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DATA DISCREPANCIES IN AND NEW EXPERIMENTS FOR D+D, D+T, AND T+T FUSION REACTIONS

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We investigate the accuracy of the basic fusion data for the reactions $T(d,n)^4He$, $T(t,2n)^4He$, $D(d,n)^3He$, and $D(d,p)T$ in the 10-100 keV bombarding energy region of interest in the design of fusion reactors, magnetic or inertial. The history of the data base for these reactions, particularly the most critical one: $T(d,n)^4He$, is based on 25-year-old experiments whose accuracy (often assumed to be 5%) has rarely been questioned. In all except the d + d reactions significant differences among data sets exist. The errors of the basic data sets may be considerably larger than previously expected and the effect on design calculations should be significant. Much of the trouble apparently lies in the accuracy of the energy measurements which are difficult at low energies. We feel that systematic errors of up to 50% are possible in the reactivity values of the present $T(d,n)^4He$ data base. The errors in the reactivity would propogate proportionately into the errors in fusion probabilities in reactor calculations. The $D(d,n)^3He$ and $D(d,p)T$ cross sections appear to be well known and consistent. The $T(t,2n)^4He$ cross section is poorly known and may be subject to large systematic errors. Improved absolute measurements in the 10-100 keV bombarding energy region for the above reactions are underway at Los Alamos. The experiment features a windowless cryogenic target, calibration of the target density with a high energy Van-de-Graaff beam, measurement of the beam intensity with a calorimeter, use of a negative ion source for the 10 to 100 keV measurements, and a time-of-flight laser spectrometer to determine the absolute energy. Both the source and target will be capable of handling tritium. Accuracies of better than 5% are anticipated.

[Data discrepancies, 10-100 keV, T(d,n), T(t,2n), d + d reactions, absolute cross section measurement.]

Introduction

The purpose of this work is to investigate the accuracy of the basic fusion reaction data for the reactions $T(d,n)^4He$, $T(t,2n)^4He$, $D(d,n)^3He$, and $D(d,p)T$, and to describe an elaborate experiment in progress at the Los Alamos Scientific Laboratory to remeasure the cross sections with improved accuracy.

The history of the data base for these reactions, particularly the most critical one: $T(d,n)^4He$, is based on 25-year-old experiments whose accuracy (often assumed to be 5%) has rarely been questioned. As reactor experiments and reactor design become more sophisticated and various discrepancies stand out; it will be important to understand the influence of the uncertainty in the basic fusion data. The errors of the basic data sets may be considerably larger than previously expected and the effect on design calculations should be significant. This conclusion provides a motivation for an improved experiment.

The energy region of interest is from 10 to 120 keV bombarding energy. This corresponds, (assuming a triton beam), to a temperature of an interacting D + T plasma of from 0.5 to 20 keV. This difference of energy scale arises from the folding of the Maxwell distribution of velocities in the plasma with the cross section and from a lab to center-of-mass conversion.

The Lawson criterion[1] indicates conditions necessary for "break even" in a burning D + T plasma. It indicates that the optimum plasma temperature for the lowest $n\tau$ is around 20 to 30 keV temperature. Early reactors would likely operate on the lower side of this minimum, say from 1 to 30 keV temperature. This corresponds to a laboratory bombarding energy in the range we are concerned with.

A detailed report of discrepancies in fusion data is being published as a Los Alamos report (LA-8087). A study of the relation of the accuracy of the basic fusion data on the design of nuclear weapons has been done.[2]

Data Survey

$T(d,n)^4He$

The T(d,n) low energy data base rests on three main references. Arnold[3] et al., at Los Alamos, measured $\sigma(90°)$ down to about 10 keV (lab bombarding energy) claiming 2% accuracy. Since the reaction is isotropic in the c.m. system below several hundred keV, the $\sigma(90°)$ is easily converted to an integrated cross section σ_T. Conner, Bonner, and Smith[4] at Rice University measured $\sigma(90°)$ down to 10 keV, with 3% accuracy, and Katsaurov[5] at the Lebedev Institute measured σ_T down to 45 keV claiming 2-3% accuracy. Earlier experiments like those of Jarvis and Roaf[6] in England (20-40 keV, about 10% accuracy) were adjudged to be in some disagreement with the later U.S. experiments and were not commonly used. Most data bases in fusion reactor calculations come eventually from the work of Arnold[3] and Conner[4], sometimes circuitously. Many of the data bases depend on a compilation by Greene[7], whose calculations use mainly the work of Arnold and Conner. The fractional error in the reaction rate in a burning plasma is expected to be equal to the fractional error in the cross section[8].

Figure 1 shows the $T(d,n)^4He$ data. The line is an R-Matrix fit by Stewart and Hale[9] which agrees with standard references 3 and 4, and excludes the Katsaurov data because of an apparent energy shift in the Russian data. Study of the details of Katsaurov's work indicate that it was a carefully done experiment with due regard to the difficult problem of measuring such a low energy. It is not clear in whose work the energy discrepancy lies. The circles, Katsaurov data, are seen to be shifted to lower energies by about 6 keV leading to a cross section discrepancy (standard values low) of 10-30% in the low energy region. Figure 2 shows the low energy detail. Included in this graph is a point by Jarvis and Roaf which, if correct, would agree with the energy scale of Katsaurov. The Jarvis data were also not included in the Stewart and Hale report.

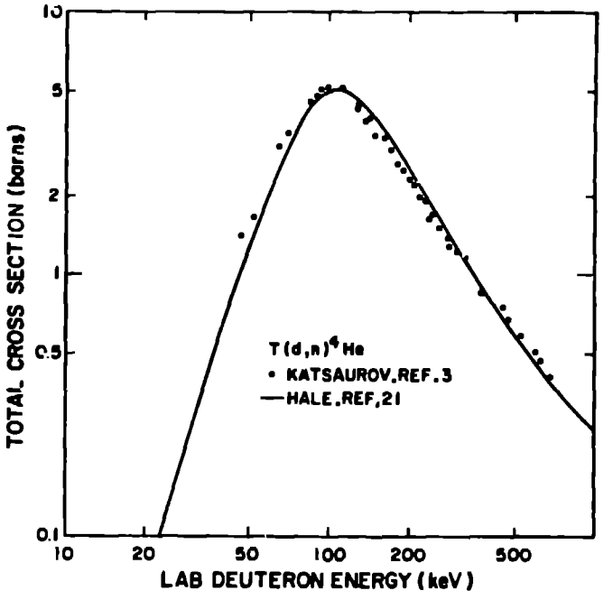

Fig. 1 The $T(d,n)^4He$ total cross-section. The line is an R-Matrix fit (Ref. 9) to known data other than those of Katsaurov. Of note is the apparent energy shift between the Katsaurov values (Ref. 5) and the other data.

The accurate measurement of the bombarding energy is difficult at low energies and is suspected by us to be the main cause of the cross section discrepancies. Because the cross section is falling in a steep exponential, slight energy shifts can produce a large error in the cross section magnitude. One can calculate, for example, that at 20 keV, a shift of only 0.5 keV in the bombarding energy will produce a 10% change in the cross section. At the lower energies the fractional cross section error varies as $dE/E^{3/2}$, so that the effect gets larger as the energy decreases.

The experimental equipment for the $T(d,n)^4He$ reaction was often used in the measurement of similar reactions which also show discrepancies. For example, the main U.S. groups: Bonner, Conner, and Lillie[4], and Arnold[3] et al., also measured the $^3He(d,p)^4He$ reaction total cross section with essentially the same apparatus. Kunz[10], in a subsequent experiment in the low-energy region, disagrees with the above data, having an apparent energy shift of from 5-15 keV <u>higher</u> so that his cross section values are 30-50% <u>lower</u> than the previous work.

It should be noted that Kunz normalizes his absolute scale by also measuring the D(t,n) reaction with his equipment and normalizing to peak of the T(d,n) measurement of Conner, Bonner, and Smith[4]. His agreement with Bonner, Conner, and Lillie at the peak of the resonance is then no surprise, but the disagreement at lower energies again indicates an energy measurement problem.

Detail of the low energy $^3He(d,p)$ reaction is given in Fig. 3. Again the work of Jarvis and Roaf[6] disagree with the Rice and LASL experiments and agree with Kunz[10]. Note that the apparent energy shift of the "standard" work is in the direction <u>opposite</u> to the T(d,n) case in Fig. 2.

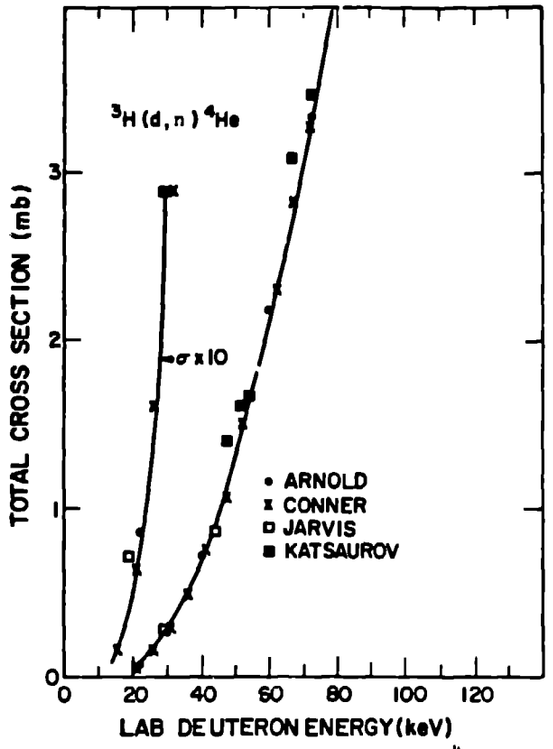

Fig. 2 Low energy detail of the $T(d,n)^4He$ total cross-section data again showing the energy shift of the Katsaurov data (Ref. 5).

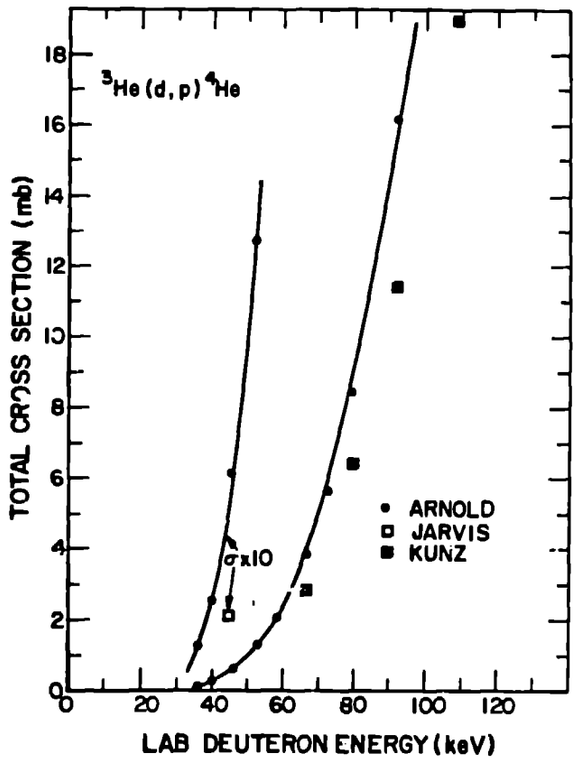

Fig. 3 Low-energy detail of the $^3He(d,p)^4He$ total cross section. It is of interest to compare this figure with Fig. 2.

An unpublished report of a measurement on the $^3He(^3He,2p)^4He$ reaction was made in 1969 by Dwarakanath[11] in which he included a measurement of the $^3He(d,p)^4He$ total cross section. His data are not available in tabluar form. Inspection of his graphical results indicates, paradoxically, that his data agree with Arnold et al. and Bonner, Conner and Lillie at low energies.

The same accelerator and absolute energy measurement used in the Arnold et al.[3] T(d,n) measurement was used by Sawyer and Phillips[12] in the $^6Li(p,^3He)^4He$ reaction. Figure 8 of Elwyn et al.[13] shows the data of Sawyer and Phillips to be high by a factor of 2 or 3 in the low energy region compared to the data of Fiedler and Kunze[14] and Gemeinhardt[15]. It is not clear how much of this discrepancy is due to a possible energy shift.

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

Greene's compilation is again the source of data as used in the design codes. His work depends largely on Govorov et al.[16] who measures σ_T from 60 to 1140 keV (5% accuracy). He excludes the data of Agnew[17] et al. (down to 40 keV, $\sigma(90°)$ 4% accuracy). Experiments done since Greene's publication are those of Strel'nikov et al.[18] who measure $\sigma(90°)$ from 40 to 200 keV (15% uncertainty claimed) and Serov, Abramovioh, and Morkin[19] who measure $\sigma(0°)$ and σ_T from 30 to 160 keV. Serov's numerical data are available[20]. For completeness we should mention the work of Govorov et al.[21] who measure $\sigma(90°)$ from 230 to 1000 keV; and the measurement of the neutron and alpha spectra by Bame and Leland[22], Wong, Anderson, and McClure[23], and Larose-Poutissou, and Jeremie[24], and Jarmie and Allen[25].

Low energy $T(t,2n)^4He$ data are discrepant and poorly understood. In some cases the total cross section is measured and sometimes the zero degree differential cross section. Comparison of the two kinds of data is not simple because the conversion between the two is not simple, even assuming isotropy in the c.m. system. The reason for this results from the 3-body breakup; and either an angular distribution must be measured or a model dependent calculation made. The conversion is also energy dependent.

In Fig. 4 the zero-degree differential cross section is presented to show the trend of the data. Shown is the prediction of the compilation of Duane[26] which was derived from the Agnew[17] data. The σ_T data of Govorov[16], divided by 10 (which is thought to be a reasonable conversion, see the discussion in ref. 9) follows the Greene curve. The Serov[19,20] data clusters around the Strel'nikov[18] curve. The prediction of Greene[7] (divided by 10) is shown for comparison. It is seen that large differences occur between various data, leading to a considerable lack of reliability in the source of fusion-calculation data sets (Greene's compilation).

Stewart and Hale[9] show that there are severe internal inconsistencies between the various sets of data concerning the conversion from $\sigma(0°)$ to σ_T. This may help explain that when the data are plotted as σ_T vs energy they look somewhat less discrepant. An R-matrix solution by Hale, Young, and Jarmie[27] to the total cross section data of ref's. 16, 20, and 25 up to 2 MeV leads to a prediction of the reactivity of the $T(t,2n)^4He$ reaction about 50% smaller than that predicted by Greene, below 50 keV bombarding energy. The data in this low-energy region are dominated by the work of Serov et al. who made a concerted effort to measure the bombarding energy accurately. Even if they were successful at this difficult task, their energy error is still 2 to 3 keV, and the stated error in their cross sections are from 20 to 30%. Considering the other inconsistencies mentioned, our knowledge of $T(t,2n)^4He$ cross sections is not secure.

$D(d,n)^3He$ and D(d,p)T

Many experiments measuring absolute cross section have been done partially because of a report of a narrow resonance near E_d = 100 keV and the comparison of the two branches. Unlike the T(d,n) and T(t,2n) reactions the angular distribution is highly anisotropic at low energies. A good summary of the experiments is given by Theus[28].

McNeill[29] has revised the total cross section data of Arnold et al.[3] upwards by 3-12% to account for improved anisotropy measurements. When this is done, the several absolute experiments agree within experimental errors which are generally 10-15% except for Arnold[3] who quotes 2-5%. It seems then that the data for the d + d reactions are in satisfactory agreement.

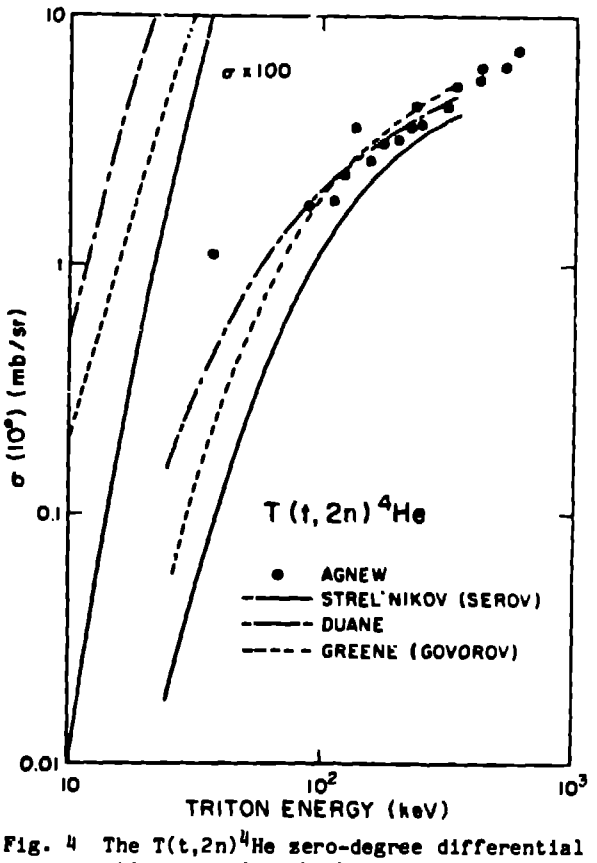

Fig. 4 The $T(t,2n)^4He$ zero-degree differential cross section vs triton bombarding energy. Greene's (Ref. 7) total cross section prediction, based on Govorov (Ref. 16), is divided by 10 to give the curve shown. Duane's prediction (Ref. 26) is based on the Agnew data (Ref. 17). The Serov data (Ref. 20) closely follows the Strel'nikov data (Ref. 18) represented by the solid line.

The d + d data of Arnold et al.[3] were taken with the same apparatus as in their T(d,n) experiment. The apparent agreement of Arnold's d + d data with the other experiments in that system adds another curious heuristic element in the question of the reliability of their T(d,n) data.

Cross Section Experiment

An experiment is now in progress at Los Alamos to measure the absolute cross sections of the reactions under discussion from 10-100 keV bombarding energy to an reliable accuracy of better than 5%. Since knowledge and control of the absolute energy is of some concern, great effort has been made in the design to achieve a good energy measurement.

The schematic of the experiment is shown in Fig. 5. There are several key elements in the experimental design. 1. The target is a windowless, continuous flow, cryogenic device, with the outflowing gas trapped on 4°K surfaces. The avoidance of windows is a critical factor in obtaining a reliable determination of the energy. The target will be capable of handling tritium. A typical target density is about $10^{16}/cm^3$. Precise measurement of gas flow and target temperature is necessary. 2. Because of charge exchange in the target, the beam intensity will be measured by a precision calorimeter following a design by Thomann and Benn[30]. 3. The 5-120 keV ion source will produce a negative beam to eliminate unwanted ion species and supress effects of slitedge scattering. It will be capable of accelerating tritons. Beam currents will be from 1-50 microamps. 4. Energy loss in the target will be explored with a laser spectrometer[31]. This device uses a precise time-of-flight measurement of a beam pulse created by photodetachment of the beam negative ions with a pulsed Nd: YAG laser. Both the laser spectrometer and a precision resistor stack will be used to measure the absolute energy. An attempt will be made to keep all sources of error in the beam energy less than 50 V. 5. Calibration of the target density will be made using a high energy Tandem Van-de-Graaff beam. A reaction with well known cross section, such as D(p,p)D or T(p,p)T will be used. If necessary, the calibrating cross section will be measured separately at Los Alamos to better than 1%.

At this writing, the cryogenic target is complete, the ion source installed and running, the calorimeter complete and tested and all of the beam optic elements installed. Both 100 keV and 10 MeV beams have successfully bombarded a deuterium target and reaction particles have been detected. The laser spectrometer and tritium handling equipment are under construction. A photograph of the system is shown in Fig. 6.

We plan to first measure the D + D system to work out problems in the system; then accelerate tritons to study D + T and finally flow tritium in the target to study the T + T reaction.

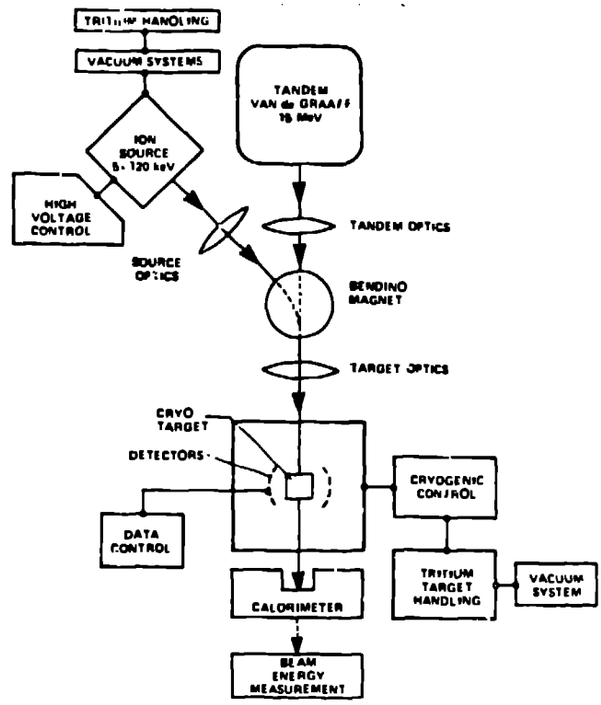

Fig. 5 LOW ENERGY CROSS SECTION EXPERIMENT

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References

1. F. L. Ribe, T. A. Oliphant, Jr., and W. E. Quinn, Los Alamos Scientific Laboratory report LA-3294-MS (1965), and J. D. Lawson, Proc. Phys. Soc. B70, 6 (1957).

2. N. Jarmie and J. Wallace, private communication.

3. W. R. Arnold, J. A. Phillips, G. A. Sawyer, E. J. Stovall, Jr., and J. L. Tuck, Phys. Rev. 93, 483 (1954). See also, Los Alamos Scientific Laboratory report LA-1479 (1953).

4. J. P. Conner, T. W. Bonner, and J. R. Smith, Phys. Rev. 88, 468 (1952) and T. W. Bonner, J. P. Conner, and A. B. Lillie, Phys. Rev. 88, 473 (1951).

5. L. N. Katsaurov, Akad, Nauk, USSR, Fizicheskii Inst., Trudy, 14, 224 (1962); and, E. M. Balabanov, I. Ia. Barit, L. N. Katsaurov, I. M. Frank, and I. V. Shtranikh, Supplement No. 5 of Soviet Journal of Atomic Energy, Atomnaya Energiya, p. 43 (1957).

6. R. G. Jarvis and D. Roaf, Proc. Roy. Soc. A218, 432 (1953).

7. S. L. Greene, Jr., Lawrence Radiation Laboratory report UCRL-70522 (May 1967).

8. R. Santoro and J. Barish, Nuc. Sci. and Engineering 59, 189 (1976) and ORNL-TM-4933 (1976)

9. L. Stewart and G. M. Hale, Los Alamos Scientific Laboratory report LA-5828-MS (January 1975); See also G. M. Hale, this conference.

10. W. E. Kunz, Phys. Rev. 97, 456 (1955).

11. M. R. Dwarakanath, Thesis, California Institute of Technology (1969).

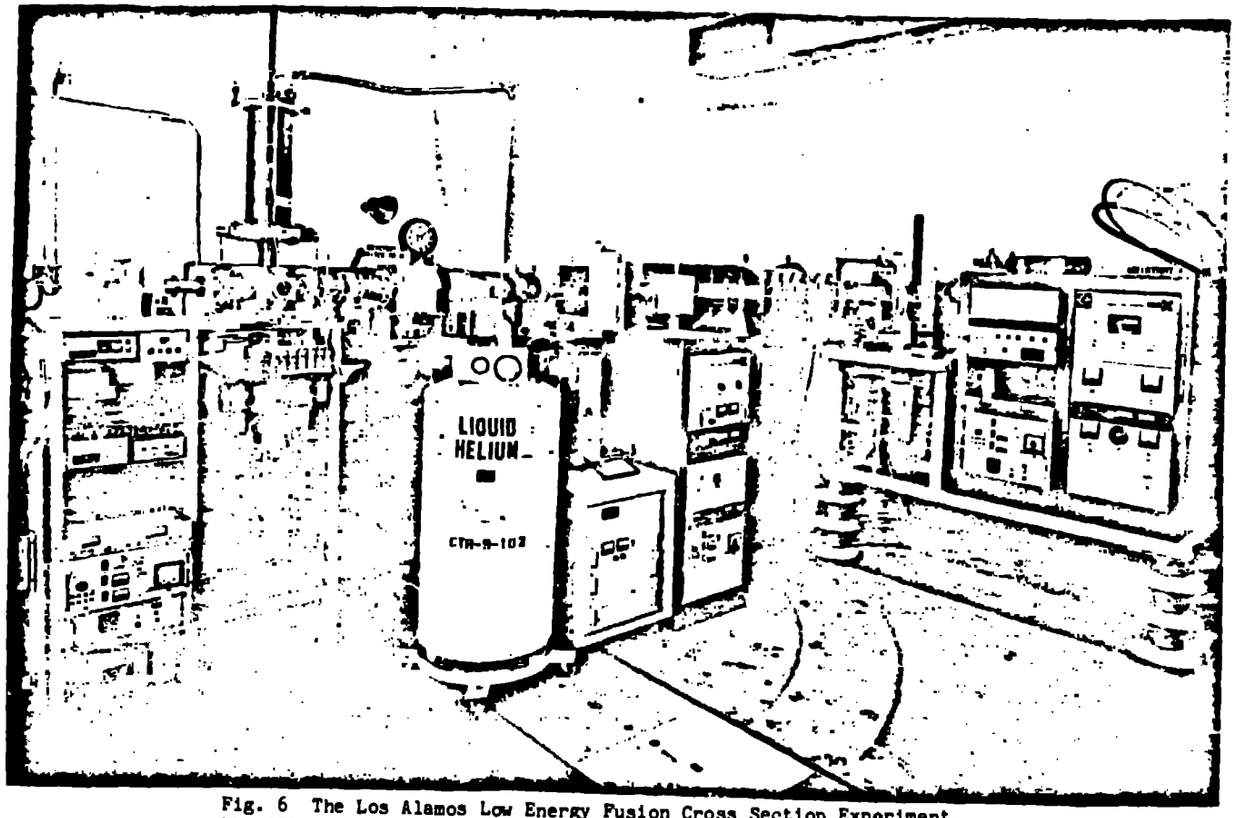

Fig. 6 The Los Alamos Low Energy Fusion Cross Section Experiment. The 120 keV ion source is on the right; the partially disassembled target at the left. The tandem beam line is hidden.

12. Sawyer and Phillips, Los Alamos, LA-1578 (1953).

13. A. J. Elwyn, R. E. Holland, C. N. Davids, L. Meyer-Schutzmeister, and F. P. Mooring, Phys. Rev. to be published. See also Bull. Amer. Phys. Soc. 23, 97 (1978).

14. O. Fiedler and P. Kunze, Nucl. Phys. A96, 513 (1967).

15. W. Gemeinhardt, D. Kamke and Chr. von Rhoneck, Zeit. fur Physik 197, 58 (1966).

16. A. M. Govorov, Li Ka-Yeng, G. M. Osetinskii, V. I. Salatskii, and I. V. Sizer, Sov. Phys. JETP 15, 265 (1962).

17. H. M. Agnew, W. T. Leland, H. V. Argo, R. W. Crews, A. H. Hemmendinger, W. E. Scott, and R. F. Taschek, Phys. Rev. 84, 862 (1951).

18. Yu. V. Strel'nikov, S. N. Abramovich, L. A. Morkin, N. D. Yur'eva, Bull. Acad. Sci. USSR Ser. hys. (Isvestia) 35, 149 (1971).

19. V. I. Serov, S. N. Abramovich, and L. A. Morkin, Sov. J. of Atomic Energy 42, 66 (1977).

20. Nat. Nuclear Data Center, Brookhaven Nat. Lab. Data Base CSISRS (EXFOR) #A0007, 770825.

21. A. M. Govorov et al., Sov. Phys.-JETP 14, 508 (1962).

22. S. J. Rame, Jr., and W. T. Leland, Phys. Rev. 106, 1257 (1957).

23. C. Wong, J. D. Anderson, and J. W. McClure, Nucl. Phys. 71, 106 (1965).

24. R. Larose-Poutissou, and H. Jeremie, Nucl. Physics A218, 559 (1974).

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

26. B. H. Duane, in Pacific Northwest Laboratory Report on Controlled Thermonuclear Reactor Technology-1972. W. C. Wolkenhauer, Ed., Battelle Northwest Laboratory report BNWL-1685 (November 1972) p. 75.

27. G. M. Hale, P. G. Young, and N. Jarmie, Los Alamos Scientific Laboratory, Private Communication; see also G. M. Hale, this conference.

28. R. B. Theus, W. I. McGarry, and L. A. Beach, Nucl. Phys. 80, 273 (1966).

29. K. G. McNeill, Phil. Mag 46, 800 (1955).

30. C. Thomann and J. E. Benn, Nuc. Instr. & Methods 138, 293 (1976).

31. G. G. Ohlsen et al., Bull. Amer. Phys. Soc. 24, 822 (1979).