV bombarding energy. The dashed line and solid circles are for the n^{3}He channel, and the solid curve and crosses are for the pT channel. The curves are from our least squares fit to the data $(a + b \cos^2\theta)$. Note the supressed zero.

Fig. 4. Excitation function for the D(d,^{3}He)n reaction integrated cross section. The absolute error bars are smaller than the plotting symbol.

Fig. 5. Preliminary integrated D+D S Functions. Note the supressed zero. Relative errors are shown. The curves are least-squares fits to a straight line.

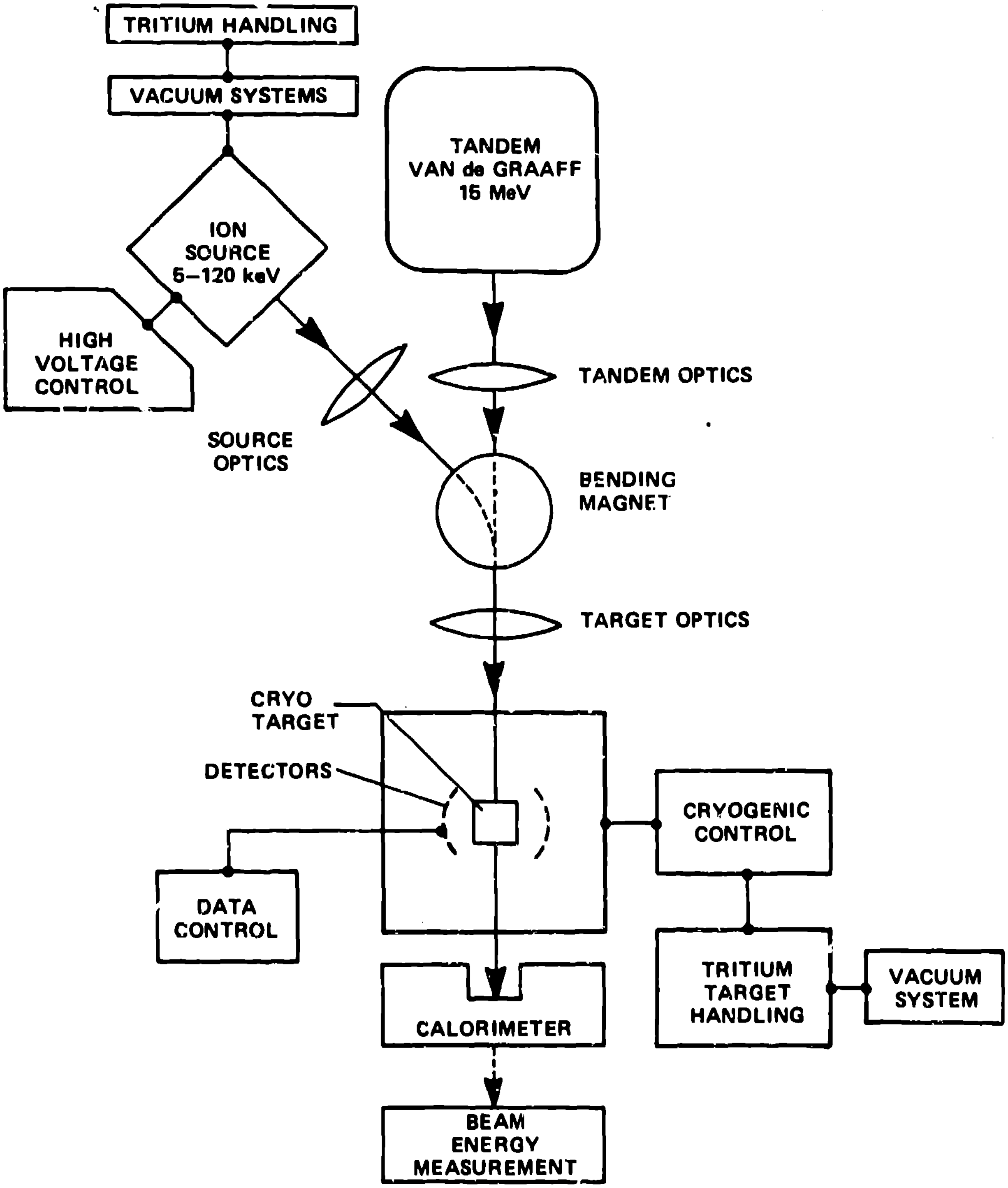
Fig. 6. The D+D S functions compared with those of other experiments. Absolute errors are shown. We have assigned 3% errors to our data (black circles) and expect in the final analysis that the errors will be smaller. Also shown are a representative selection of data from other experiments (Ref. 7).

Fig. 7. S functions for D+D P- and S-wave interactions for each channel, S_a and S_b. Note the supressed zero for S_a. The curves are only eye guides.

Fig. 8. T(t,α)nn reaction raw data for 45° lab angle and 115-keV bombarding

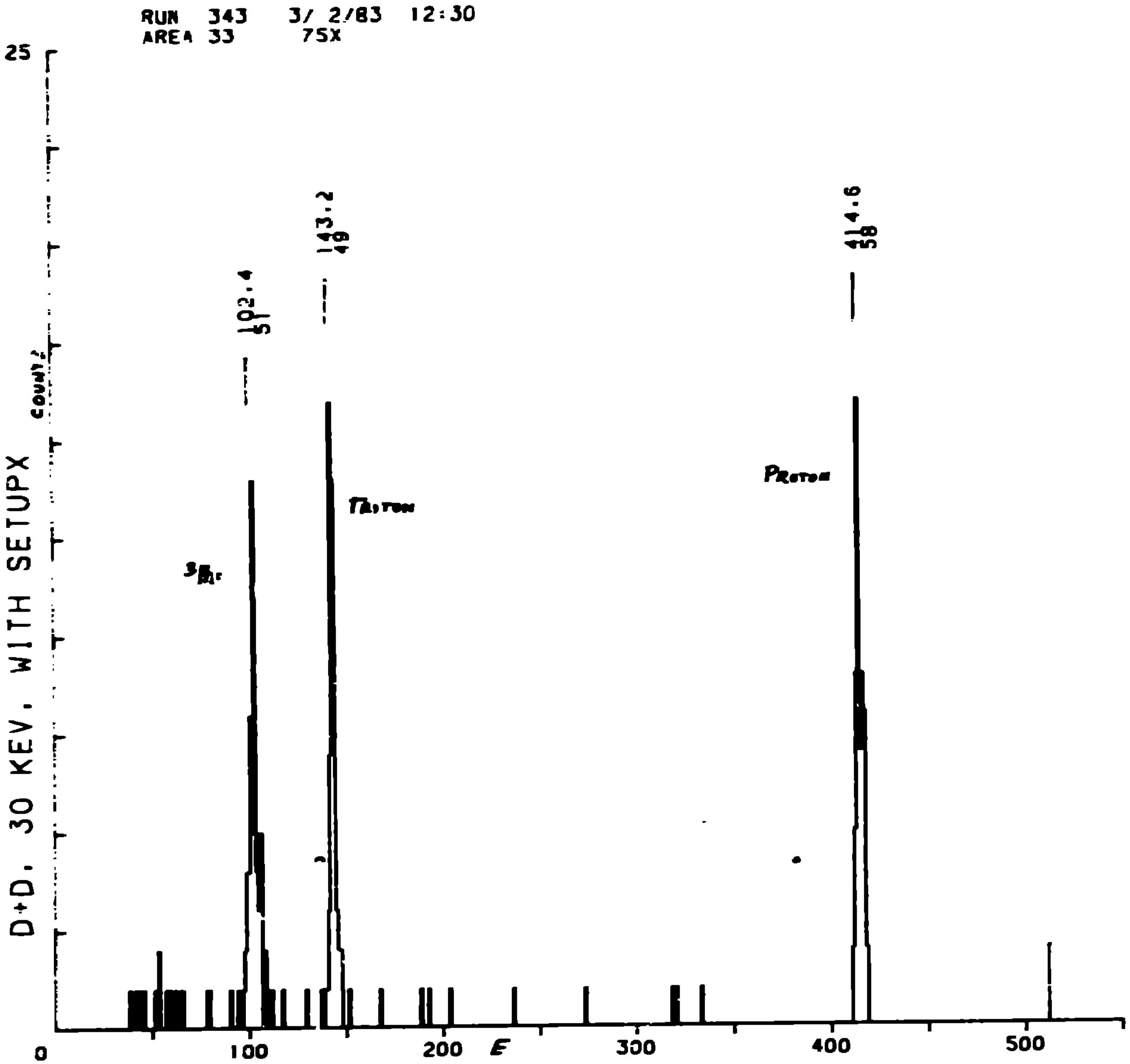
energy. Note the large peak of alpha particles from the 0.5% deuterium contaminant in the target gas.

Fig. 9. Integrated S functions for the T(t,α)nn reaction. Our preliminary data are the black circles with 5% absolute errors. Also shown are the data of Govorov et al. (triangles) Ref 10; Agnew et al. (crosses) Ref. 11; and Serov et al. (squares) Ref.12. The solid curve is an R-Matrix prediction of Hale, Ref. 13, and the dashed curve is from the compilation of Greene, Ref. 14.



LOW ENERGY CROSS SECTION EXPERIMENT

[illegible]


RUN 343 3/ 2/83 12:30
AREA 33 75X
D+D. 30 KEV. WITH SETUPX
COUNTS
25
0
100
200
300
400
500
E
102.4
51
143.2
49
414.6
58
3He
TRITON
PROTON

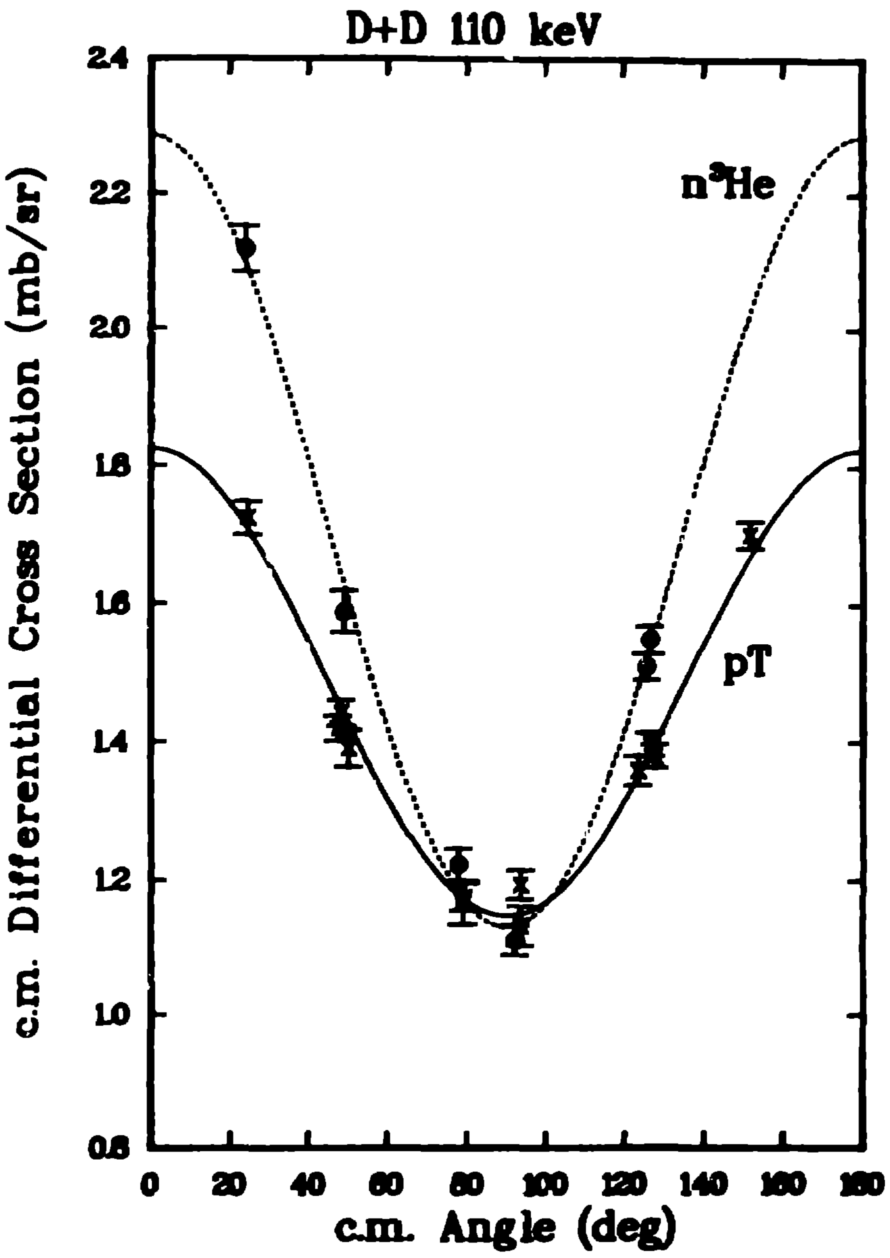
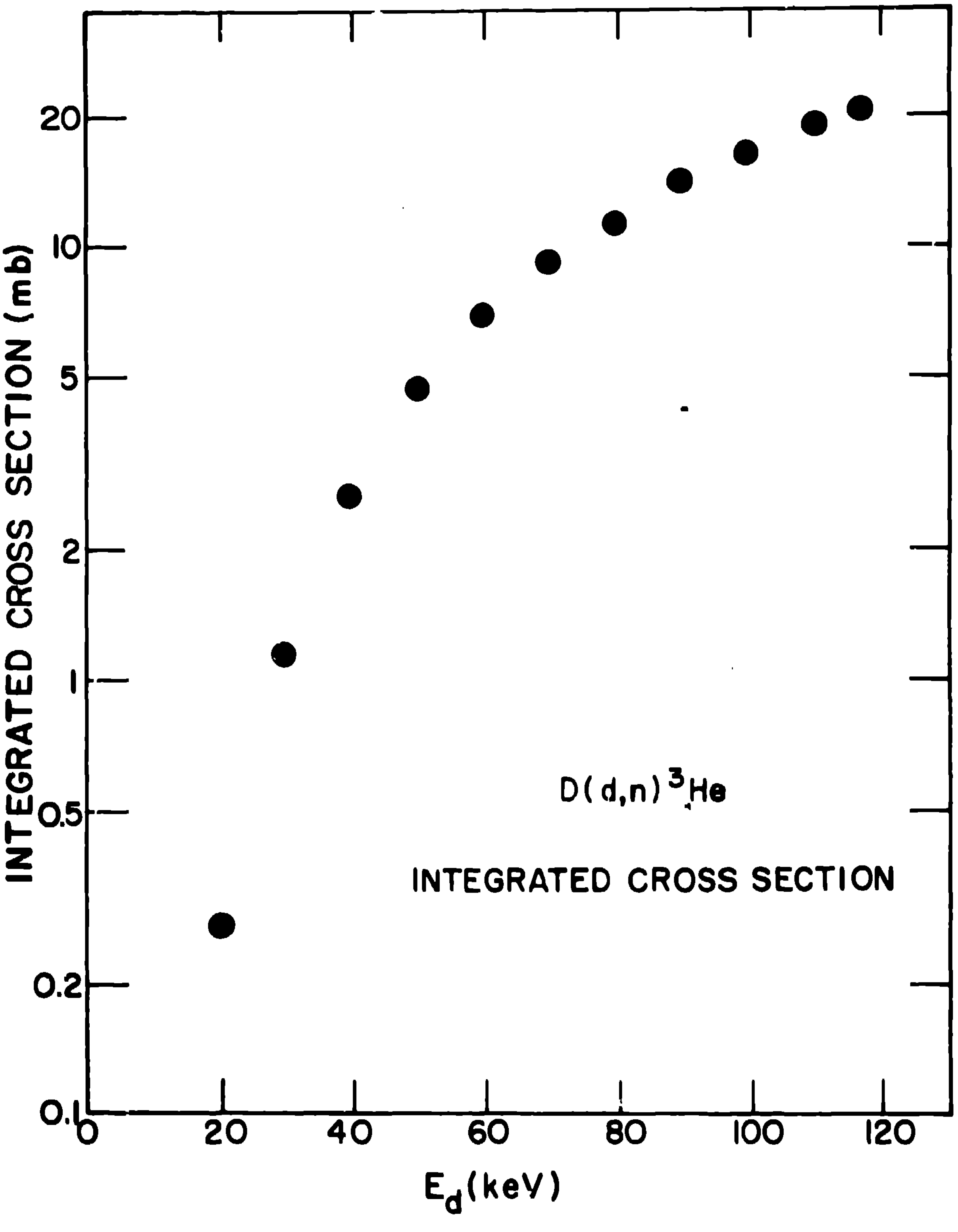
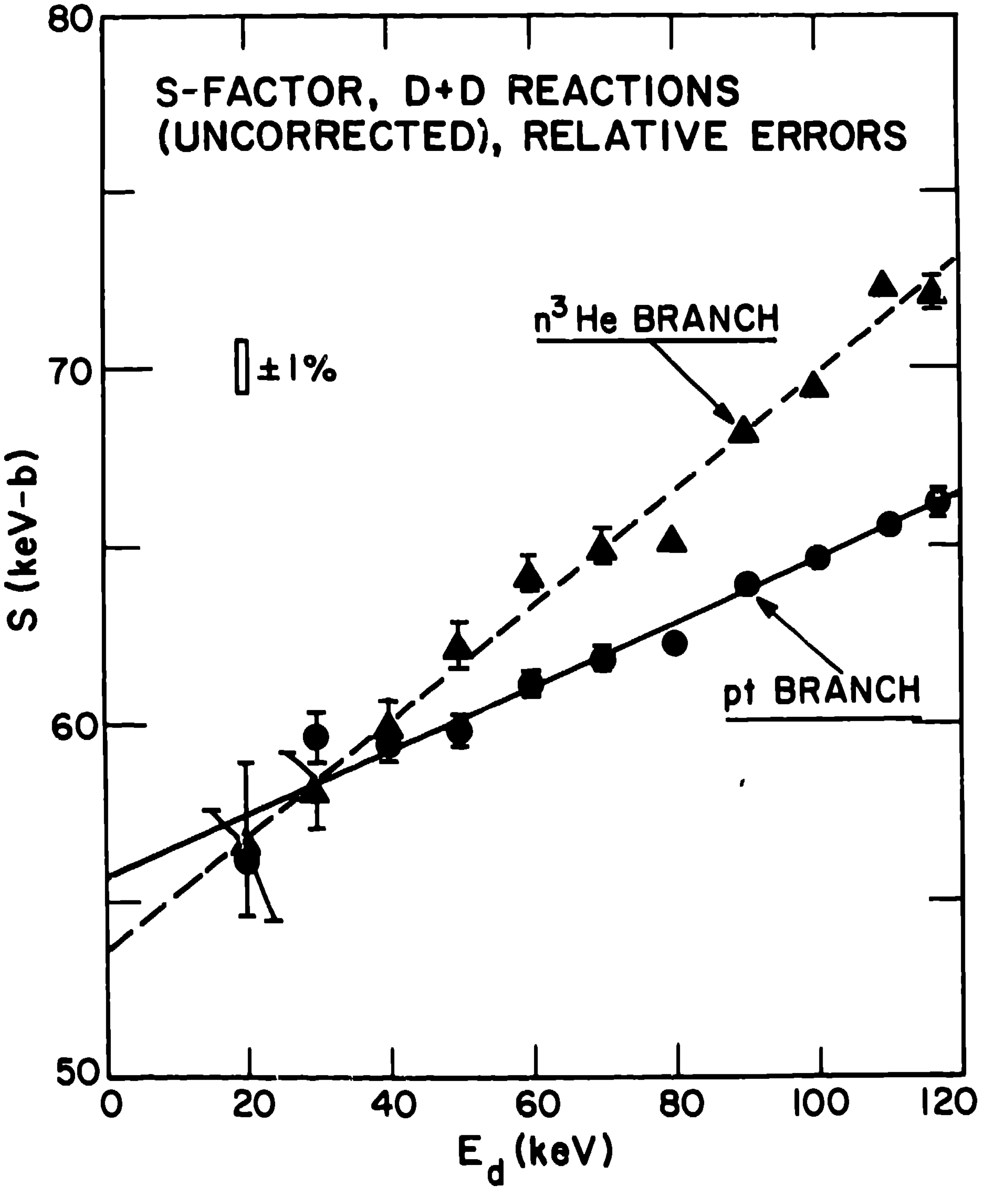
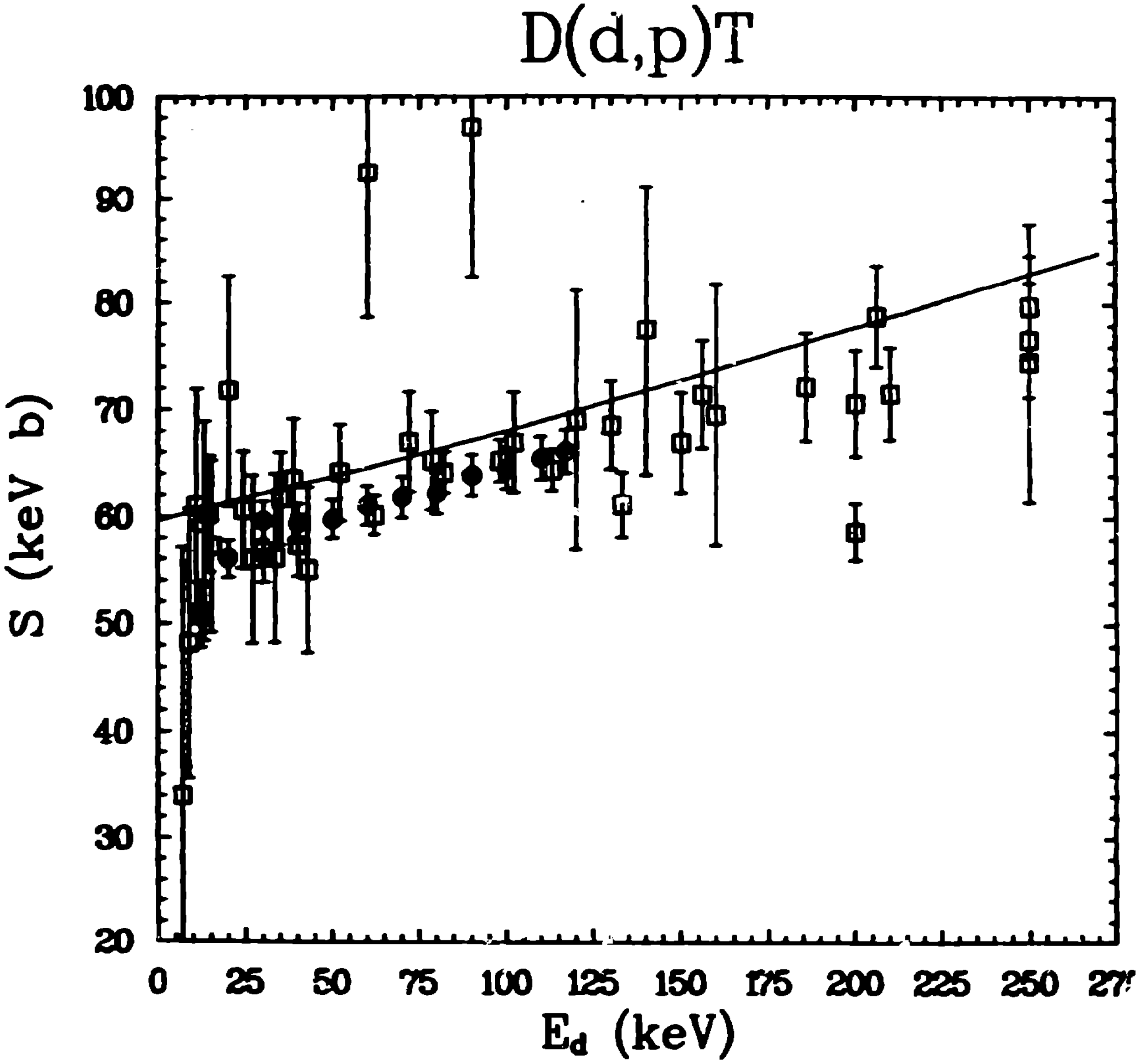
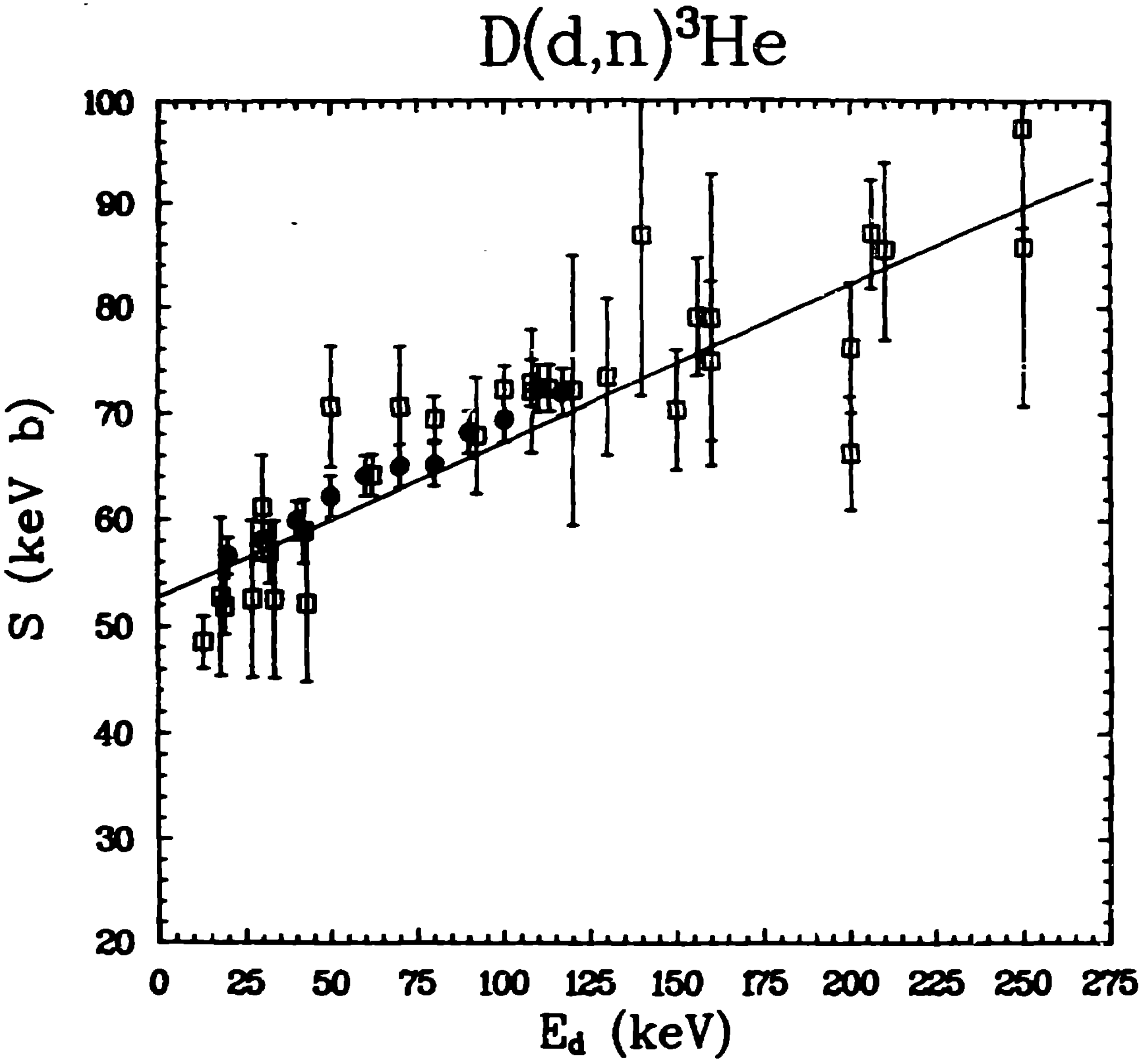

D+D 110 keV
c.m. Differential Cross Section (mb/sr)
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
n^3He
pT
0
20
40
60
80
100
120
140
160
180
c.m. Angle (deg)

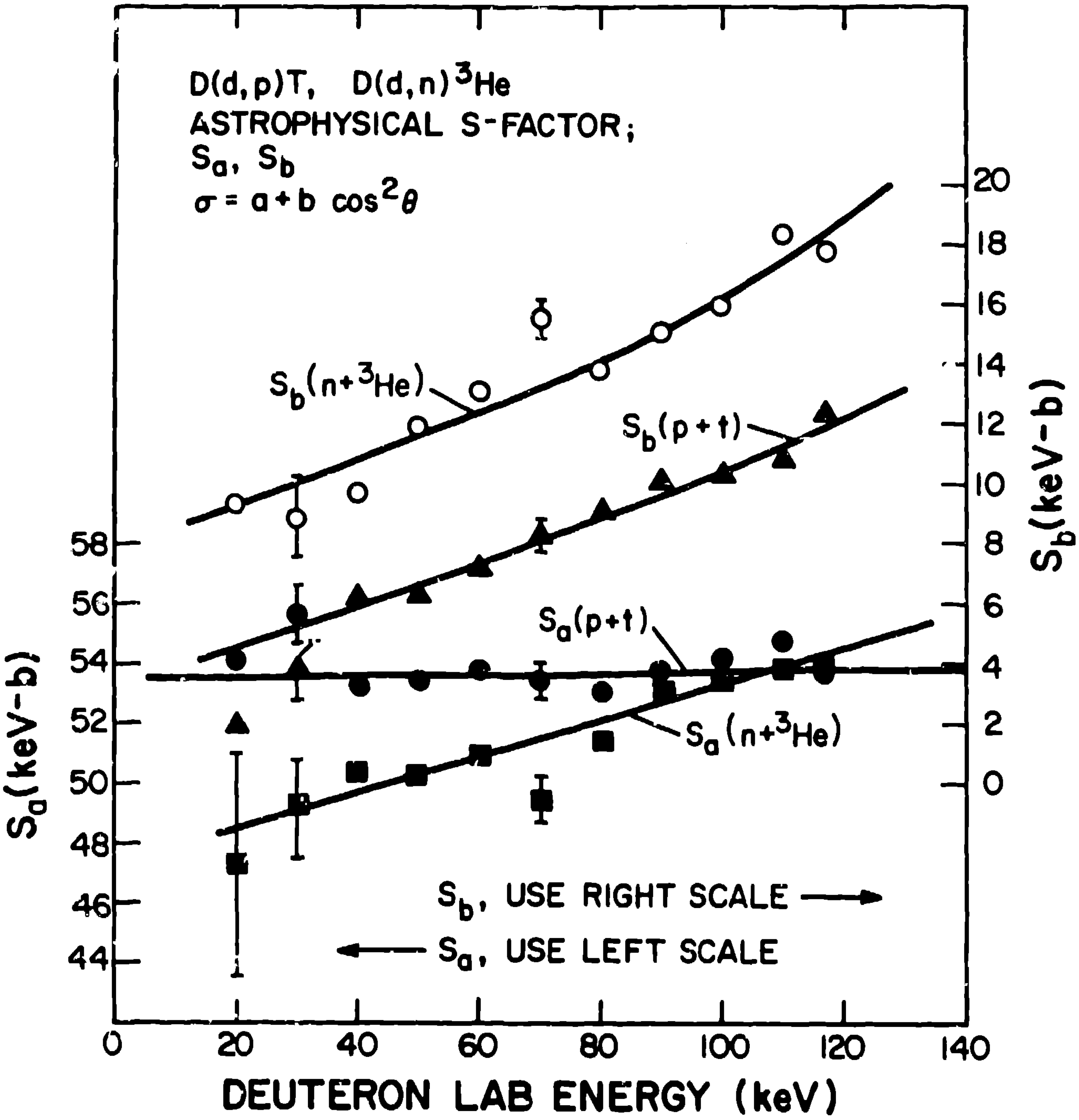
Fig 3


INTEGRATED CROSS SECTION (mb)
20
10
5
2
1
0.5
0.2
0.1
0
20
40
60
80
100
120
E_d(keV)
D(d,n)^{3}He
INTEGRATED CROSS SECTION


S-FACTOR, D+D REACTIONS
(UNCORRECTED), RELATIVE ERRORS
±1%
n³He BRANCH
pt BRANCH
S (keV-b)
E_d (keV)
80
70
60
50
0
20
40
60
80
100
120


D(d,p)T
S (keV b)
100
90
80
70
60
50
40
30
20
0
25
50
75
100
125
150
175
200
225
250
275
E_d (keV)


D(d,n)^{3}He
S (keV b)
100
90
80
70
60
50
40
30
20
0
25
50
75
100
125
150
175
200
225
250
275
E_d (keV)


D(d,p)T, D(d,n)³He
ASTROPHYSICAL S-FACTOR;
Sa, Sb
σ = a + b cos²θ
Sb(n+³He)
Sb(p+t)
Sa(p+t)
Sa(n+³He)
Sb, USE RIGHT SCALE
Sa, USE LEFT SCALE
Sa (keV-b)
Sb (keV-b)
44
46
48
50
52
54
56
58
0
2
4
6
8
10
12
14
16
18
20
0
20
40
60
80
100
120
140
DEUTERON LAB ENERGY (keV)

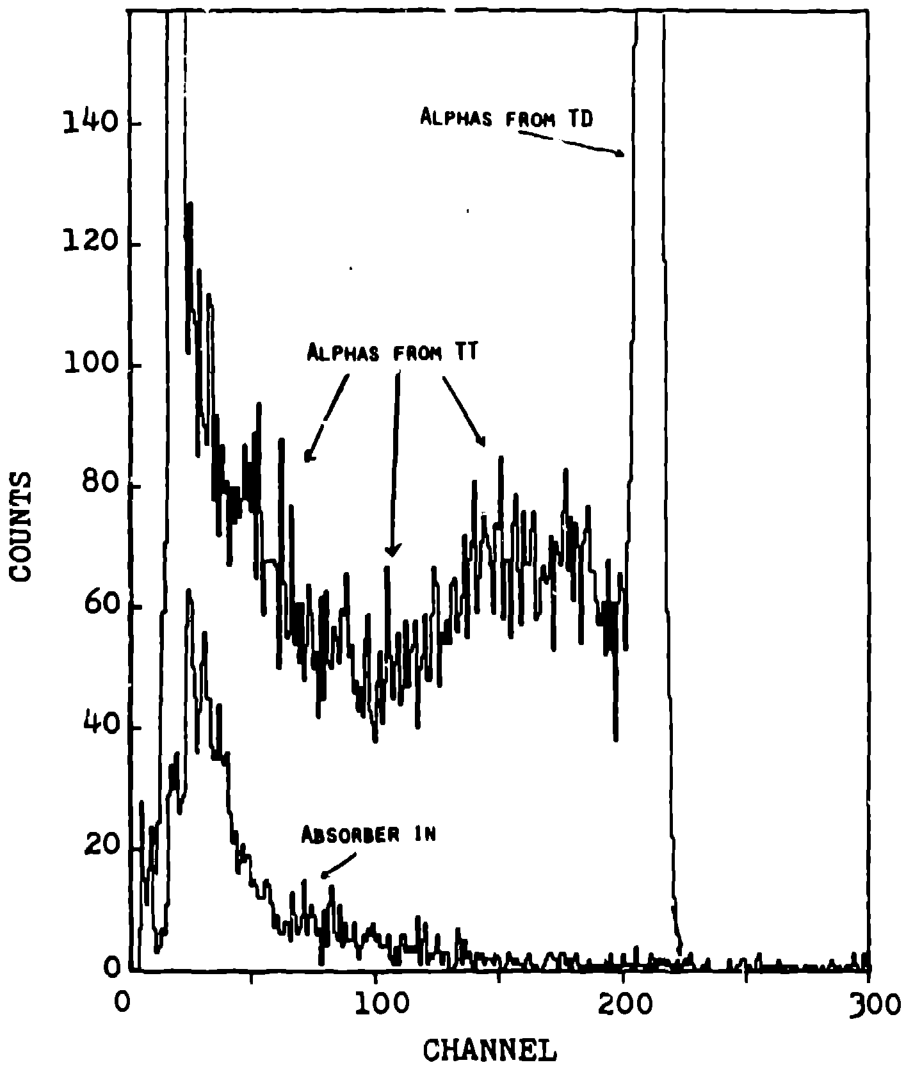
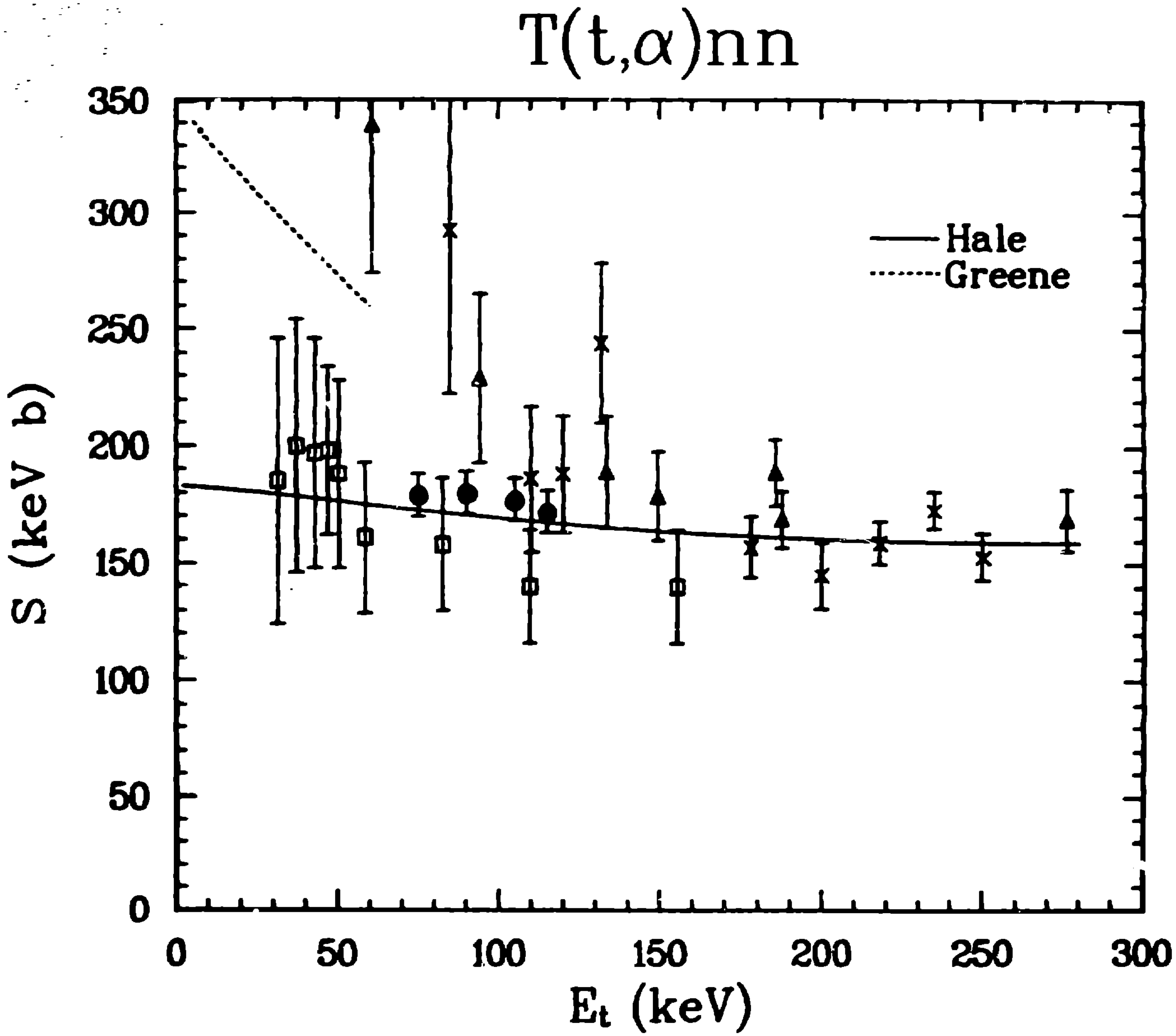

ALPHAS FROM TD
ALPHAS FROM TT
ABSORBER IN
COUNTS
0
20
40
60
80
100
120
140
0
100
200
300
CHANNEL

FIG 8


T(t,α)nn
Hale
Greene
S (keV b)
350
300
250
200
150
100
50
0
0
50
100
150
200
250
300
E_t (keV)