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Fusion Cross Sections from Los Alamos R-Matrix Analyses

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Introduction

We have been using R-matrix theory for many years at Los Alamos to describe reactions in light systems, especially those containing fusion reactions. The theory is ideally suited for describing the resonances that are usually seen in light-element reactions, and at the same time it builds in the correct energy dependence of the transition matrix elements at low energies by making explicit use of the solutions for the external (long-ranged) parts of the interaction (Coulomb and angular momentum barriers, etc.). Thus, the method gives reliable extrapolations to low energies for both neutron- and charged-particle-induced reactions.

We will present here the results of analysis that have been done, or are in progress, for reactions in the four- and five-nucleon systems, containing the fusion reactions of major interest: $T(d,n)^4He$, $^3He(d,p)^4He$, D(d,p)T, and $D(d,n)^3He$. These analyses contain all possible types of data (in addition to the cross sections) that have been measured for the two-body reactions of these systems, a method that we have found crucial for determining their true resonant structures, and for ensuring reliable R-matrix interpolations and extrapolations of even the cross-section data. Integrated cross sections will be presented in the form of astrophysical S-functions, as functions of center-of-mass energy, in order that their low energy behavior might be better displayed.

In addition to the R-matrix results, we will also show earlier cross-section parametrizations by Duane [1] and by Peres [2] that still are used widely within the fusion reactor community. Some severe shortcomings of these earlier data sets are revealed by comparisons with modern measurements and with the R-matrix calculations. More details about these comparisons and useful representations of the R-matrix cross sections and their associated reactivities ($<\sigma v>$) recommended for use in fusion reactor design are given in a paper by Bosch and Hale [3] that has been submitted for publication.

The Reaction $T(d,n)^4He$

The R-matrix analysis of the ^5He system that we completed several years ago gives a remarkably good description of all the reactions involving d+t and $n+^4He$. The results have been used to investigate the pole structure of the famous $J^\pi=3/2^+$ resonance [4,5] and to study nuclear effects on the low-lying states of the dtμ molecule [6].

The S-function for the reaction $T(d,n)^4He$ is shown in Figs. 1 and 2. Fig. 1 shows a selection of earlier data, along with the more recent data of Brown [7] and Jarmie [8], at center-of-mass energies below 75 keV. Some of the earlier data disagree quite strongly with the most recent measurements at energies below the peak of the resonance, and even the Arnold [9] data have a different low-energy behavior. The R-matrix calculation follows the Brown and Jarmie data quite well down to the lowest measured energies, where it disagrees with the earlier parametrization of Peres [2], and especially with that of Duane [1]. In Fig. 2, the calculations are compared with data measured up to higher energies. Good agreement is seen with Conner's measurement [10] at all but the lowest energies, where the first point is consistent with the parametrization of Duane [1].

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

The R-matrix analysis of the reactions in the ^5Li system was done more than 10 years ago, at a time when the measurements of the $^3He(d,p)^4He$ reaction cross section near its peak, especially, were in significant disagreement. This can be seen in the S-function for the reaction, shown at low energies in Fig. 3 and at higher energies in Fig. 4. One also sees in these figures that the R-matrix calculation did not agree particularly well with the data that were included in the fit, but agrees much better with measurements of Krauss [11] and of Möller [12] that were made well after the analysis was done. This is probably a consequence of the theoretical constraints imposed by R-matrix theory on the energy dependence of a near-threshold resonance, and of the multi-reaction, multi-observable approach used at Los Alamos for these analyses.

Neither of the other parametrizations accounts as well for the more recent measurements as does the R-matrix calculation. Duane's dotted curve shows its characteristic roll-off at low energies below the Krauss data, and Peres' dashed curve shows a displacement in the peak of the S function away from the position indicated by the recent measurements [11,12].

The d+d Reactions

The A=4 analysis is particularly interesting because it illustrates the ability to incorporate fundamental theoretical constraints in R-matrix descriptions. In this case, all possible reactions involving the channels n+T, n+^{3}He, p+T, p+^{3}He, and d+d are described using a single set of Coulomb-corrected, charge-independent R-matrix parameters [13]. The T=1 parameters were first determined by fitting p+^{3}He scattering data, checked by a prediction of the n+T total cross section, then taken essentially unchanged into an analysis of the reactions in the ^{4}He system in which only the T=0 parameters were varied (along with an overall Coulomb energy shift of the T=1 levels). Isospin constraints were used to relate the p-T and n-^{3}He widths in the T=0 levels, and a small amount of Coulomb isospin mixing was allowed in the d-d widths. Such a model accounts quite well for the experimental data in the ^{4}He system, including those indicating sizeable differences between the two branches of the d+d reaction.

Figs. 5 and 6 show the calculated S-function for the D(d,p)T reaction compared to a selection of the data, and to the parametrizations of Duane and of Peres. The R-matrix calculation follows closely the recent measurements of Brown [14] and the earlier ones of Wenzel [15]. The Duane curve again falls off sharply at low energies, as do the earlier data of Arnold [16].

Similar plots for the D(d,n)^{3}He reaction are shown in Figs. 7 and 8. The R-matrix calculation follows the recent measurements of Brown [14] and the earlier measurements of Ganeev [17] and of Preston [18]. The curves of Duane [1] and Peres [2] do not give large enough D(d,n) cross sections at the higher energies, despite the fact that they are unconstrained by a charge-independent fit, as is the R-matrix calculation.

Predictions

A novel application of the A=4 analysis has been to compare its results [13] with measurements being done for the d+d muon-catalyzed fusion (μCF) reactions. Information from the standard scattering experiments done at low energies involves mainly the S-wave transitions of the reactions. Because of the selection rules involved in muon fusion at room temperature, however, μCF experiments give information primarily about the P-wave transitions at low energies. Such measurements [19] give the surprising result that the branching ratio for the P-wave part of the d+d reactions favors the n+^{3}He branch over that for p+T by about 40%. At lower temperatures, where the molecular transitions allow increasing amounts of S-wave formation between the two deuterons, the branching ratio has recently been observed [20] to decrease toward unity.

The P-wave branching ratio calculated from the analysis is 1.43, while that for the S-waves is 0.886, giving excellent agreement with the measured room-temperature number, and also accounting qualitatively for the decrease in the branching ratio toward unity as the S-wave admixture increases at lower temperatures. The calculated absolute muon fusion rate for both branches, using information about the molecular wavefunction and transition rates from the work of Bogdanova *et al.* [21], is $\lambda_f = 3.8 \times 10^8$ s^{-1}, compared to the measured value of $(4.1 \pm 0.1) \times 10^8$ s^{-1} [22]. Thus, the analysis successfully accounts for all the new experimental information (including the surprises) about the d+d reactions that has come from this exciting new field, confirming *by individual partial waves* the reliability of R-matrix extrapolations to low energies.

The R-matrix parameters for the ^{5}He system predict a resonance in the back-angle T(d,n)^{4}He differential cross section that is consistent with a new measurement by Drosg [23]. The calculated curve and his data point are shown in Fig. 9. Also, new measurements of the outgoing neutron polarization for the reaction just completed at Tübigen are in excellent agreement with the predictions of the analysis.

Conclusion

We have given examples that illustrate the reliability of fusion cross sections and other data obtained from R-matrix analyses that include many reactions and observable types over a wide range of energy. The analyses give good representations of the most recent measurements, even in a case where the analysis was done long before the recent data became available. Because it is relatively unaffected by inconsistent data, this approach enjoys clear advantages over methods that fit simple mathematical forms to the measured cross-section data, which are still being used by many evaluators.

These R-matrix calculations have also been used to predict with high accuracy the results of conventional beam-target experiments, and the sometimes surprising results of muon-catalyzed experiments that probe the fusion reactions at energies below the range of usual measurements. The latter comparisons, especially, verify that the calculations provide reasonable extrapolations of the unscreened nuclear cross sections to very low energies in every partial wave.

Acknowledgments

Figures 1-8 were taken from the preprint of Ref. [3], and were prepared by H.-S. Bosch, of the IPP, Garching. We thank M. Drosg of the University of Vienna for making available the unpublished datum shown in Fig. 9. Much of this work was supported by the Division of Nuclear Physics of the US DOE.

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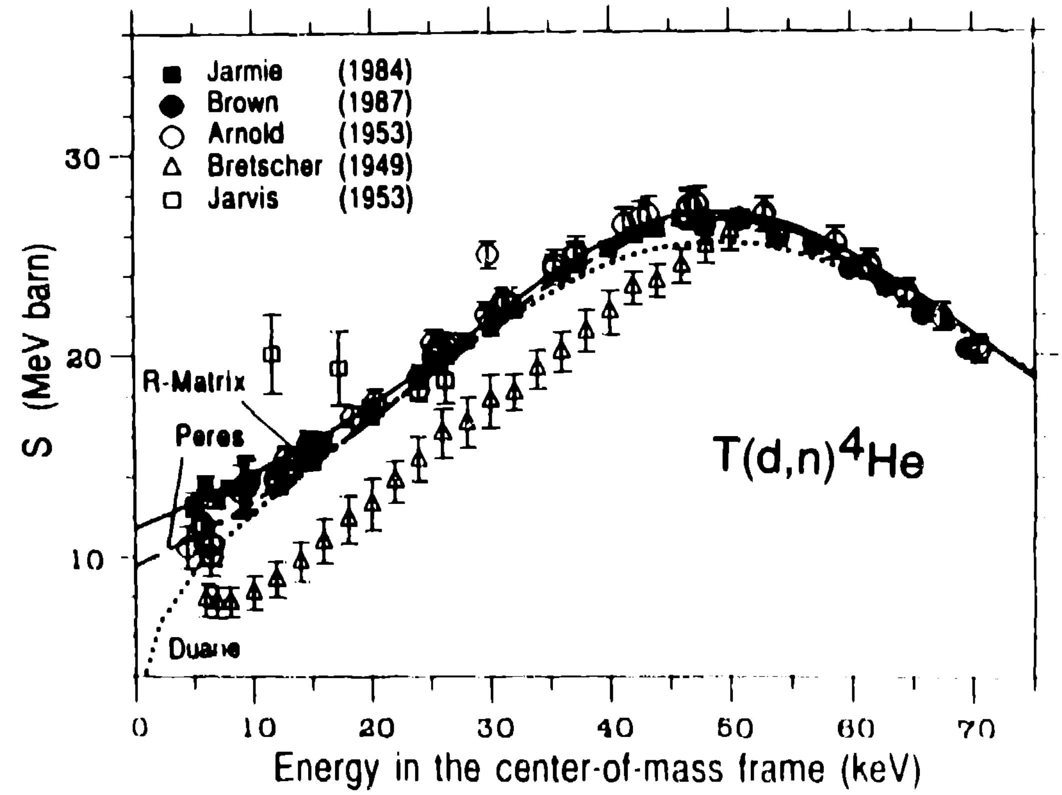

Fig. 1. Calculated S-functions for the $T(d,n)^4He$ reaction at energies below 75 keV compared with various measurements. In this, and all subsequent figures, the solid line is the LANL R-matrix calculation, the dotted line is Duane's [1] parametrization, and the dashed line is that of Peres [2].

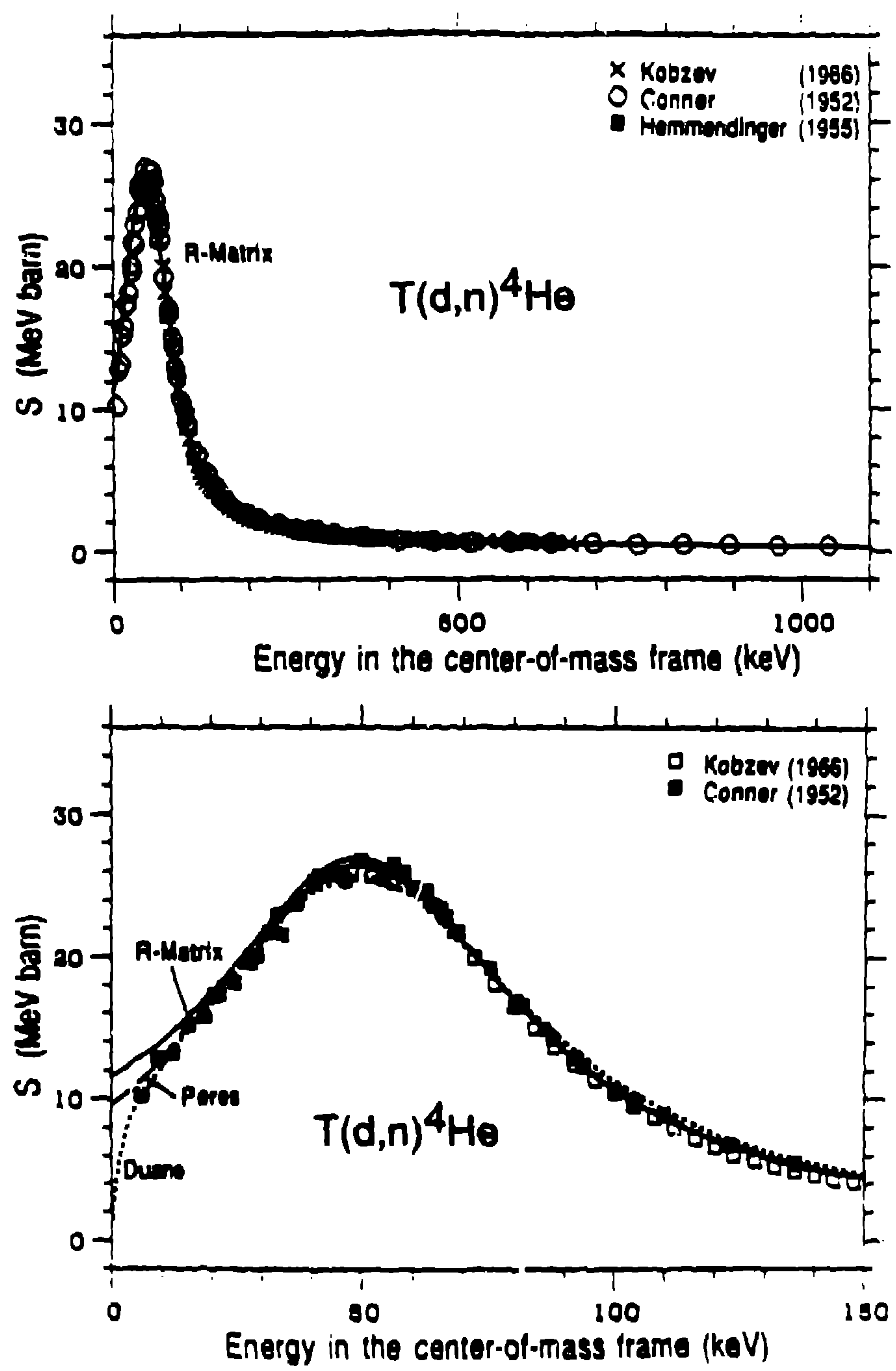

Fig. 2. Calculated S-functions for the $T(d,n)^4He$ reaction at energies below 1.1 MeV compared with various measurements.

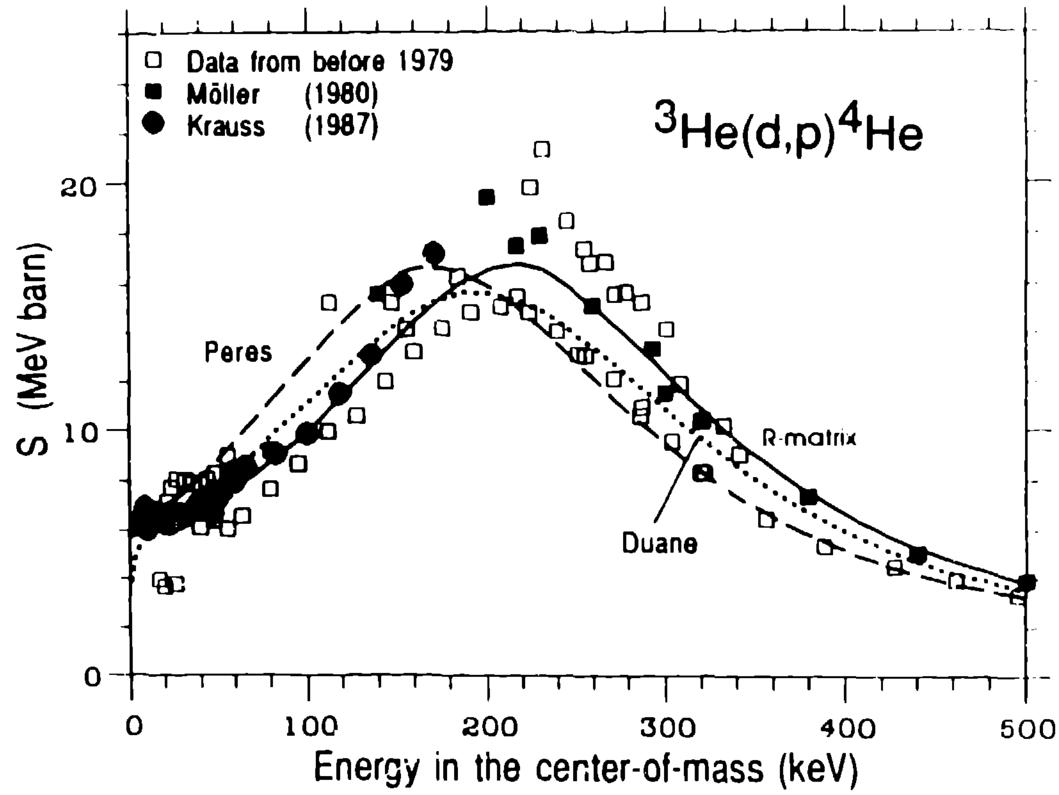

Fig. 4. Calculated S-functions for the $^3He(d,p)^4He$ reaction at energies below 500 keV compared with various measurements.

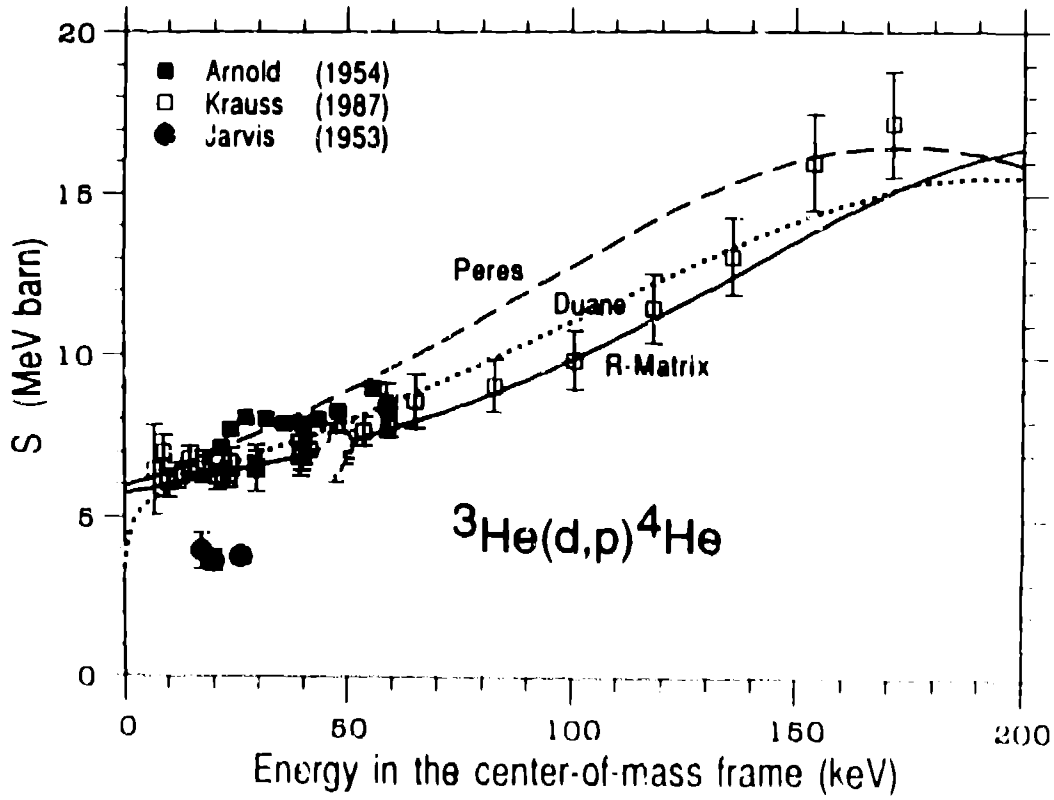

Fig. 3. Calculated S-functions for the $^3He(d,p)^4He$ reaction at energies below 200 keV compared with various measurements.

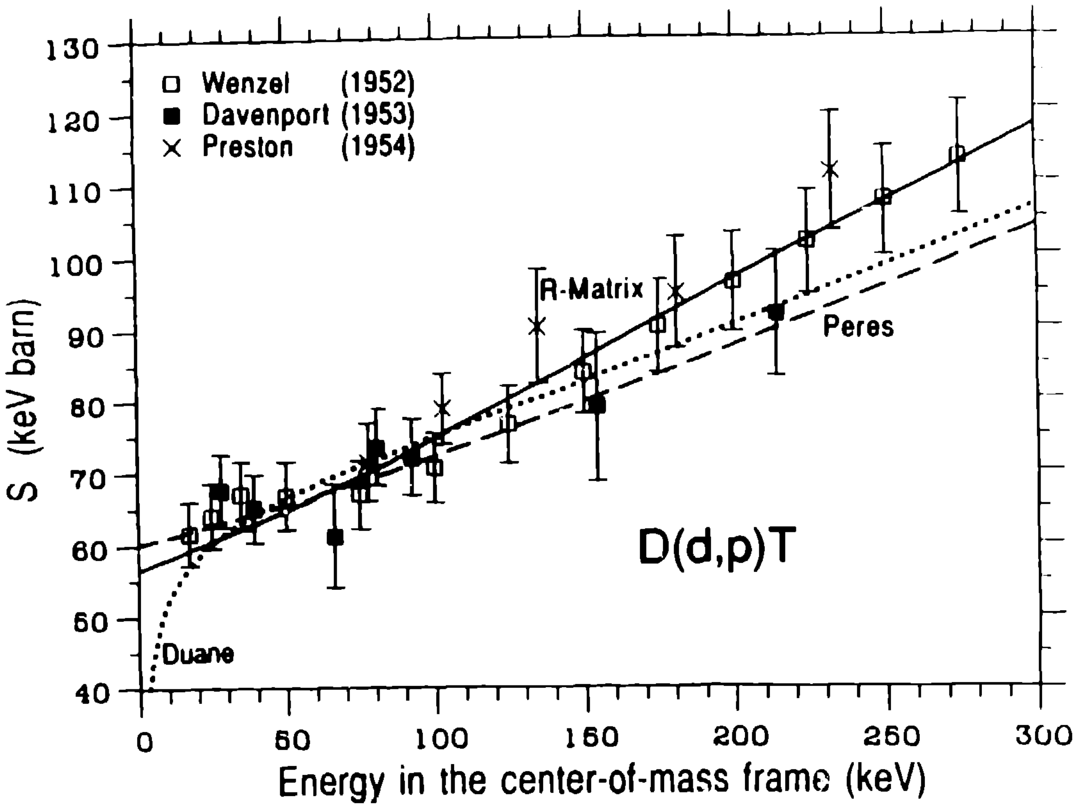

Fig. 6. Calculated S-functions for the D(d,p)T reaction at energies below 300 keV compared with various measurements.

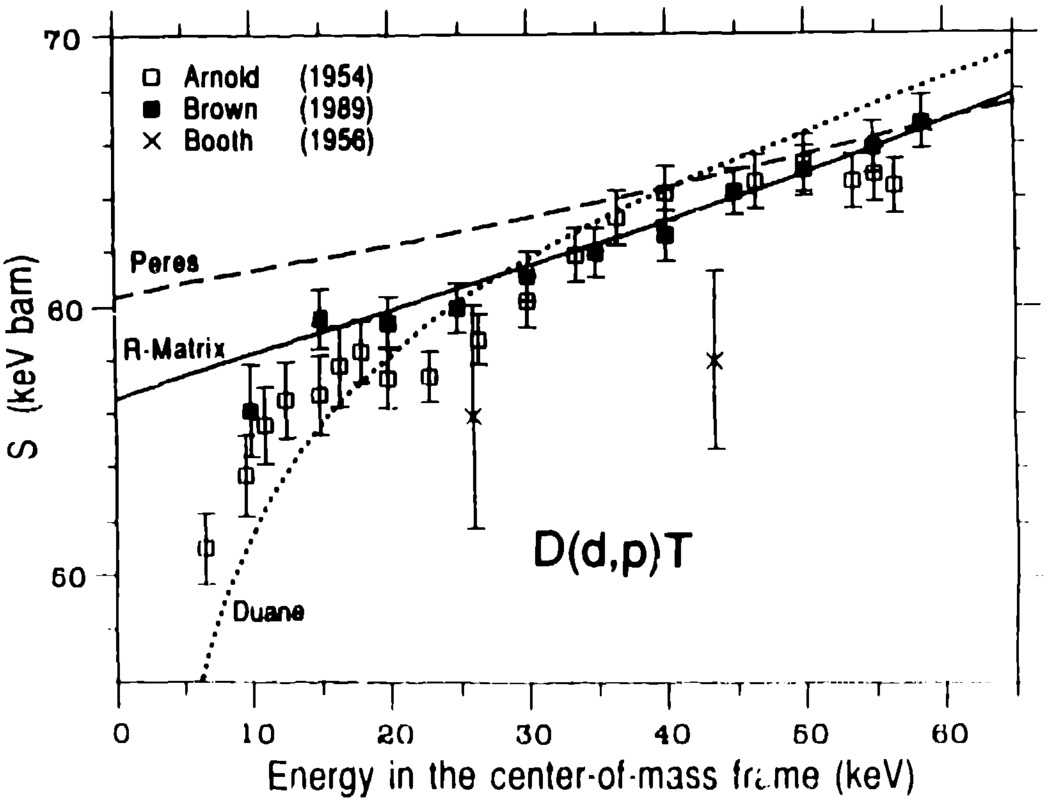

Fig. 5. Calculated S-functions for the D(d,p)T reaction at energies below 65 keV compared with various measurements.

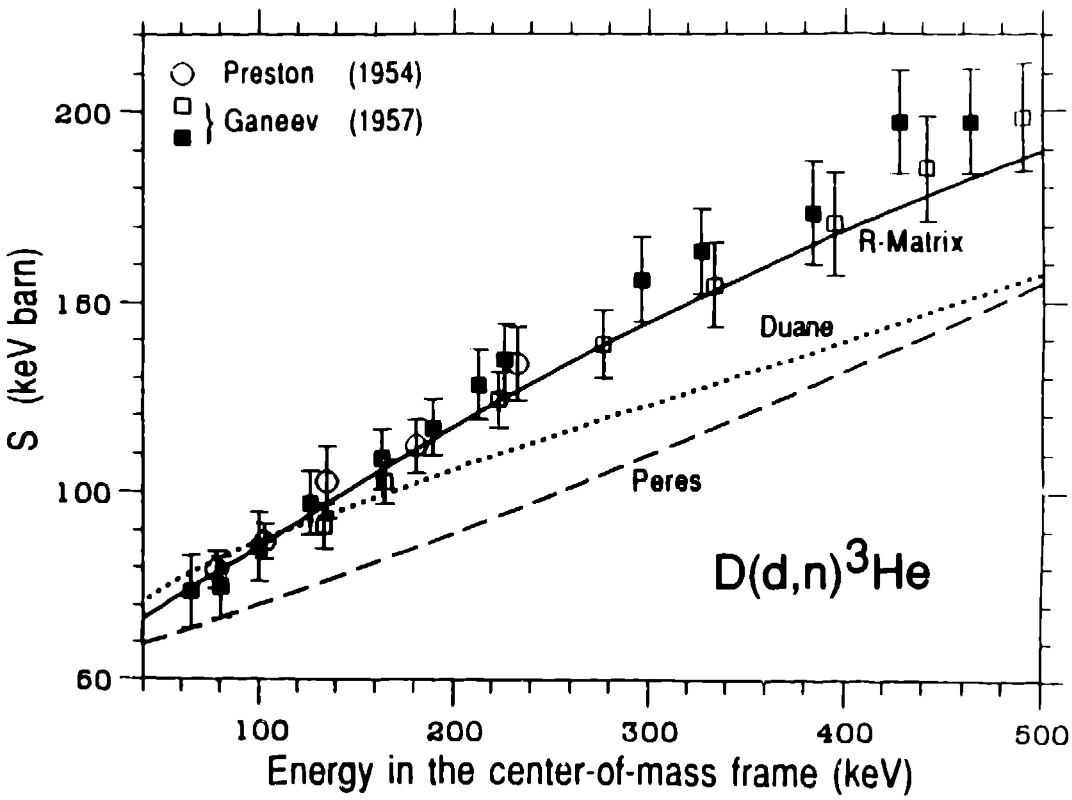

Fig. 8 Calculated S-functions for the $D(d,n)^3He$ reaction at energies between 70 and 500 keV compared with various measurements.

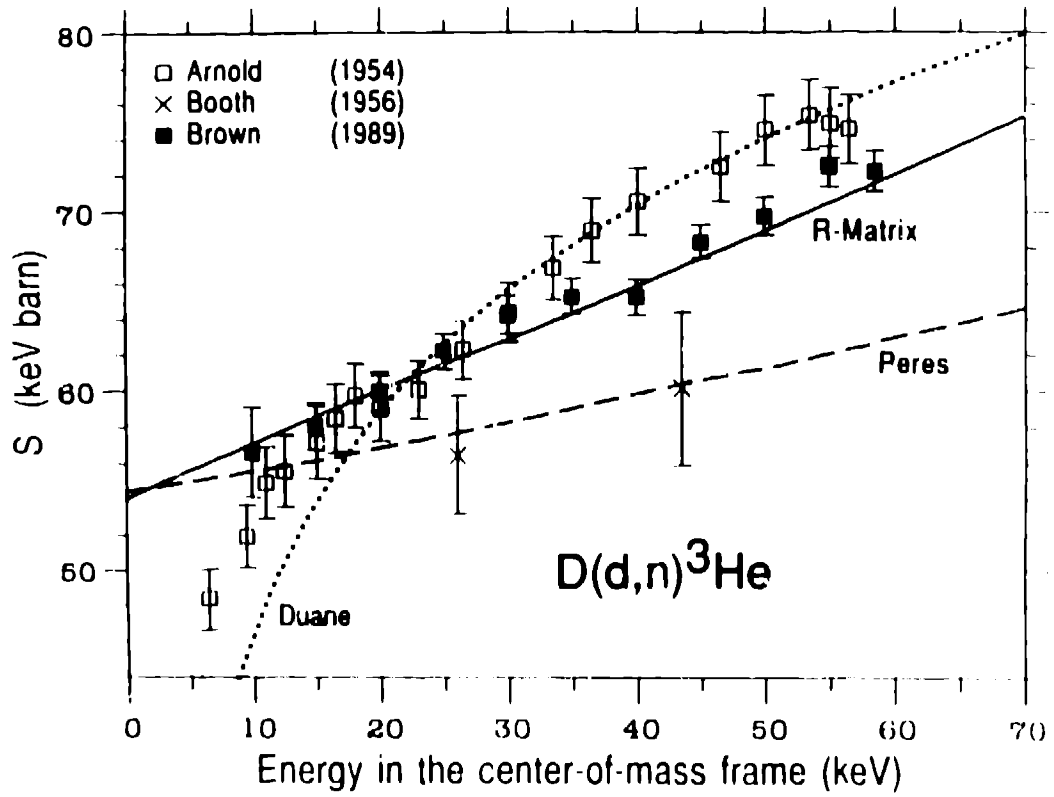

Fig. 7. Calculated S-functions for the $D(d,n)^3He$ reaction at energies below 70 keV compared with various measurements.

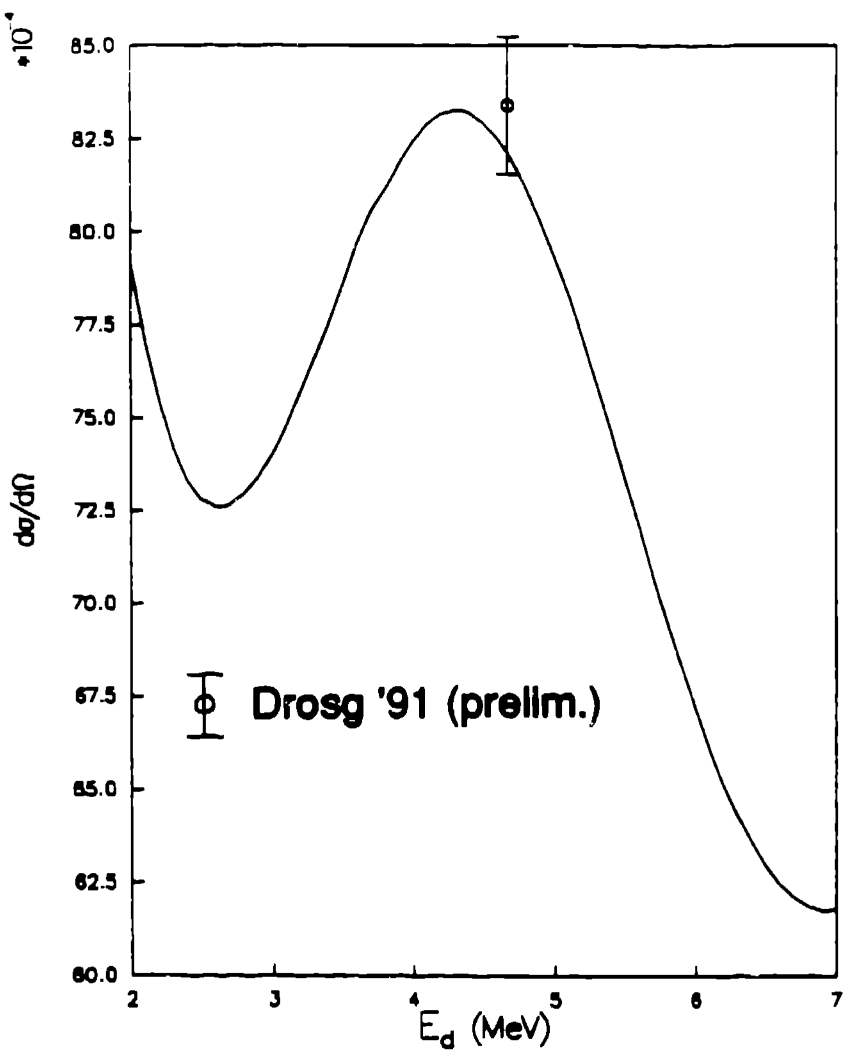

Fig. 9. Calculated center-of-mass differential cross section for the $T(d,n)^4He$ reaction at 180^0 for laboratory. deuteron energies between 2 and 7 MeV The data point is from Drosg [23].