LA-5828-MS
Informal Report

Co3

USNDC-CTR-2
UC-34c
Reporting Date: December 1974
Issued: January 1975

The T(d,n) ^{4}He and T(t,2n) Cross Sections at Low Energies

by

Leona Stewart
Gerald M. Hale

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

UNITED STATES
ATOMIC ENERGY COMMISSION
CONTRACT W-7405-ENG. 36

In the interest of prompt distribution, this LAMS report was not edited by the Technical Information staff.

This work was supported by US Atomic Energy Commission's Division of Controlled Thermonuclear Research.

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22151
Price: Printed Copy $4.00 Microfiche $2.25

THE T(d,n)^{4}He AND T(t,2n) CROSS SECTIONS AT LOW ENERGIES

by

Leona Stewart and Gerald M. Hale

ABSTRACT

The present status of the T(d,n)^{4}He and T(t,2n)^{4}He cross sections is reviewed for incident-particle energies below 1 MeV. Parameterizations of the T(d,n) cross section in this energy region are discussed along with predictions from a preliminary, but comprehensive, R-matrix analysis of reactions in the five-nucleon system at low energies. Tabular values of these predictions are given at energies between 5 keV and 1 MeV.

I. INTRODUCTION

During a recent visit to Oak Ridge National Laboratory (ORNL), Dr. V. I. Pistunovich of the Soviet Union suggested that the experimental T(d,n) cross sections used by Soviet scientists[1] were significantly different from those reported in LA-2014[2] and BNWL-1685,[3] which are currently used for most fusion calculational programs in the U. S. Pistunovich recalled values of the T(d,n) cross section which were a factor of two lower near 60 keV, a peak cross section of approximately 5 barns, and therefore a resonance width which is narrower than predicted by U. S. and Russian measurements available through 1971. As a further check, it should be noted that Greene[4] summarized the U. S. data through 1964 and performed a least squares fit. The cross sections are presented only in graphical form but they show good agreement with the results in BNWL-1685, as they should since essentially the same input data were used by both Duane[3] and by Greene.[4]

A reduction of the T(d,n) cross section as suggested by Pistunovich could produce serious problems in some of our present CTR design studies. In addition, the suggested use of the T(t,2n) reaction in the Princeton Test Reactor as a diagnostic tool has increased CTR interest in this cross section. Other less important reactions taking place in the plasma are the D(d,n)^{3}He, D(d,p)T, ^{3}He(d,p)^{4}He and T(^{3}He,x).

At the USNDC CTR Subcommittee meeting held in Washington, D. C. in November, 1974, LASL was asked to prepare a status report on the fusion cross sections for distribution and further study by the Subcommittee. Due to the time element involved and the hundreds of papers which must be perused and reviewed on the D(d,n), D(d,p) and ^{3}He(d,p) reactions, it was decided to limit this study to the T(d,n) and T(t,2n) reactions with the hope that the other reactions can be studied at a later date along with the extension of all the fusion reactions to higher incident particle energies.

II. GENERAL BACKGROUND

LA-2014[2] is a graphical compilation of the "best" charged-particle cross sections available through the Spring of 1956, for targets of hydrogen through fluorine. As such, curves through experimental data were sometimes plotted instead of the measurements themselves; this was often the case when the "smoothed curves" were the only tabular data presented by the authors.

BNWL-1685,[3] although published in 1972, is based on the compilation, LA-2014. The "experimental" data presented in Tables E.1 through E.6 were evidently prepared by reading the graphs in LA-2014. A nonlinear least squares fit was then made to these points using from two to five adjustable parameters, depending upon the reaction. The analytical expressions and parameters found in the fits are included in the title captions for Figs. E.1 through E.6.

UCRL-70522[4] includes experimental data through 1964; least squares fits were performed and Maxwell averaged cross sections are presented for d-D, d-T, t-T, t-^{3}He, and d-^{6}Li reactions. This report is more up to date than BNWL-1685; for example, factors of three exist between present measurements on t-^{3}He and those used in BNWL-1685.

Pistunovich[5] found beam amplification factors for T(d,n) which are higher than the Dawson, Furth, and Tenney calculations.[6] This difference is attributed to his use of the Artsimovich parameterization[7] of the cross section which does not properly account for the resonance. Figure 1 shows this parameterization along with the least squares fit by Battelle[3] and a preliminary evaluation[8] at LASL using a multichannel, multilevel R-matrix code. Unfortunately, tabular values of the cross sections used in UCRL-70522 are not available for comparison.

III. MEASUREMENTS OF THE T(d,n)^{4}He CROSS SECTION

Very few changes or additions were made to the data compiled in LA-2014 and used in the Battelle analysis. In 1957, Bame and Perry[9] lowered their cross sections by ~ 10% and Katsurov[10] completed measurements from 50 to 700 keV in 1962. Since it is impossible to compare all of the data on one graph, different representations have been chosen for the sake of clarity. Figure 2 shows most of the US measurements, while Fig. 3 gives the Katsurov data compared to the results of Conner et al.[11] Note the apparent energy shift between these two experiments.

The most comprehensive experiments below 1 MeV are those of Conner et al.[11] who used thin tritium targets (~ 1 keV at 50 keV). They employed a Cockcroft Walton at low energies and observed the alpha particles at 90°. They then employed a long counter to detect the neutrons at 90° and a Van de Graaff accelerator to overlap and extend the energy range. The two separate experiments of Conner et al. are plotted in Fig. 4 along with the least squares fit in BNWL-1685 and the preliminary evaluation by LASL. Cross sections measured at 90° have been multiplied by 4π to obtain the points shown in Fig. 4 upon assuming, at most, p-wave anisotropy in the center of mass and neglecting the small laboratory to center-of-mass conversion. Since Bame and Perry measured the angular distributions of the neutrons, a check was made of the above assumption; $4\pi \times \sigma(90°)$ was within 1/2% of Bame's measured integral at 500 keV and within 4% at 1 MeV.

Finally, all of the measurements* mentioned previously are compared in Fig. 5 with the LASL evaluation. Also included are the integrated cross sections using incident tritons by Argo et al.[12] and Hemmendinger and Argo.[13] Although Arnold et al.[14] observed the alpha particles from the T(d,n) reaction from 22 to 120 keV, tabular values were reported only for a smooth curve through the points including an extrapolation based on a Gamow plot. The experimental datum points could not be reproduced from the published graphs, but their curve shows fairly good agreement with other measurements below 100 keV.

IV. PARAMETERIZATIONS OF THE T(d,n)^{4}He CROSS SECTION

The two parameterizations of the T(d,n) cross section most commonly used in fusion calculations are those of Artsimovich[7] and Duane[3] (BNWL-1685). These authors attempt to represent the cross section over the resonance with a single few-parameter set, rather than with piece-wise polynomial fits, as used by Greene[4] and others. For comparison, we also discuss the predictions of a preliminary LASL multichannel, multilevel R-matrix analysis of reactions in the five-nucleon system at low energies (see the Appendix). The three calculated curves are shown in Fig. 1.

Artsimovich expressed the cross section in terms of four numbers as the product of a Gamow penetrability and a Lorentzian,

$$\sigma_{ART} = \left[\frac{e^{-1500/\sqrt{E}}}{E}\right]\left[\frac{6 \times 10^{-17}}{1 + \frac{(E - 10^5)^2}{3 \times 10^{10}}}\right] \quad \text{cm}^2 \quad (E \text{ in eV}).$$

This parameterization is not sufficiently complex to be useful above the resonance (~ 100 keV), as can be seen from Fig. 1. Despite the fact that the calculated cross section peaks well above the experimental values (8 barns at 180 keV, compared to 5 barns at 107 keV), it has been used in Russian fusion calculations[5] at energies extending to nearly 1 MeV and is responsible for major disagreements between those calculations and similar ones performed in the U. S.[6] using the BNW parameterization.

The BNW parameterization resulted from a least squares fit to data contained in LA-2014,[2] a graphical compilation of charged-particle cross-section

---

*For clarity, a few of the experimental points near the peak have been omitted from all of the graphs.

data available in 1956. The cross section is expressed through five parameters as the product of a Mott penetrability[*] and a shifted Lorentzian,

$$\sigma_{BNW} = \left[\frac{10^3}{E(e^{1453/\sqrt{E}}-1)}\right]\left[\frac{502 \times 10^2}{1+(1368\times10^{-8}E - 1.076)^2} + 409\right]$$

with σ in barns and E in eV. This parameterization follows the experimental cross sections reasonably well (see Fig. 2) at energies up to 1 MeV. However, the least squares value (1453) in the exponential of the penetrability factor differs from the value it should have (1404) to give the correct energy dependence of the cross section at very low energies.

The cross-section predictions of the R-matrix analysis cannot be expressed in a simple closed form[†] but they resemble the single-level Breit-Wigner result for two channels,

$$\sigma_{RES} \sim \frac{1}{E}\left[\frac{\Gamma_d\Gamma_n}{(E_\lambda + \Delta_d + \Delta_n - E)^2 + \frac{1}{4}(\Gamma_d + \Gamma_n)^2}\right] ,$$

in which $\Gamma_{d,n}(E)$ and $\Delta_{d,n}(E)$ vary with energy as do the Coulomb penetrability and shift functions, respectively, in the entrance (d-T) and exit (n-^{4}He) channels. Since this resonance has a large reduced width in the entrance channel, the effects of Δ_d and Γ_d upon the energy dependence of the denominator in the expression for σ_{RES} are pronounced even at low energies, with the result that the cross section begins to deviate from the Gamow form at a few keV.

Since the Artsimovich parameterization is not valid at energies above the resonance, we will compare only results of the BNW parameterization (σ_{BNW}) and of the R-matrix analysis (σ_{RES}). The differences are difficult to see in Fig. 1 so we have plotted the ratio $\sigma_{RES}/\sigma_{BNW}$ as a function of energy in Fig. 6. The differences are largest at low energies (~ 45% at 5 keV), and range from ~ -10% to +15% at energies between 20 keV and 1 MeV. The large difference at low energies comes mainly from the fact, mentioned previously, that the constant in the penetrability of the Battelle expression is about 3.5% too high. The difference at higher energies can be attributed to the rapid energy dependence of Δ_d and Γ_d in the R-matrix calculation above 20 keV. The Battelle parameterization appears to accommodate only a linear change in Δ_d with energy, and to take the total width, $\Gamma_d + \Gamma_n$, independent of energy. Energy-dependent (rather than constant) distant-level contributions in the R-matrix calculation also account for a part of the difference observed near 1 MeV, where, as Figs. 3-5 show, the scatter in the experimental points becomes severe.

We conclude that, if one desires a few-parameter representation of the T(d,n) reaction cross section at energies below 1 MeV, certainly the BNW parameterization is preferred over that of Artsimovich. However, the BNW parameterization appears to differ in detail from results of a full R-matrix calculation, particularly at low deuteron energies.

Although present measurements of the T(d,n) cross section (Fig. 5) are not sufficiently precise or extensive to discriminate sharply between the two curves, we feel that the shape of the R-matrix calculation is more nearly correct,[*] since the formalism takes proper account of the energy-dependent terms of a broad resonance near threshold, and since the resonance parameters were determined by fitting many types of data in addition to the reaction cross section (see the Appendix). Partly for the latter reason, we also feel there is no compelling evidence that the resonance is appreciably narrower than experimental data presently available in the U. S. indicate.

V. THE T(t,2n)^{4}He CROSS SECTION

Only three measurements have been made of the total cross section. Agnew et al.[15] measured the

---

[*] BNW's use of the Mott form in place of the Gamow form of the penetrability has little consequence in this reaction; at energies sufficiently high to distinguish between the two forms, neither one gives the correct Coulomb penetrability.

[†] Values of the reaction cross section[8] calculated from the R-matrix parameters are listed in Table I on an energy grid hopefully suitable for interpolation.

[*] NOTE ADDED IN PROOF: We have obtained a report (LA-1479) containing the actual measurements of Arnold et al.[14] It is striking that the R-matrix calculations agree much better with the data below 20 keV than does the authors' Gamow fit (see Table II). The R-matrix calculation deviates at most by 9% from the measured values, while the Gamow curve deviates by 30% at several points. This comparison is not conclusive, since the authors, themselves, discount the reliability of their low-energy data, but it does indicate that the R-matrix calculation follows more closely the low-energy behavior of the cross section than does a Gamow extrapolation from energies as low as 20 keV.

angular distributions of the neutrons from 0° to 120° and, by extrapolation to 180°, obtained a total cross section of 114 mb at 1.32 MeV. Jarmie and Allen[16] observed the alpha particles at 1.9 MeV at 4 angles and found a cross section of 106 mb after extrapolation to 0° and 180°. Govorov et al.[17] used a large tank to measure the integral neutron yields from 60 to 1140 keV and fit their data to an equation of the form (a + b log E). Unfortunately, the parameters reported give a cross section which goes negative at 43 keV. Therefore, the only energy-dependent measurement available today does not allow a reasonable estimate of the T(t,2n) cross section in the low-keV range. The experimental data, as reproduced from graphical results, are shown in Fig. 7. The curves in this figure will be discussed in the next section.

The cross sections reported in BNWL-1685 were obtained by fitting the zero-degree cross section[15] measured by Agnew et al., presumably after applying a multiplicative factor of ten.* The expression for the least squares fit reported in BNWL-1685:

$$\sigma(E) = [E(e^{A_1/\sqrt{E}} - 1)]^{-1}[A_2/\{1 + (A_3E - A_4)^2\}],$$

again contains the Mott penetrability factor, in which A_1 is uniquely determined from the charges and masses of the interaction. Although this constant for T + T should be 1720, they obtained 1214 by allowing A_1 to be a variable parameter in the fit. This difference in A_1 gives low-energy cross sections which are in definite disagreement with recent measurements from the USSR.

Strel'nikov et al.[18] observed the neutrons at zero degrees from 40 to 200 keV using thin targets. Tabular data are not available and the graphical presentation does not permit accurate reproduction of the points. The Gamow fit to their data, however, touches every experimental point except one below 150 keV. Therefore, an attempt has been made to represent the experimental data in Fig. 8 by parameters of the Gamow fit as published (dashed curve). The experimental points are those of Agnew et al. and the smooth curve is the BNW least squares fit divided by ten. Note that the Russian zero-degree measurements are more than a factor of ten lower than that of Agnew et al. near 40 keV.

Another Russian contribution is the measurement of the alpha-particle spectrum at 90° from 226 to 1006 keV by Govorov et al.[19] in 1962. Unfortunately, deuteron contamination of the target obscured part of the high-energy spectrum and alphas below 1 to 1.5 MeV were not recorded. Again, these results are not presented in reproducible form, but Strel'nikov et al. show that they follow a Gamow plot obtained from a fit to the zero-degree cross section in remarkable fashion up to 300 keV.

Strel'nikov et al. also show fairly good agreement above 100 keV between their zero-degree cross sections and the total cross sections of Govorov et al., when the latter are divided by 4π. (See the dashed curve in Fig. 7.) Below 100 keV, the latter are considerably higher, being about a factor of two higher at 60 keV.

These Russian data, therefore, tend to support the suggestion that $4\pi\sigma(\theta) = \sigma_{tot}$ up to 300 keV with $\theta = 0°$ for neutrons and 90° for alpha particles, where all angles refer to the laboratory reference frame. To check the validity of this assumption, 3-body phase-space calculations were performed for the T(t,2n) reaction. The laboratory to center-of-mass cross-section conversion factor approaches 1 as $E \to 0$, and this results in isotropic angular distributions near zero incident triton energy. In spite of the large positive Q involved, however, there is pronounced peaking of the laboratory cross section in the forward direction at fairly low incident energies, even though isotropy in the center-of-mass system is assumed. The results of phase-space calculations at two energies are reproduced below for comparison:

	NEUTRONS		α PARTICLES	
Triton Energy (keV)	Lab 0°/180°	$4\pi\sigma(90°)/\sigma_{tot}$	Lab 0°/180°	$4\pi\sigma(90°)/\sigma_{tot}$
100	1.22	0.998	1.88	0.983
250	1.37	0.996	2.72	0.957

The experimental evidence so far indicates sequential modes of decay for the T-T reaction, rather than a pure phase space, even though the latter is

---

*Although Agnew et al. suggested that the integrated cross section at 1.32 MeV was approximately ten times the zero-degree cross section, this statement would not necessarily be valid at all incident triton energies. Of some importance, perhaps, the authors do not provide information on how the data were extrapolated from 120° to 180°.

a reasonable approximation to the experimental distributions observed. It should be noted that a final state interaction mechanism, such as the dineutron, would tend to produce greater forward peaking in the laboratory system.

Therefore, it is somewhat surprising that the Russian data on $\sigma(0°)$, when multiplied by 4π (dashed curve in Fig. 7), show very good agreement with σ_{tot} above 100 keV but not below 100 keV; the converse would be expected. It is also surprising that the BNW least squares fit to ten times the 0° measurements of Agnew et al. agree well with the Russian total cross-section measurements. This comparison is shown as the smooth curve in Fig. 7.

Note that the zero-degree cross sections of Agnew et al. are high compared to the measurements of Strel'nikov et al. (Fig. 8). Note also that $4\pi\sigma(0°)$ should be an upper limit on the integrated cross section due to the forward peaking of the neutrons in the laboratory system (forward peaking increases with increasing incident triton energy). Such a trend, however, is not apparent from the data in Fig. 7.

Other measurements have been made where a one-particle spectrum has been observed at one angle, usually on a relative scale. Such experiments have not been included here on a quantitative basis.

The only conclusions which can be drawn from the measurements discussed above are that the T(t,2n) cross section is not well known and particularly so at low energies. The least squares fit reported in BNWL-1685 is not recommended for use due to the inclusion of a resonance near 2 MeV, which has not been supported by experiment, and the fact that an incorrect value of A_1 was used in the Gamow expression in fitting the data. The best guess at this time is that the T(t,2n) cross section below 100 keV is much lower than predicted in BNWL-1685.

VI. RECOMMENDATIONS

A. $T(d,n)^4He$

We feel that a more extensive evaluation of the T(d,n) cross section, using a comprehensive approach of the type described in Appendix A, would provide a more reliable data set to be used in fusion studies. Even though few low-energy measurements exist, the experimental difficulties expected in the few-keV range are so great that further analysis is warranted to assess the accuracy of our present cross-section set. It may well be that other experimental information on the five-nucleon system, when used in conjunction with the presently available T(d,n) cross sections, will determine the T(d,n) cross section with acceptable accuracy. If not, then such analysis could certainly determine the deuteron energy range over which measurements should be requested.

B. $T(t,2n)^4He$

More thin-target experiments are required before much improvement should be expected in a further analysis of the present data. LASL has a triton source which could conceivably cover the range from ~ 20 to 90 keV. One would expect a Gamow extrapolation of the T(t,2n) cross section to be valid from somewhat higher energies than in the case of T(d,n), since the T(t,2n) reaction does not appear to show a broad resonance at low energies. Measurements at energies down to 20 keV would be of great value in determining the extrapolation of the cross section to very low energies. If requested, further exploration into the experimental possibilities will be made. If experiments on the T(t,2n) are needed, then cross sections on the D(t,n) should also be measured at the same triton energies, since these could then be used as confirmation of older T(d,n) measurements.

ACKNOWLEDGEMENTS

It is with pleasure that we acknowledge the helpful discussions with Robert Haight (LLL) and R. G. Alsmiller, Jr. (ORNL) on the T(d,n) cross sections. Both concur with our conclusions that we find little reason to doubt the validity of the U. S. measurements below ~ 1 MeV, certainly to within factors of two. We wish to thank Phil Young for his help in several areas, in particular for reviewing the paper and for performing the 3-body calculations. To John Hogan (ORNL), we express our appreciation for providing the results of the discussions with Pistunovich at ORNL and also for sending further interpretation of the data and several pertinent references. To Lester K. Price (AEC-DCTR) and Don Steiner (ORNL), who initiated this study, we wish to extend our thanks for their encouragement and concern.

APPENDIX A

R-MATRIX ANALYSIS OF REACTIONS IN THE FIVE-NUCLEON SYSTEM AT LOW ENERGIES

The R-matrix analysis[8] discussed in Section IV of this report is the multichannel extension of a simultaneous charge-symmetric analysis of n-α and p-α elastic scattering described in Ref. 20. That is, data from reactions in the n-α, d-T system (or ^{5}He) were analyzed simultaneously with data from reactions in the p-α, d-^{3}He system (or ^{5}Li) at energies corresponding to E_d below 1 MeV. (This includes neutron or proton energies up to about 23 or 24 MeV). The reduced widths of corresponding levels in the two systems (^{5}He and ^{5}Li) were constrained to be equal, as one would expect approximately from the charge independence of nuclear forces. The level energies in the two systems were not constrained to differ by a common Coulomb energy shift, however, as they were in the n-α/p-α analysis.[20]

Data were included from the reactions T(d,d)T, T(d,n)^{4}He, and ^{4}He(n,n)^{4}He in the ^{5}He system, and from the reactions ^{3}He(d,d)^{3}He, ^{3}He(d,p)^{4}He, and ^{4}He(p,p)^{4}He in the ^{5}Li system. A complete list of data references would be too lengthy to give here, but the types of measurements analyzed include integrated cross sections, differential cross sections, polarizations, and analyzing tensors for polarized deuterons incident. The T(d,n)^{4}He integrated cross-section data analyzed were those of Conner et al.,[11] Argo et al.,[12] and of Bame and Perry.[9] The data of Katsurov[10] were not included because of an apparent energy shift relative to the U. S. measurements; tabulated values reported by Arnold et al.[14] were deleted from the analysis since these were based on a smooth fit and extrapolation of the original data points.

Partial waves through $\ell = 2$ (D-waves) were included in the d-T and d-^{3}He (deuteron) channels, while states through $\ell = 4$ (G-waves) were allowed in the n-^{4}He and p-^{4}He (nucleon) channels. Channel radii were fixed at 5.0 fm in the deuteron channels and 2.9 fm in the nucleon channels. In accordance with charge symmetry, the same boundary condition numbers were used for corresponding states in ^{5}He and ^{5}Li. Level parameters were obtained from an automated search that located a good fit to all the data included from both systems. In addition to the lowest known levels (3/2- and 1/2- below the deuteron threshold, and 3/2+ just below the deuteron threshold), the search positioned relatively low-lying levels in 7/2+, 5/2+, 1/2+, and 1/2- states, and distant levels in all states. Low-lying levels above the 3/2+ resonance are probably not well determined by the analysis, since they occur above the highest energy at which data are included. However, data at higher energies indicate the possible existence of several resonances in the region $2 \leq E_d \leq 12$ MeV.[21]

The data in the two systems were fit satisfactorily within the charge-symmetric framework imposed by the analysis. In particular, the difference in the experimental widths of the T(d,n) resonance at 107 keV[22] and of the ^{3}He(d,p) resonance at 430 keV came naturally out of the different penetrabilities for the two systems. For this reason, we feel fairly confident that the width of the T(d,n) resonance cannot be substantially different from that determined by the analysis. The position of the peak cross section (predicted to be 109 keV for the T(d,n) reaction) was not subject to charge-independent constraints, however. It is possible that including measurements of the T(d,n) cross section indicating a different position for the peak could change substantially the predictions of the analysis at low energies.

REFERENCES

1. The results of these discussions were made available to the USNDC CTR Subcommittee through a letter from Dr. John T. Hogan (ORNL) to Dr. S. O. Dean (AEC-DCTR) and also via further communication from Hogan to Stewart.
2. N. Jarmie, J. D. Seagrave, R. C. Allen, A. Armstrong, H. V. Argo, S. J. Bame, J. E. Brolley, J. H. Coon, G. M. Frye, A. Hemmendinger, T. M. Putnam, F. L. Ribe, G. A. Sawyer, A. W. Schardt, L. Stewart, T. F. Stratton, W. R. Stratton, N. J. Terrell, M. M. Thorpe, S. Whetstone, J. L. Yarnell, "Charged Particle Cross Sections," Los Alamos Scientific Laboratory report LA-2014, (March 1956).

3. W. C. Wolkenhauer, Ed., "The Pacific Northwest Laboratory Annual Report on Controlled Thermonuclear Reactor Technology - 1972," Battelle Northwest Laboratory report BNWL-1685 (Nov. 1972). See the contribution by B. H. Duane, "Fusion Cross Section Theory," p. 75.

4. Samuel L. Greene, Jr., "Maxwell Averaged Cross Sections for Some Thermonuclear Reactions on Light Isotopes," Lawrence Radiation Laboratory report UCRL-70522 (May 1967).

5. V. I. Pistunovich, Atomnya Energya 35, 11 (1973).

6. J. M. Dawson, H. P. Furth, F. H. Tenney, Phys. Rev. Lett. 26, 1156 (1971).

7. L. A. Artsimovich, Controlled Thermonuclear Reaction (in Russian), Fiz., Moskow, p. 60 (1961).

8. R. A. Nisley, G. M. Hale, and D. C. Dodder, Los Alamos Scientific Laboratory, unpublished.

9. S. J. Bame and J. E. Perry, Jr., Phys. Rev. 107, 1616 (1957).

10. L. N. Katsurov, Akademiia Nauk USSR, Fizicheskii Institut, Trudy, V. 14, p. 224-262 (1962).

11. Conner, Bonner, and Smith, Phys. Rev. 88, 468 (1952).

12. H. V. Argo et al., Phys. Rev. 87, 612 (1952).

13. A. Hemmendinger and H. V. Argo, Phys. Rev. 98, 70 (1955).

14. Arnold et al., Phys. Rev. 93, 483 (1954).

15. H. M. Agnew et al., Phys. Rev. 84, 862 (1951).

16. N. Jarmie and R. C. Allen, Phys. Rev. 111, 1121 (1958).

17. Govorov et al., Soviet Physics (JETP) 15, 266 (1962).

18. Y. V. Strel'nikov et al., Bull. Acad. Sci. USSR, Phys. Ser. 35, 149 (1971).

19. Govorov et al., Soviet Physics (JETP) 14, 508 (1962).

20. D. C. Dodder, G. M. Hale, R. A. Nisley, K. Witte, and P. G. Young, "Models Based on Multichannel R-Matrix Theory for Evaluating Light Element Reactions," to be published in the Proc. of the EANDC Topical Discussion on Critiques of Nuclear Models and Their Validity in the Evaluation of Nuclear Data, Tokyo, March, 1974; also LA-UR-74-738.

21. See, for example, F. Seiler, Nuclear Physics A187, 379 (1972).

22. F. Ajzenberg-Selove and T. Lauritzen, Nuclear Physics A227, 1 (1974).

TABLE I

LASL PREDICTIONS FOR THE T(d,n)^{4}He CROSS SECTION FROM 5 keV TO 1 MeV[8]

Energy (keV)	σ barns	Energy (keV)	σ barns	Energy (keV)	σ barns	Energy (keV)	σ barns	Energy (keV)	σ barns
5	8.65×10^{-6}	55	1.62	120	4.88	320	1.16	550	0.518
10	1.53×10^{-3}	60	2.04	140	4.28	340	1.05	600	0.461
15	14.2×10^{-3}	65	2.49	160	3.59	360	0.963	650	0.415
20	52.9×10^{-3}	70	2.95	180	2.99	380	0.886	700	0.378
25	129.0×10^{-3}	80	3.82	200	2.52	400	0.819	750	0.347
30	0.250	90	4.51	220	2.15	420	0.762	800	0.322
35	0.421	100	4.91	240	1.86	440	0.711	850	0.300
40	0.643	105	4.99	260	1.63	460	0.666	900	0.281
45	0.919	109	5.012	280	1.44	480	0.627	950	0.266
50	1.25	110	5.01	300	1.29	500	0.591	1000	0.252

TABLE II

COMPARISON OF THE R-MATRIX PREDICTIONS TO THE MEASURED AND CALCULATED T(d,n)^{4}He CROSS SECTIONS OF ARNOLD ET AL., (LA-1479) AT SELECTED ENERGIES BELOW 20 keV

E_d (keV)	σ_{expt} (Arnold) (barns)	σ_{calc} (R-matrix) (barns)	σ_{Gamow} (Arnold) (barns)
7.53	2.16×10^{-4}	2.33×10^{-4}	2.82×10^{-4}
9.60	11.93×10^{-4}	11.90×10^{-4}	14.07×10^{-4}
10.94	24.02×10^{-4}	26.23×10^{-4}	30.57×10^{-4}
20.00	56.31×10^{-3}	52.86×10^{-3}	55.12×10^{-3}

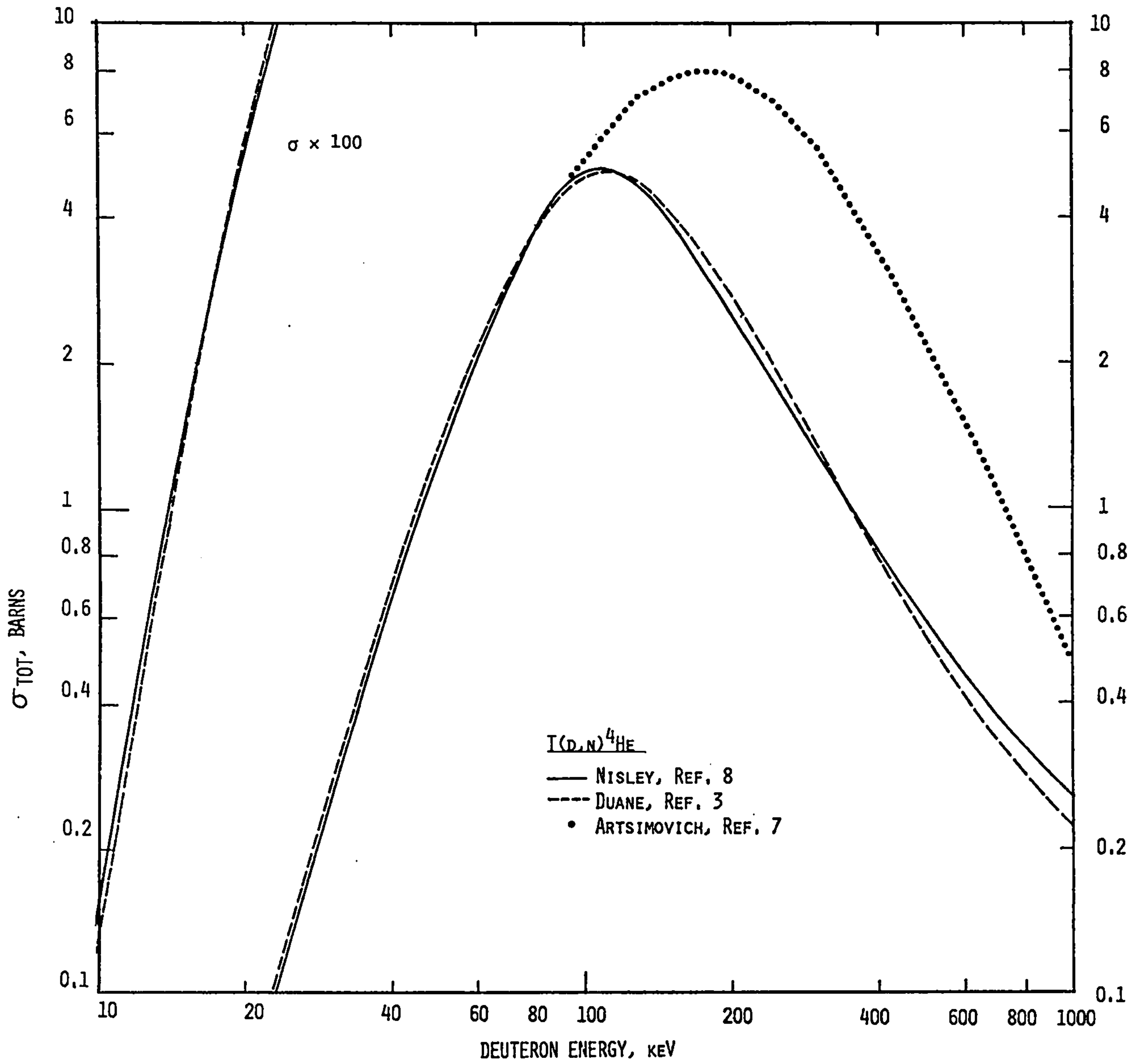

Fig. 1. Various predictions of the T(d,n)^{4}He cross sections below 1 MeV. The Artsimovich results (dotted curve) are not shown below the resonance since they show only small differences with the LASL and Battelle predictions.

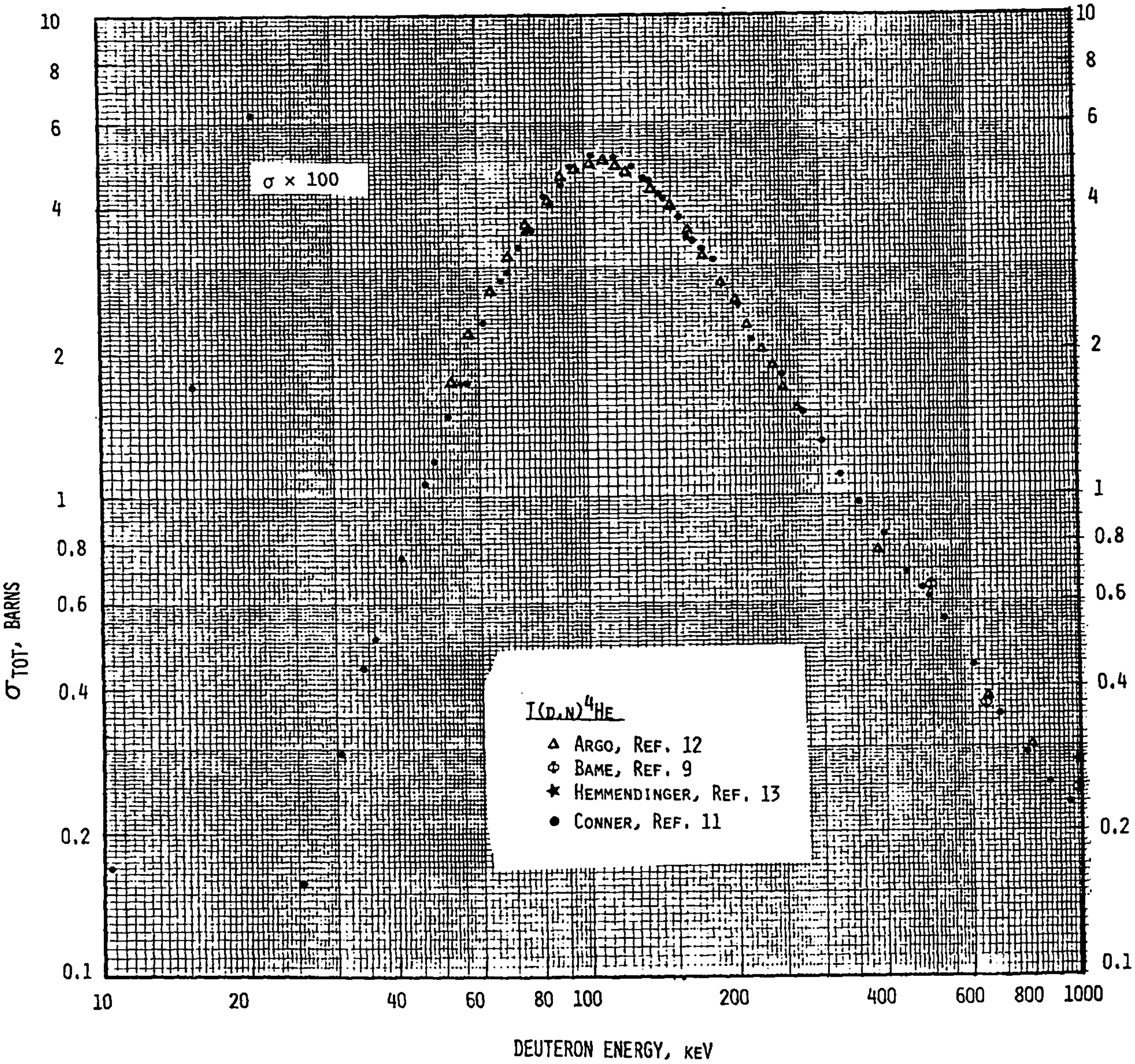

Fig. 2. U. S. measurements available for the D-t and T-d reactions. Some of the points near the peak have been omitted for the sake of clarity. Also, the data of Arnold et al. have been omitted since the tables available are not the experimental results.

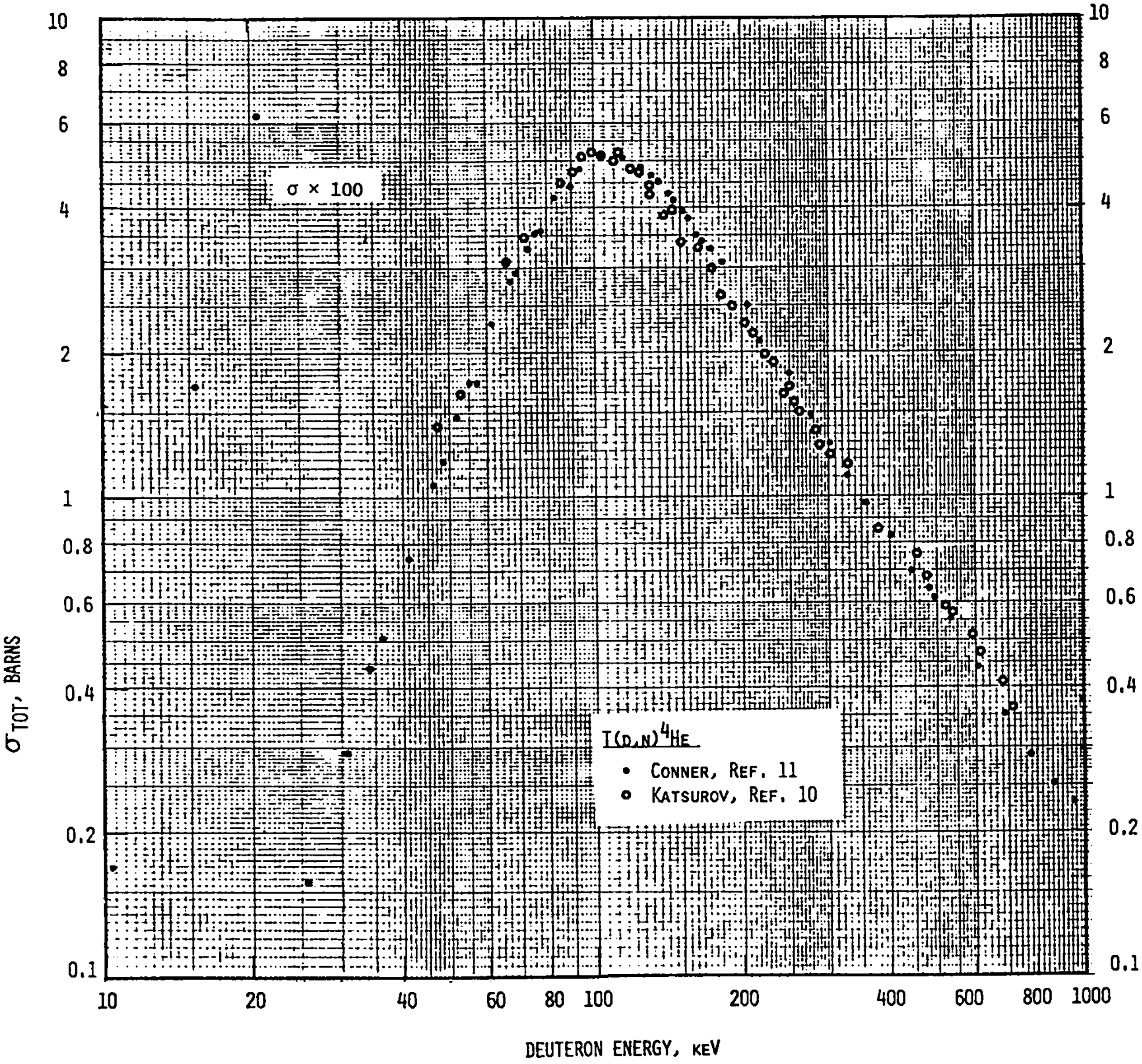

Fig. 3. Comparison of the 1962 Russian data with the results of Conner et al. A few of the Russian points were averaged before plotting. Note the apparent energy shift between the two experiments.

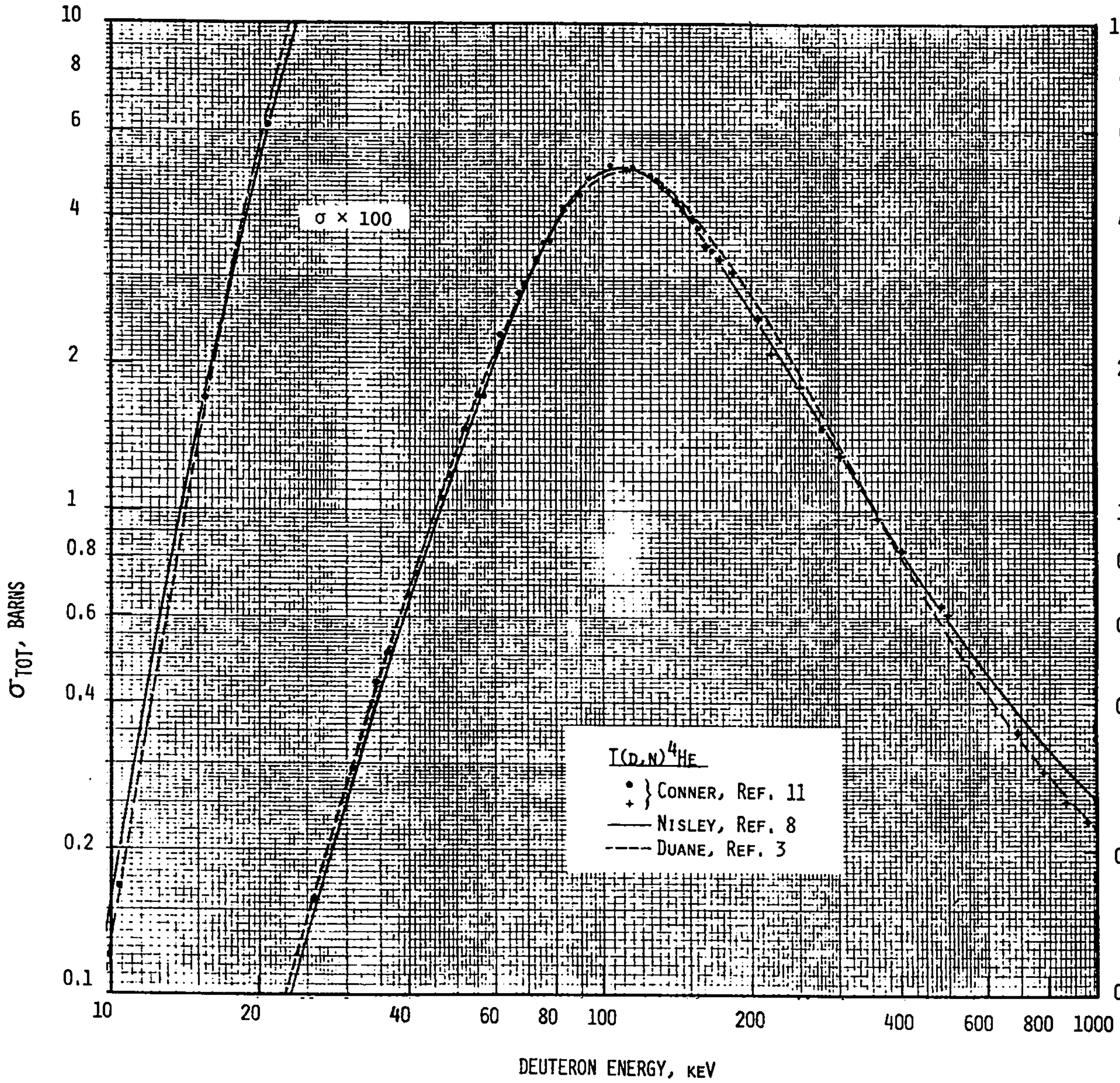

Fig. 4. Comparison of the data of Conner et al. with the LASL and BNWL predictions of the cross sections. The ..... represent α-particle measurements on a Cockcroft Walton, while the + + + denote neutron experiments with a Van de Graaff.

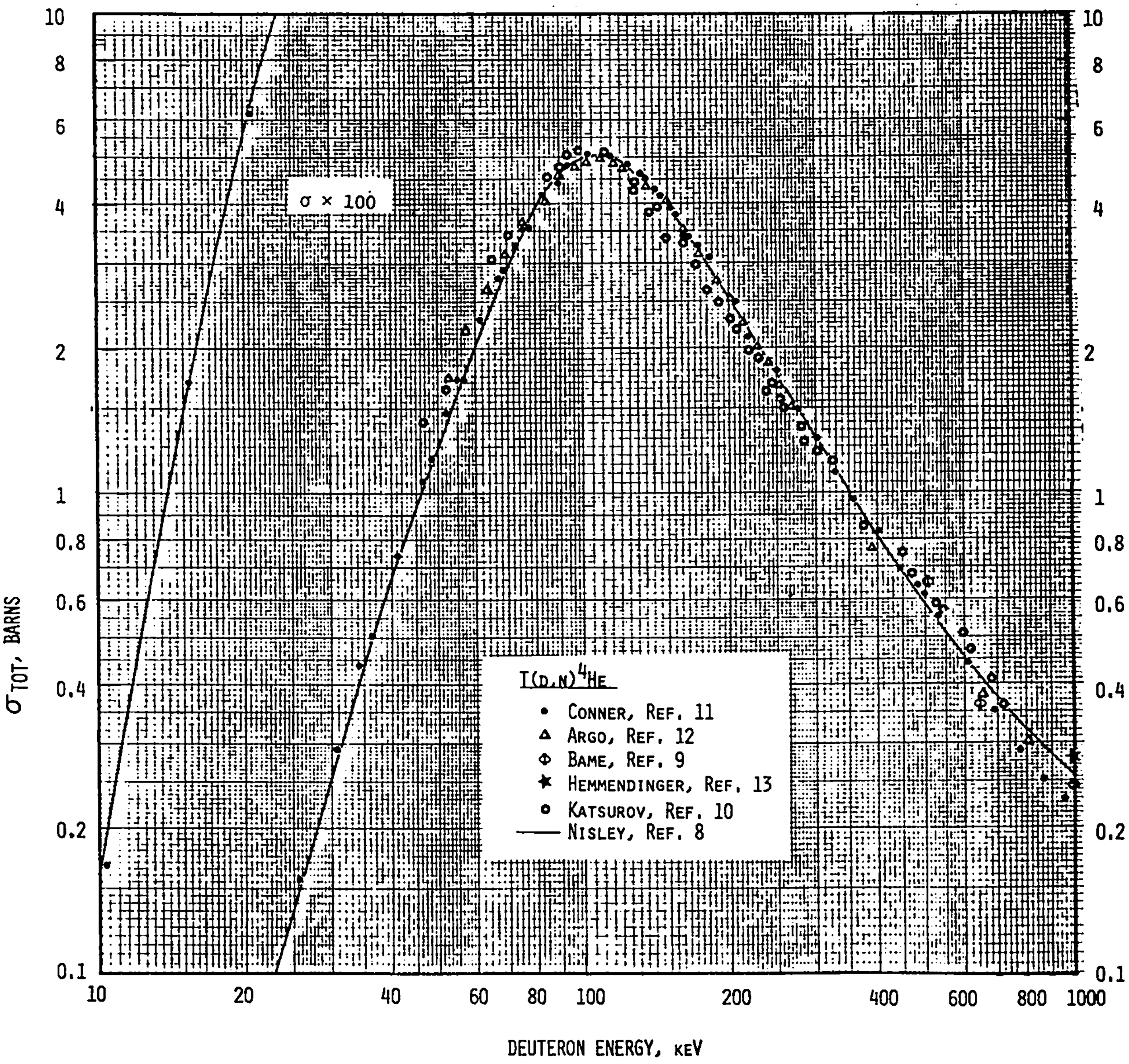

Fig. 5. Comparison of the U. S. and Russian experimental data with the LASL prediction of the cross section. The importance of predicting the correct resonant energy is readily apparent in this figure.

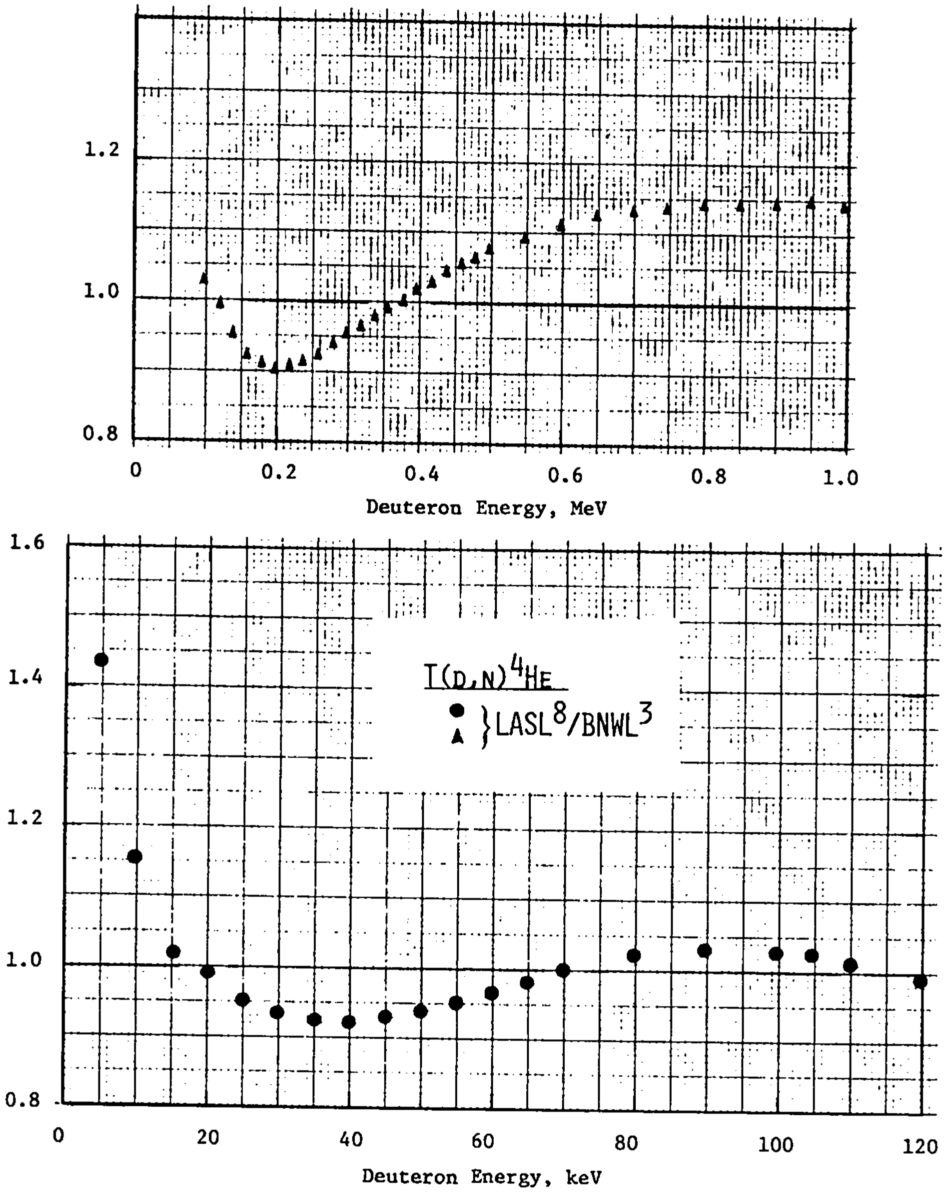

Fig. 6. Ratio of the T(d,n)^{4}He cross sections as predicted by LASL to those by Battelle. Note the large differences which appear at the lowest energies.

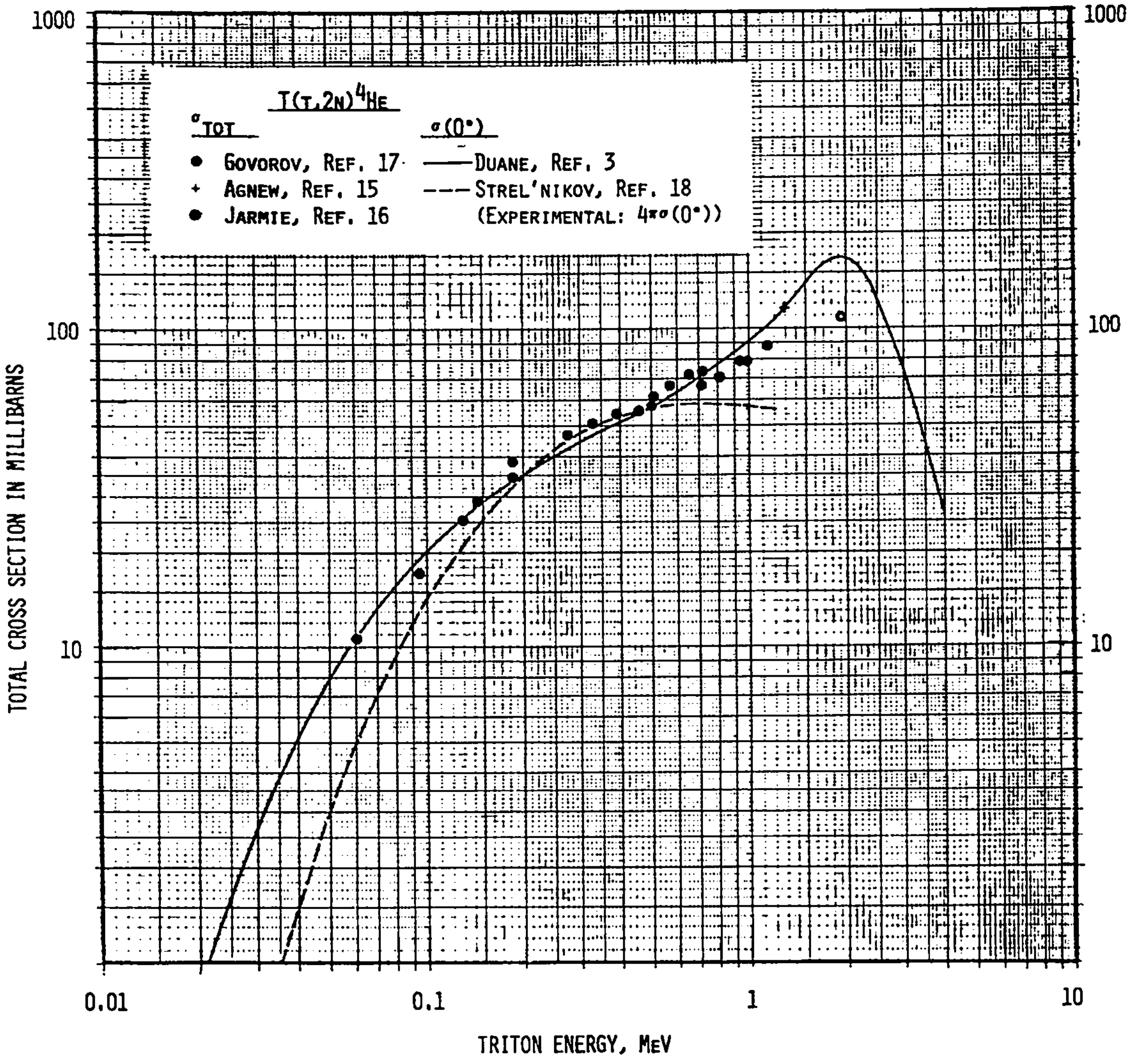

Fig. 7. The T(t,2n)^4 total cross section. The points are measurements of the total. The smooth curve is a fit by Duane to ten times the zero-degree cross section of Agnew et al. The dashed curve is 4π times the zero-degree cross section measurements of Strel'nikov et al.

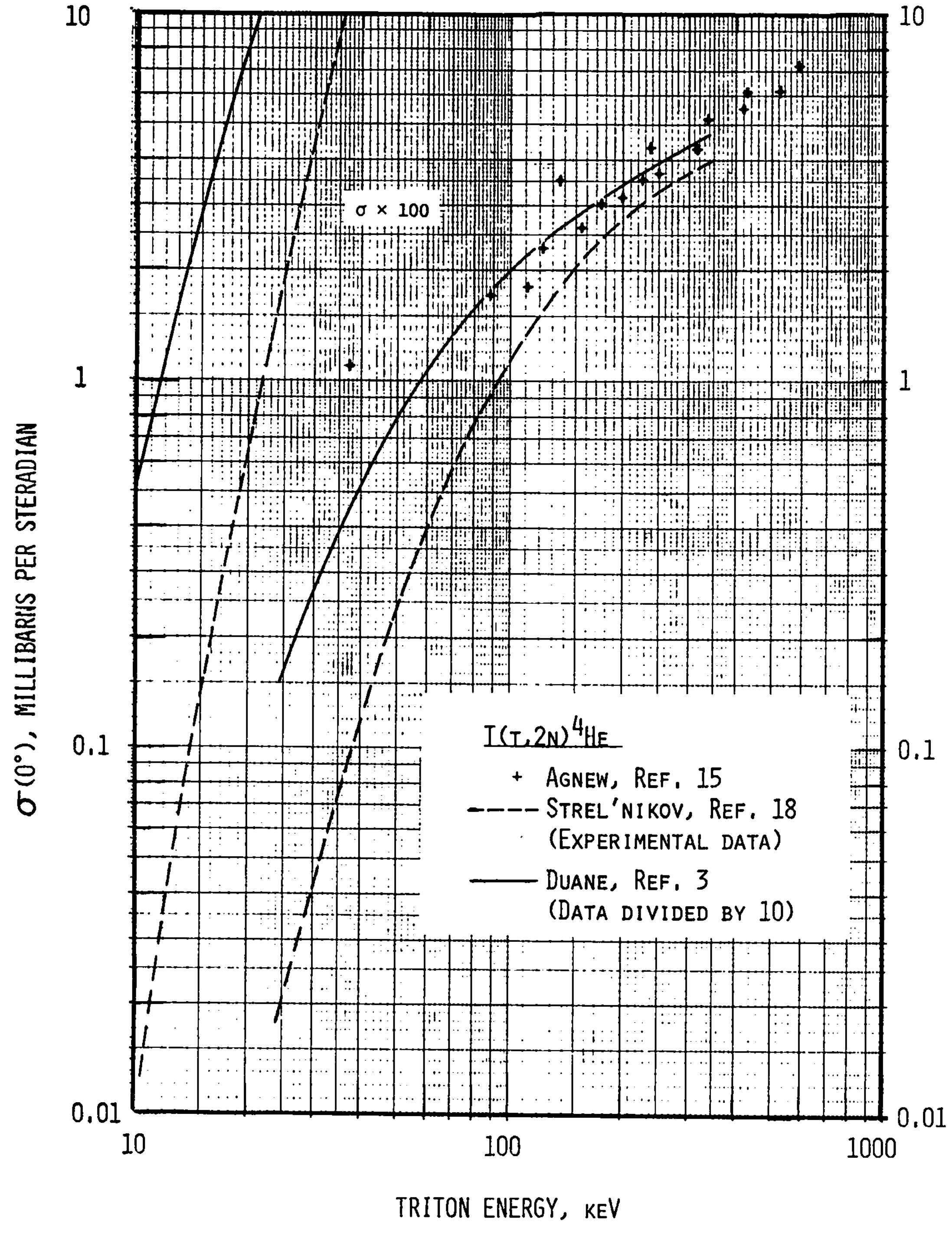

Fig. 8. T(t,2n)^{4}He zero-degree cross section. The Gamow fit to Strel'nikov's data has been extended to energies below the lowest measurement (40 keV) in order to compare with Duane's curve.