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REQUIREMENTS FOR CHARGED-PARTICLE REACTION CROSS SECTIONS IN THE D-D, D-T,T-T, AND D-^{3}He FUEL CYCLES*

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ABSTRACT

This paper reviews the status of experimental data and data evaluations for charged-particle reactions of interest in fusion-reactor design. In particular, the ^{2}H(t,α)n, ^{2}H(d,p)^{3}H, ^{2}H(d,^{3}He)n, ^{3}H(t,α)nn and ^{3}He(d,p)^{4}He reactions at low energies are studied. Other secondary reactions are considered. The conclusion is that such cross sections are well known for the near and medium term, and that no crucial experimental lack exists. There is a serious lack of standard evaluations of these reactions, which should be in an internationally acceptable format and easily accessible. Support for generating such evaluations should be given serious consideration.

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This paper reviews the status of experimental data and data evaluations for charged-particle reactions of interest in fusion-reactor design. In particular, the ^{2}H(t,α)n, ^{2}H(d,p)^{3}H, ^{2}H(d,^{3}He)n, ^{3}H(t,α)nn and ^{3}He(d,p)^{4}He reactions at low energies are studied. Other secondary reactions are considered. The conclusion is that such cross sections are well known for the near and medium term, and that no crucial experimental lack exists. There is a serious lack of standard evaluations of these reactions, which should be in an internationally acceptable format and easily accessible. Support for generating such evaluations should be given serious consideration.

1. Introduction

As progress in the design and development of both magnetic and inertial-confinement fusion reactors takes place, the need for reliable and accurate cross section measurements of the basic fuel cycle nuclear reactions increases. A 1981 evaluation [1] of past work on the d + t reaction and of other nuclear reactions important for fusion energy indicated the possibility of large systematic errors in some of the experiments. Since that time several careful experiments have much improved the data sets. In addition, several widely used parametrizations of the cross sections and reactivities have been compared [2-5] and found to be discrepant---sometimes seriously--especially at the lower energies.

The ^{2}H(t,α)n reaction is dominated by a $J^\pi=3/2^+$ resonance, causing the cross section to peak at a value of about 5 b near a deuteron bombarding energy of 107 keV. With a 17.6 MeV Q-value and such a high cross section, this reaction will certainly dominate the energy production in 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 that lie in the range of energies studied in this review. In a burning mixture of deuterium and tritium, the reactions ^{2}H(d,p)^{3}H, ^{2}H(d,^{3}He)n, and ^{3}H(t,α)nn will also be important. The reaction ^{3}He(d,p)^{4}He is of importance as it burns the ^{3}He coming from the d + d reaction in a DT plasma, and would also be of interest as the main energy producer in an advanced low-neutron reactor whose future has been stimulated by speculation that large amounts of ^{3}He may be available on the surface of the moon [6]. In the fuel-cycle reactions, both reactants and at least one resultant particle are charged allowing accurate measurements to be made perhaps more easily than in neutron experiments.

Because the most important data lies at a low energy where the cross section is dominated by the penetration of the Coulomb barrier and is steeply falling in value as the energy decreases, we shall display all the data in this review as the astrophysical S function [7,8], or S factor. This function factors out from the cross section in the incident channel the energy dependence of the Coulomb penetrability and wavelength of the bombarding particle, and consequently emphasizes the nuclear effects and makes more meaningful comparisons possible. Specifically, for S in keV-b:

$$\text{for d+t,} \quad S = 0.59962\,\sigma\, E_d \exp(1.40411\ E_d^{-1/2}), \qquad (1)$$

$$\text{for d+d,} \quad S = 0.50000\,\sigma\, E_d \exp(44.4021\ E_d^{-1/2}), \qquad (2)$$

$$\text{for t+t,} \quad S = 0.50000\,\sigma\, E_t \exp(54.3378\ E_t^{-1/2}), \qquad (3)$$

$$\text{for } {}^3\text{He+d,} \quad S = 1.00000\,\sigma\, E_c \exp(68.7380\ E_c^{-1/2}), \qquad (4)$$

where E_d or E_t is the corresponding laboratory energy, E_c is the c.m. energy, (all energies are in keV), and σ (cross section) is in barns.

After commenting on the data requirements for fusion reactor design, I shall review the present status of data for the above reactions, their mathematical parametrizations and give suggestions for future experimental work and evaluations. Local data lists and parametrizations exist at numerous laboratories [9]. Some well-known previous evaluations of fuel-cycle reaction cross sections and reactivities include those of Greene [10], Duane [11], Miley [12], Peres [13], Slaughter [14], Kozlov [15], Stewart and Hale [16], and Hively [17].

Review topics at this conference given by R. Feldbacher, and G.M. Hale are also of interest concerning the subjects discussed in this review. Note that nuclear-reaction cross-section data should be used with caution below 10 keV where shielding by electrons in the particular atomic or plasma environment becomes important (see comments on page 2045 of Ref. [2]).

2. Fuel Cycle Data Requirements for Reactor Design

After questioning a number of people working on fusion reactor design, it became apparent that a concise statement would be impossible. The question "What uncertainties in the fuel-cycle reaction cross sections would begin to make a difference in your calculations?" brought a great variety of answers (ranging from 10% up to factors of 2 or more), reflecting the difficulties in the present state of plasma physics and reactor design. This situation is complicated also by the fact that an error in the reactivity could be compensated by a change in another parameter like a small change in the magnetic field. Considering all this, I submit the following statement as at least a fair approximation of the data

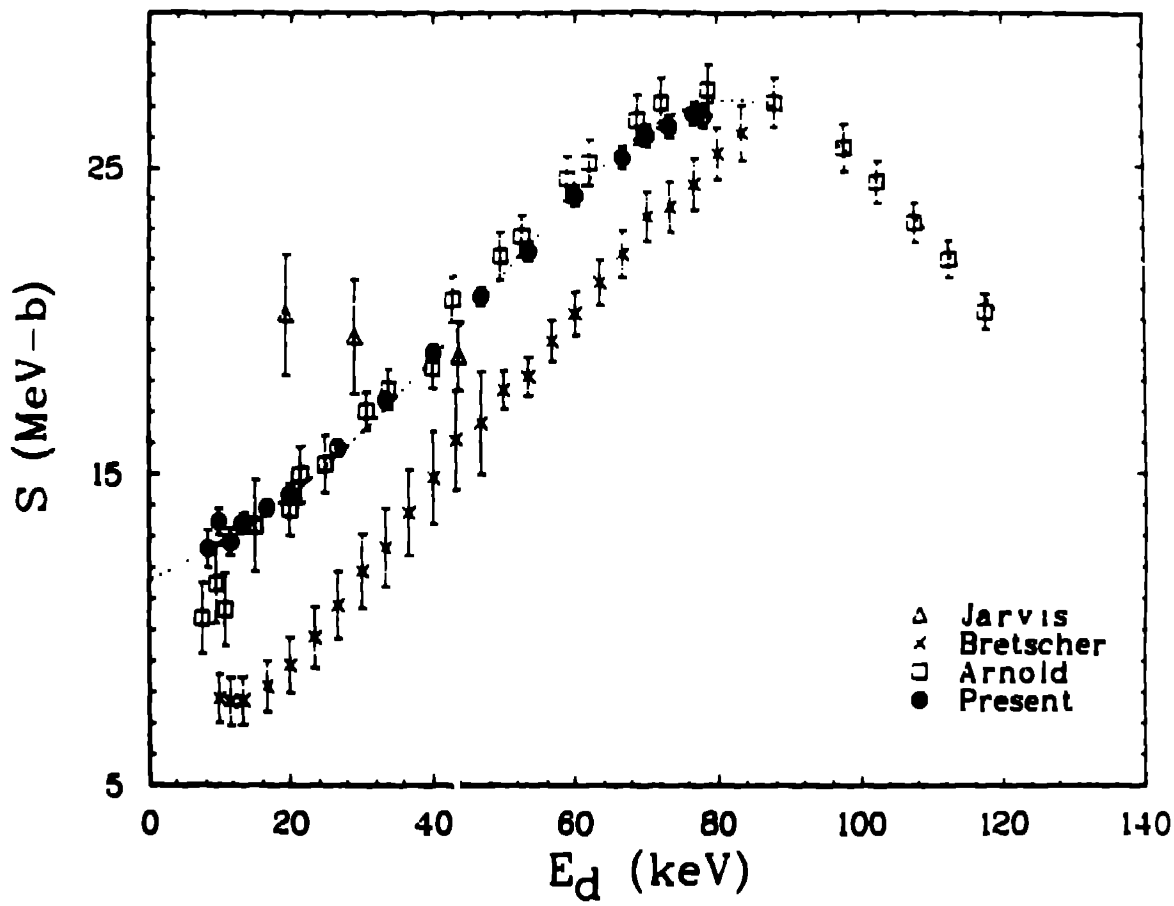

Fig. 1. The S function, [see Sec. I, Eq. (1)], vs equivalent deuteron bombarding energy for the D(t, α)n reaction. Shown are the Los Alamos data [2] and a selection of some of the previous data [46]. Note the suppressed zero. Total errors are shown. The curve is the result of a single level R-matrix fit to an edited data set [2].

requirements:

a. Up to now, cross sections known to 15-20% have been sufficient.

b. As experimental devices reach a state of significant burning or ignition, design calculations are calibrated and become more accurate. Then, 5-10% uncertainties would become highly desirable. Some devices are entering this region at the present time.

c. For the long term, 1-2 % uncertainties, at least for the main energy-producing reactions, would be needed for well engineered reactors.

Previous statements and studies of fuel-cycle data requirements include those of Cheng [18]; Gohar [19]; Head [20]; Haight and Larson et al. [21]; The 1986 Argonne Fusion-Data Advisory Meeting [22]; Cheng Mathews, and Schultz [23]; and Larson and Haight [24].

3. The ^{2}H(t,α)n Reaction.

Experiments at the Los Alamos facility called LEFCS (Low Energy Fusion Cross Sections) measured [2-4] the total cross section from 8-80 keV deuteron bombarding energy with an absolute error of 1.4% for most of the points. This accurate work helped settle the discrepancies mentioned in Ref. [1]; an example is given in figure 1. Details and complete references are given in Ref. [2]. That paper also provides several

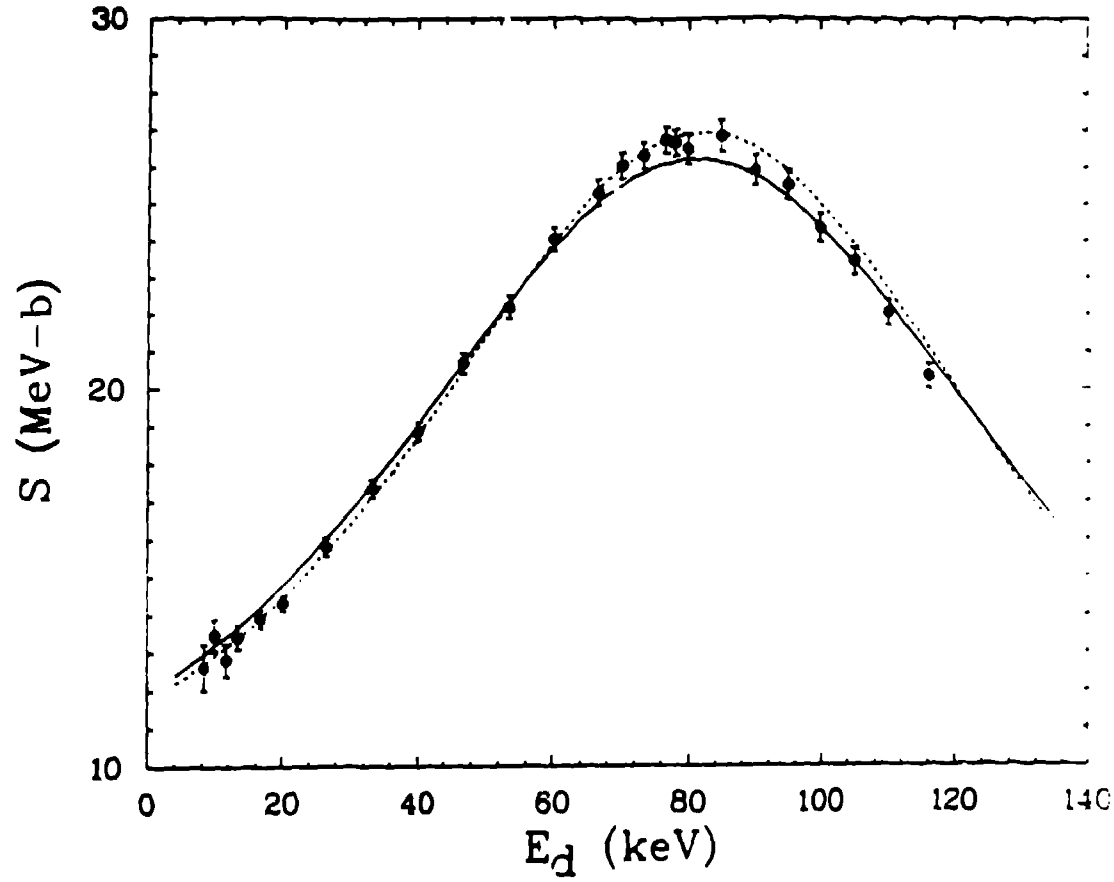

Fig. 2. The S function [Eq. (1)] vs deuteron bombarding energy E_d for the $^3H(d, \alpha)n$ reaction. The eight highest energy points show the newest Los Alamos data [25], and the remaining points are those of Ref. [2], which has been measured with the same apparatus . The dashed curve is from a two-level, two-channel R-matrix fit to a data base including the data shown and other data selected from the literature (see Ref. 2) up to a deuteron energy of 250 keV. The solid curve is from a multilevel, multichannel R-matrix fit [26,28] using data up to a deuteron bombarding energy of 8 MeV.

parametrizations of the data. The authors calculate the parameters for a two-channel single-level R-matrix fit for their data and other selected experiments up to 250 keV (E_d). In addition they compute coefficients for a power-series polynomial fit to their cross section data and to the corresponding reactivity: $\langle\sigma v\rangle$.

Los Alamos has recently added 8 more points [25] over the resonance (80 to 116 keV, E_d) with an absolute error of 1.6%, see figure 2. These data were taken by exchanging the beam and target particle, $^3H(d,\alpha)n$. Shown is a preliminary 2-level R-matrix fit as above including the new data , and a preliminary fit with an EDA R-matrix code [26] that uses a large set of data in all mass-5 channels up to 8 MeV. The new Los Alamos data with final fits and parametrizations will be published soon. In addition, G. Hale has now calculated his final EDA fit with all of the new LEFCS data [28] , and has tabulated it in an ENDF-like MASS-storage file for a CRAY computer in a revision of Ref. [27].

I conclude that the $^2H(t,\alpha)n$ data is now accurate enough for the

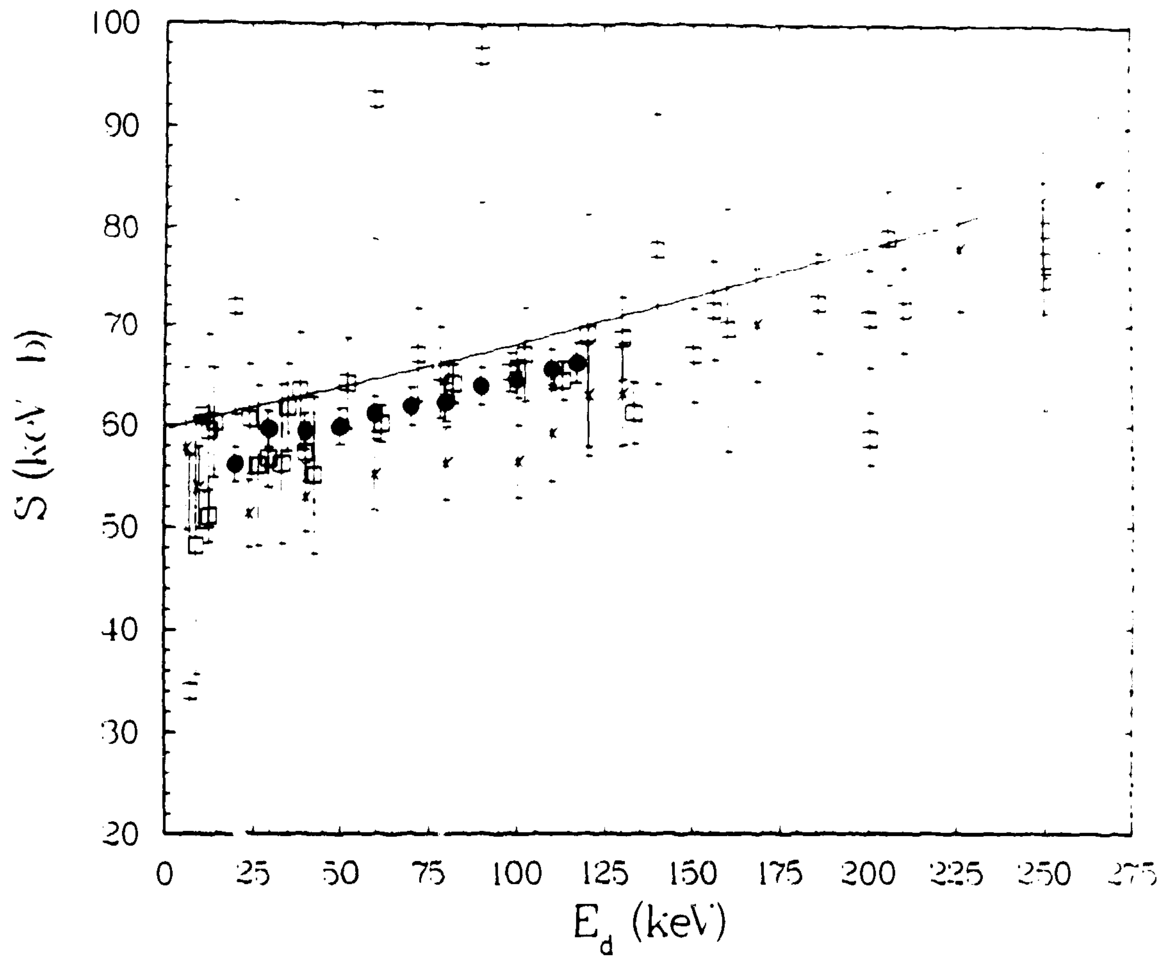

Fig. 3. The S function [Eq. (2)] for the $^2H(d,p)^3H$ reaction as a function of deuteron bombarding energy. Absolute errors are shown. The solid circles are the Los Alamos data [3,4] shown with 3% errors (will be less than 2% with the final analysis). The crosses are the Münster data [30]. The squares are a representative selection of other data from other experiments [29]. The curve is from a unified, mass-4, R-Matrix analysis [26] that does not include the Los Alamos or Münster data.

indefinite future and is unlikely to be improved. The only remaining question is how to make the best evaluated fits available to the international community in the most efficient way.

4. The $^2H(d,p)^3H$ and $^2H(d,^3He)n$ Reactions.

The Los Alamos LEFCS group has also made the most accurate absolute measurements [3,4] for these reactions in the range 20-117 keV laboratory bombarding energy. Previous data were not discrepant but lacked sufficient accuracy. The Los Alamos data (solid circles) are shown in Figure 3 and 4 in comparison to a representative set of data of other experiments [29]. The Los Alamos errors are shown as 3% but will be in the range 1.6 to 2.0% when some final small corrections are made. The lines are R-matrix fits from a unified mass-4 R-matrix analysis [26,27] that did not include the LEFCS results. Also shown are 26 representative points (crosses) from an important new experiment at Münster by Krauss, Becker, Trautvetter, Rolfs and Brand [30] whose measurements have a

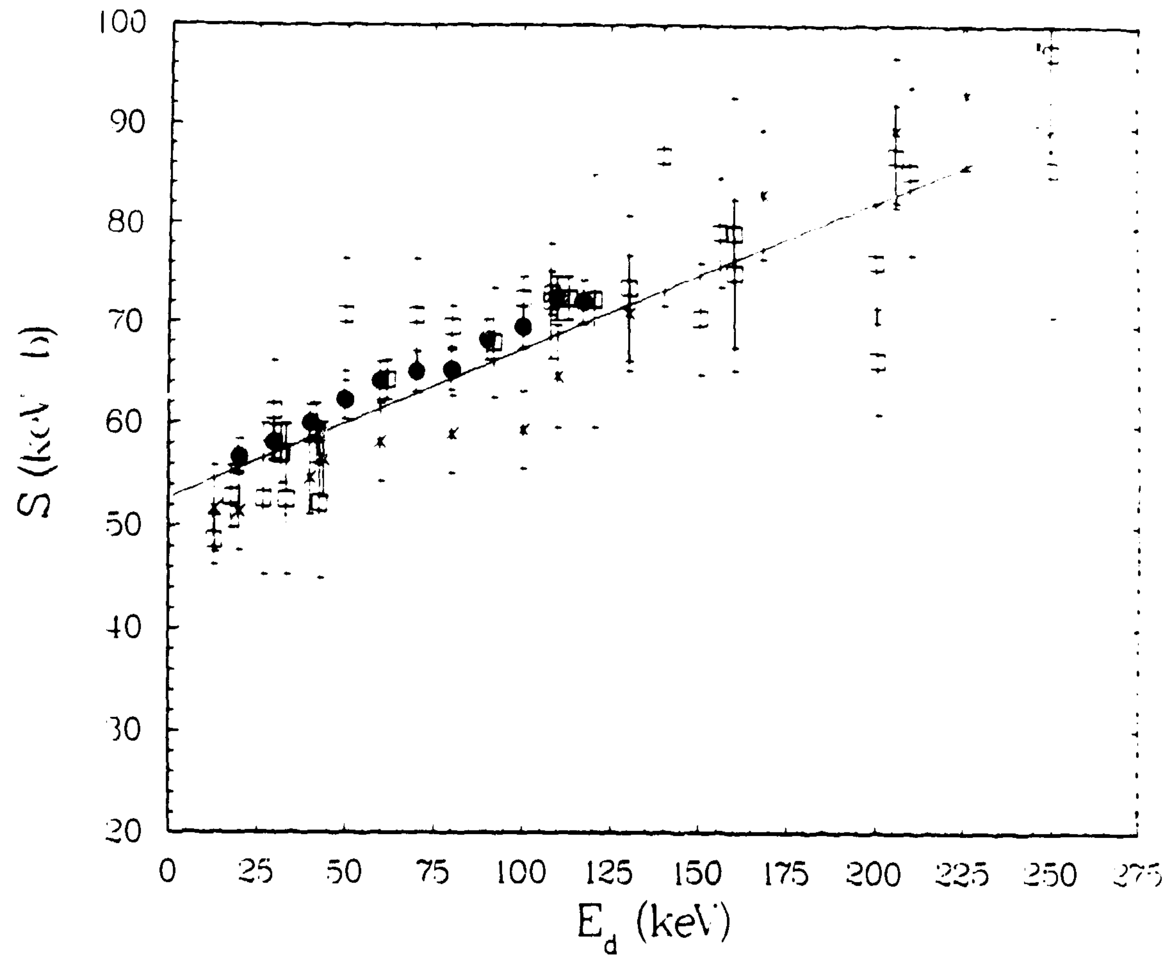

Fig. 4. The S function [Eq. (2)] for the $^2H(d,^3He)n$ reaction as a function of deuteron bombarding energy. Absolute errors are shown. The solid circles are the Los Alamos data (3,4) shown with 3% errors (will be less than 2% with the final analysis). The crosses are the Münster data [30]. The squares are a representative selection of other data from other experiments [29]. The curve is from a unified, mass-4, R-Matrix analysis [26] that does not include the Los Alamos or Münster data.

larger energy range, 6 to 325 kev laboratory energy. Their data are in fairly good agreement with the LEFCS work (considering that the Münster absolute error is 6-8%, their data being roughly 5-10% lower.) Those interested in the d+d angular distributions and anisotropies should refer to the work of Theus, McGarry, and Beach [31] as well as Krauss et al. [30] and Jarmie and Brown [3,4].

An important new experimental facility [32] at Bruyères-Le-Châtel, France, is beginning experiments at low energy which will include the study of the d+d reactions. Accurate cross sections from this effort will improve knowledge of the d+d data.

Experimentally, the data for the d+d reactions are fairly well known for present needs. An additional accurate experiment [32] would be useful. A careful evaluation and parametrization including all the recent data does not exist. One would be tempted to use the polynomial fit in Krauss' paper raised in value by several percent to account for the absolute accuracy of the Los Alamos experiment. Polynomial fits will also appear in the final Los Alamos paper.

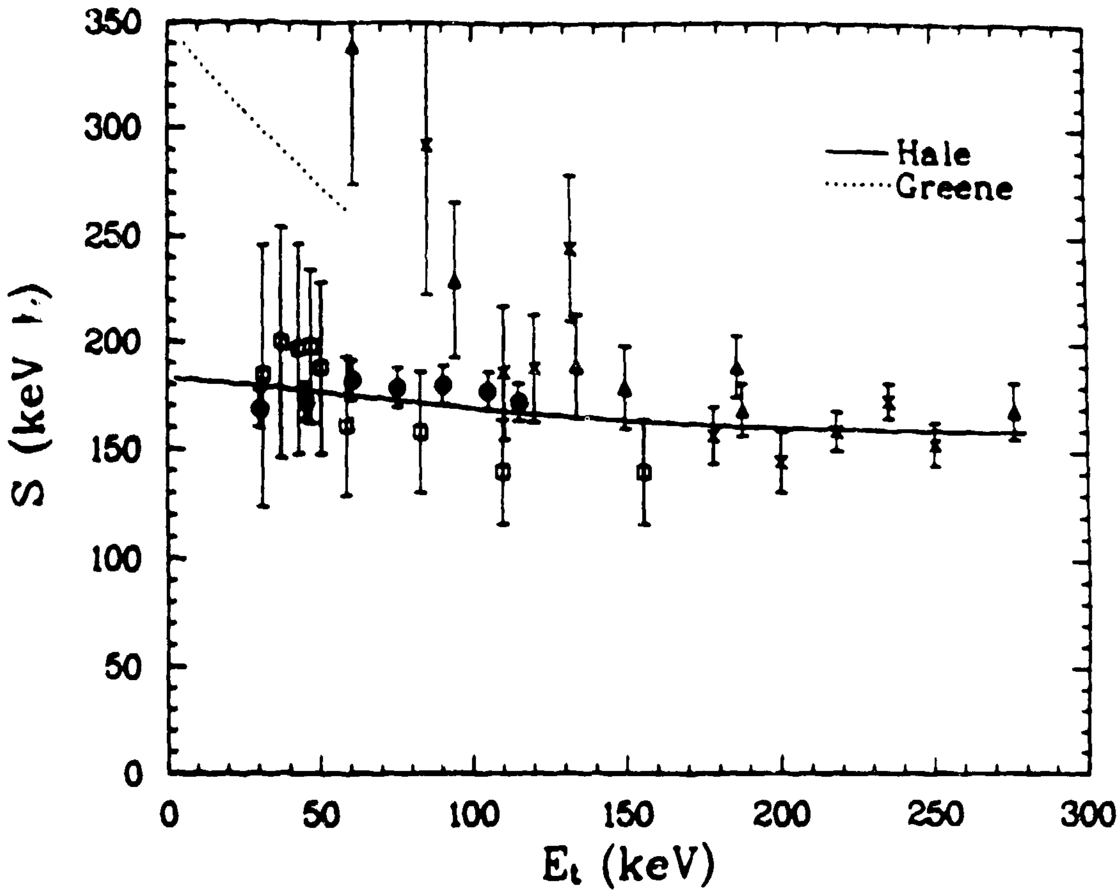

Fig. 5. The integrated S function [Eq. (3)] for the $^3H(t,\alpha)nn$ reaction vs triton bombarding energy. The solid circles are the preliminary Los Alamos data [3,4] shown with 5% absolute errors. The squares are the data of Ref. [47], triangles Ref. [48], and crosses Ref. [49]. The solid curve is an R-matrix analysis [26,27] that does not include the Los Alamos data. The dashed curve is from the compilation of Greene [10].

5. The $^3H(t,\alpha)nn$ Reaction.

Previous data for this reaction were both discrepant and inaccurate. The experiment is a difficult one, using both a tritium target and beam, and with the three-body reaction producing a spectrum of resultant particles instead of an isolated peak. The Los Alamos LEFCS group has made measurements [3,4] of the alpha spectrum in the range 30-115 keV laboratory energy, and when final corrections are made will give total cross sections accurate to 4-5%, as shown in figure 5. The black curve is from a mass-6 R-matrix analysis [26,27] that does not include the LEFCS points.

The cross sections for the $^3H(t,\alpha)nn$ reaction are now well known, with errors on the order of of 5%. Improvement will be difficult. An experiment measuring the neutron spectrum directly would be useful but would be very difficult. A data evaluation including the present data and in accessible form would be desirable. Hale's fit in figure 5 is a good approximation.

6. The $^3He(d,p)^4He$ Reaction.

One look at figure 6 should convince one that there has been trouble

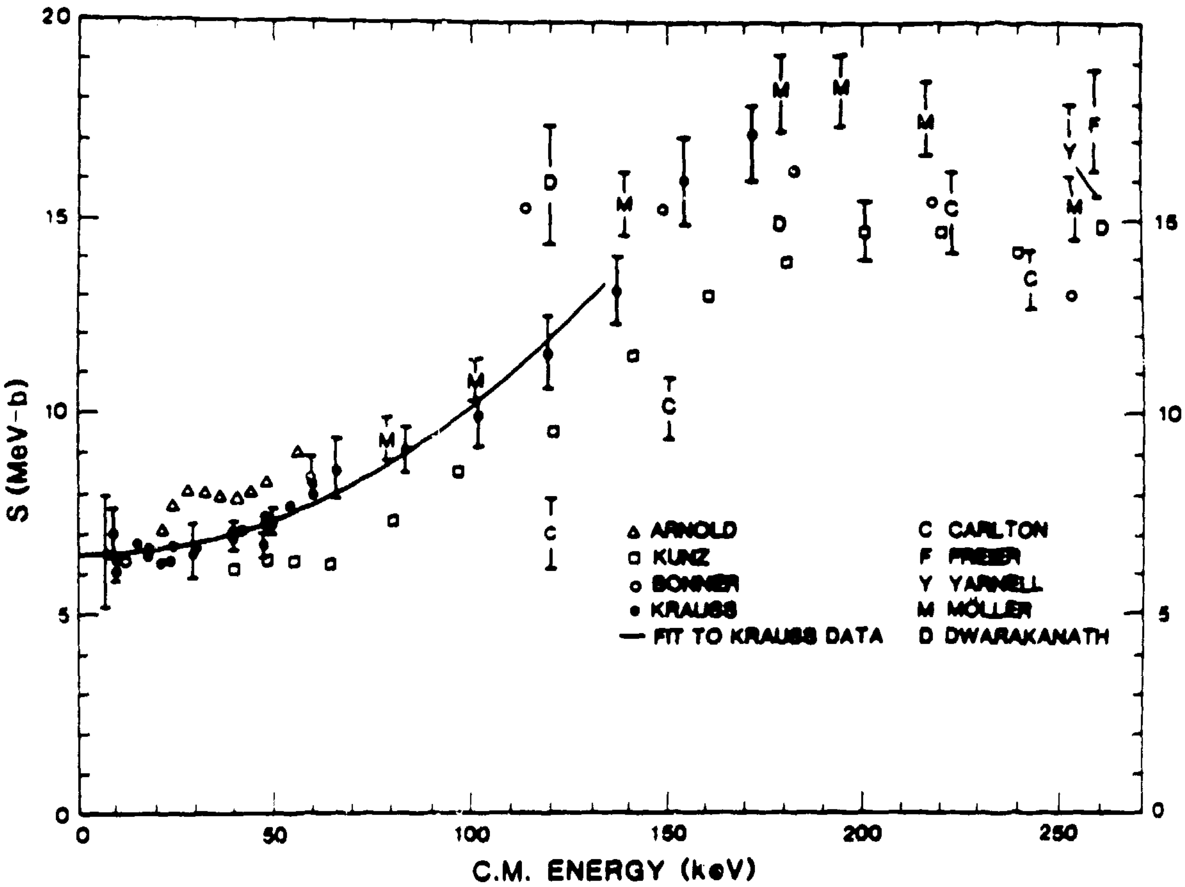

Fig. 6. The S function for the $^3He(d,p)^4He$ reaction [(Eq. (5)] vs c.m. energy. Absolute errors are shown. The curve is a polynomial fit to the Münster (Krauss) data [30], solid circles, below 130 keV. The remaining data is from Möller [40], Arnold [33], Kunz [34], Bonner [35], Carlton [36], Freier [37], Yarnell [38], and Dwarakanath [39]. Note that the S-function resonance peak is about 50 keV lower in c.m. energy than the peak position when plotted as that of the cross section, due mostly to the unfolding of the exponential penetrability.

in this reaction's cross section experiments in the past [33-39]. The recent work of Möller and Besenbacher in 1980 [40] and Krauss et al. in 1986 [30] have improved the situation. Considering the relationship of the work of Krauss and Möller in this reaction and of Krauss [30], Arnold [33], and Los Alamos [3,4] in the d+d reactions, a "best" cross section line would appear to be obtained by normalizing the Krauss fit upwards by 5% (a value less than their absolute error of 6-8%). Until a formal evaluation is done, I suggest that those desiring a parametrization for the total cross section for the $^3He(d,p)^4He$ reaction use the fitting function (equation 2) of Möller and Besenbacher [40] for c.m. energies 80 keV and higher; and the polynomial fitting function of Krauss et al. (in section 5 of Ref. [30]) multiplied by 1.05 for c.m. energies of 100 keV and lower (users choice between 80 to 100 keV). Absolute cross section values thus chosen should be good to 5%, certainly less than 10%.

Such formulae may satisfy users in the near future. Eventually, additional precision measurements on the order of 2% uncertainty would be desirable, especially in the region of the resonance. Additional accurate data from the new French effort [32], mentioned abcve, would be very welcome. A careful evaluation, perhaps with a mass-5 R-matrix analysis would be highly desirable at this time and in the future.

7. Other reactions.

Charged particle elastic scattering (or "slowing-down") cross sections in the few MeV energy region, such as $^3H(d,d)^3H$, $^3H(\alpha,\alpha)^3H$, and $^2H(\alpha,\alpha)^2H$ are needed to estimate energy losses of ions by collisions in ionized plasmas. These cross sections can be very well estimated (to 2-4%) by energy-dependent R-matrix calculations (see Hale, Dodder, and DeVeaux [41]). This method works well because the cross sections are tied to measured cross sections at Van-de-Graaff energies on the high energy side, and to Coulomb cross sections on the low energy side. The R-Matrix method is also useful for estimating other secondary reactions.

High-energy gamma rays from capture processes may be important for diagnostic measurements [42] of fusion reactor systems. Reactions of interest include $^3H(d,\gamma)^5He$, $^2H(d,\gamma)^4He$, and $^3He(d,\gamma)^5Li$. These cross sections, usually very small, have been measured in recent years to uncertainties of 5-10% [43-45]. Experiments to significantly improve the accuracy of these cross sections will be difficult, and will probably await a certain measure of success in using these reactions as a diagnostic.

Little is known about the $^3He(^3He,\alpha)pp$ reaction at low energies [50,51]. Its contribution to the power of a reacting d-^{3}He plasma is expected to be small because of the increased Coulomb barrier between the reactants. The Münster Group is planning a study [52].

8. Conclusions.

Experimental knowledge of charged particle cross sections for use in fusion reactor design appears to be good, certainly in the near to medium term. Precision experiments for the $^3He(d,p)^4He$ reaction, and for various mass-6 reactions to help pin down the $^3H(t,\alpha)nn$ reaction in an R-matrix analysis, should eventually be useful.

What are badly lacking are cross-section data evaluations for the various reactions which are considered to be the "standard", are easily available to anyone, and are in an internationally accepted format. Support for generating such evaluations should be seriously considered.

9. Acknowledgments

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