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CHARGED-PARTICLE CROSS SECTION DATA
FOR FUSION PLASMA APPLICATIONS

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ABSTRACT

Cross-section data for fusion plasma calculations are reviewed for three categories: fusion reactions, nuclear elastic and inelastic scattering. While the data base for the basic D-T fuel cycle seems adequate for present purposes, continued refinement appears warranted. Further, increasing emphasis on advanced-fuel fusion introduces requirements for new reaction rate and charged-particle scattering data over a wider range of reacting species (light elements through ¹¹⁸B) and over a larger energy range (to several MeV). These new needs are discussed along with suggestions for increased emphasis on providing the user with more convenient compilations. In particular, the extension of reactivities ($\langle\sigma v\rangle$) to non-Maxwellian distributions, scattering matrix data, and development of computer based files are noted.

INTRODUCTION

Charged-particle cross section data are important to four aspects of fusion studies: plasma energetics, beam stopping in inertial confinement targets, first wall erosion, and radiation interactions in blanket materials. The latter three areas involve charged-particle interactions with solids. This will not be considered in any detail in the present review which concentrates on data needs for fusion plasma calculations.

To date D-T fusion has achieved almost exclusive attention in fusion research. Consequently, data needs seemed quite straightforward, dealing with D-T fusion reactions, slowing down of the resulting fusion product (3.5-MeV alpha) and, to some extent, parasitic D-D fusion reactions. Recently, however, there has been a growing interest in "advanced" or "alternate" fusion fuels which

would eliminate the need for tritium breeding and reduce induced radioactivity and materials damage problems associated with large neutron fluxes.[1-5]

The advent of the advanced fuels (AFs) has greatly increased the data needs for fusion studies. As outlined in Table I, these fuels can be broadly separated into two groups: (1) deuterium (D)-based, and (2) proton (p)-based. In addition to introducing a multitude of new reaction species, some AF reactions result in fusion products that are at a higher energy than the 3.5-MeV alpha from D-T fusion, e.g., the D-³He reaction yields a 14.7-MeV proton while a multitude of energetic charged particles are involved in the chain reactions that occur in a p-⁶Li plasma. Since AF fusion represents an important new direction in fusion research, the associated data needs will receive special attention here.

GENERAL REQUIREMENTS

Data required for fusion plasma calculations are outlined in Table II. In the present review we will concentrate on fusion reactions (fusion reactivities) and high-energy scattering (including Coulombic and nuclear collisions associated with the slowing down of energetic particles in plasmas). While charge-exchange and ionization reactions also play a crucial role in many plasma calculations, these data are generally classified under atomic data[6].

Broadly speaking, fusion cross section activities can be divided into four general categories: basic measurements, evaluation, interpolation/extrapolation, and tabulation (Fig. 1). Experiments result in microscopic cross sections, hopefully including data on differential angular and energy distributions. Evaluation of these data should not only involve a comparison of independent experiments but also a comparison of experimental vs. theoretical predictions. While such evaluations have attained a fairly sophisticated level in other fields such as neutronics, there remains a noticeable lack of critical reviews in areas of interest for fusion.

It is generally desirable to have reaction cross-sections cover an energy range up to 5 or 6 kT where T is the background plasma temperature. Since advanced fuels may burn at ion temperatures of 400 or 500 keV, this implies a data range to ~ 3 MeV. Of course, data for interactions involving fusion products during slowing must extend to their birth energy, e.g., up to 14 MeV for the D-³He proton. In view of other uncertainties in plasma calculations, an accuracy better than 20-30% does not generally seem warranted. However, as the field continues to mature, continued refinement of the data base is highly desirable.

Tabulation and reduction of fusion cross section data is complicated by the variety of averages that are of interest. As indicated in Table II, the user may have need for speed-averaged fusion reaction data for various ion distributions (Maxwellian, mirror loss-cone, etc.) in addition to data related to charged-particle slowing in plasmas.

1) Fusion Reactivities

As the name *thermonuclear* fusion implies, fusion confinement concepts frequently involve reactions between ions comprising Maxwellian velocity distributions. Thus the "reactivity" $\langle\sigma v\rangle$, required to calculate the reaction rate R between species 1 and 2

$$R \equiv n_1 n_2 \langle\sigma v\rangle, \quad (1)$$

most commonly assumes a Maxwellian distribution. This average, $\langle\sigma v\rangle_m$, is defined as

$$\langle\sigma v\rangle_m = \frac{4}{(2\pi m_i)^{1/2}} \left(\frac{\mu}{m_i kT}\right)^{3/2} \int_0^\infty dE \, E \, \sigma(E) \exp\left(-\frac{\mu E}{m_i kT}\right), \quad (2)$$

where T = the temperature of both species

m_i = mass of an ion of species i

μ = reduced mass of the two fusing ions.

This form for $\langle\sigma v\rangle_m$ assumes that both ion distributions can be assigned the same temperature T .

Several variations of the basic Maxwellian "reactivities" are of interest in particular projects. For example, in some confinement concepts fusion largely occurs by interaction of an energetic ion beam with a target plasma. The TFTR "breakeven" experiment at Princeton is an example. Corresponding calculations typically assume an isotropic angular distribution for the ion beam and a Maxwellian distribution for the background or target plasma ions. Then the appropriate averaged reactivity for the beam ions at speed v_b is

$$\langle\sigma v\rangle_b = \frac{\beta}{\sqrt{\pi}} \frac{1}{v_0} \int_0^\infty \sigma\left(\frac{1}{2} m_1 v^2\right) v^2 \left\{ \exp[-\beta^2(v_0 - v)^2] - \exp[-\beta^2(v_0 + v)^2] \right\} dv, \quad (3)$$

where the various quantities are

$$\beta^2 = \frac{m_2}{2kT}$$

v_0 = velocity of injected particle

m_2 = mass of background particle

m_1 = mass of incident particle.

Note that in order to employ $\langle \sigma v \rangle_b$ in a practical case, the user must still integrate over the speed distribution corresponding to slowing down $f_b(v_0)$ of the incident beam; that is, an integration $\int dv_0 f_b(v_0) \langle \sigma v \rangle_b$ remains while evaluation of $f_b(v_0)$ requires a knowledge of the particular fusion concept involved.

Graphical and tabular presentations for $\langle \sigma v \rangle_m$ are available in various reports [7-11] while $\langle \sigma v \rangle_b$ is presented in Ref. 7. The reactions included in the most recent compilation by Howerton[11] are indicated in Table III, along with information about the base data used for the averaging.

In a mirror reactor, instead of a Maxwellian, the ions assume a loss-cone distribution.[12] Essentially this distribution corresponds to a Maxwellian with a void in the region of velocity space where ions escape through the loss cone (Fig. 2). To date, however, workers in mirror research and also in other areas where the deviation from a Maxwellian are not too severe have ignored these effects and used $\langle \sigma v \rangle_m$ in calculations. The reason is simply that other uncertainties in the analysis have been too large to warrant the added detail in $\langle \sigma v \rangle$. However, it appears to the author that we are now rapidly approaching an era where the added accuracy will be desired and important. Indeed, this will pose a new challenge for those carrying out tabulations; namely $\langle \sigma v \rangle$ tables should be enlarged to handle more cases.

If carried to the extreme, however, such tabulations could become unwieldy. The alternative of leaving the averaging to the user doesn't seem practical either. Thus, a conscious effort, involving both tabulators and users, should be undertaken to develop a list of generic distribution functions other than Maxwellian for use in future tables. An alternate approach is to develop utility processing routines that can be employed by the user to carry out the averaging over an arbitrary distribution.

2) Fast Fusion Probabilities

As noted above, integration of beam-target reactivities over the slowing down distribution of the incident beam gives the fusion rate during slowing. This is commonly expressed in terms of the fast fusion probability p_{ij} for ion j slowing in a background plasma of species i . Thus,

$$p_{ij} = 1 - \exp(-p'_{ij}) \quad (4a)$$

where

$$p'_{ij} = \int_{E_{oj}}^{3/2T_i} n_i \langle \sigma v(E) \rangle_{ij} (dt/dE)_j dE \quad (4b)$$

the energy loss rate for ion j in the plasma, $(dE/dt)_j$, is a strong function of the plasma electron temperature T_e . For example, an approximate relation assuming only Coulomb scattering is:

$$\left(\frac{dE}{dt}\right)_j \sim - \frac{4\pi e^4 \ln \Lambda}{v_j} \left[\frac{n_i}{n_i} + \frac{4}{3\sqrt{\pi}} \frac{n_e}{m_e} \left(\frac{m_e T_e}{m_j} \right)^{3/2} \right], \quad (5)$$

where the quantity $\ln \Lambda$ is about 20 for typical magnetic plasmas and about 10 for the denser inertial confinement plasmas. Assuming, as implied earlier, a plasma with $Z = 1$ and $n_i = n_e$, we have $(dE/dt)_j \propto n_i$. Consequently, the integral in Eq. (4b) turns out to be independent of target density.

An illustration of the fast fusion probability for energetic protons slowing down in a ${}^6\text{Li}$ plasma is shown in Fig. 3 for E_e ranging from 100 keV to 300 keV. If, for example, the proton occurs by a ${}^3\text{He}-{}^6\text{Li}$ reaction, it would have a birth energy of ~ 11 MeV. From Fig. 3, this proton would have a 5% probability of fusing while slowing in a 100-keV ${}^6\text{Li}$ plasma. At higher electron temperatures the slowing down time is increased so that in this example, if $T_e = 300$ keV, the probability increases to $\sim 21\%$.

3) Scattering Cross Sections Data

The slowing down of energetic fusion products in a plasma becomes increasingly important as the achievement of a "fusion grade" plasma becomes closer. As indicated in Table II, three types of "scattering" data are required: Coulombic, nuclear elastic, and nuclear inelastic. Coulombic interactions are typically treated analytically, leaving the main data needs to nuclear scattering.[13-18] The latter are particularly important for AF plasmas, and this has resulted in an increasing effort to generate nuclear elastic data in the past few years. However, virtually no data exist in the key area of nuclear inelastic scattering in a regime of interest to fusion systems.

4) Theoretical Methods

Fairly comprehensive reaction R-matrix analyses of select fusion reactions have been carried out and continued studies are in progress.[19-22] Results have been presented for $T(d,n)$, $D(d,n)$, $D(d,p)$, $T(t,2n)$ and ${}^6\text{Li}(p,{}^3\text{He})$ reactions. Future extensions to nuclear elastic scattering are planned. As pointed out by G. Hale,[19] R-matrix theory provides a framework for fitting and extrapolating cross sections whereby both long-range effects (like penetration of the Coulomb-angular momentum barrier) and short-range (nuclear) effects arise in a simple and physically meaningful way. Moreover, the interaction of these effects in the theory generally leads to a different energy dependence for the low-

energy cross sections than that obtained from the representations of fusion cross sections commonly used. Indeed, there are indications from $T(d,n)$ and $T(t,2n)$ comparisons that the R-matrix dependence is more nearly correct.[19,20]

At higher energies, the reactions appear to be dominated by broad, overlapping structures, a few of which appear as definite bumps in the integrated cross sections. These structures can be associated with definite R-matrix levels, however, with the help of angular distribution measurements, particularly those for polarization observables. Use of all the available experimental data in these analyses offers statistical advantages, especially in cases where direct measurements of the cross sections are conflicting or incomplete. In those cases, this may even allow a resolution of the difficulties.

The use of R-matrix calculations then appears as a valuable technique for interpretation, extension, and evaluation of fusion data. In principle such calculations can yield a unified cross-section data set in which both nuclear elastic scattering and reaction cross sections are calculated from the same R-matrix parameters. Such calculations should provide a most valuable aid as evaluators attempt to further resolve and refine fusion cross section data.

FUSION REACTION AND SCATTERING DATA

In the following sections we will consider reaction and scattering data in more detail, outlining sources of available information and indicating some serious gaps in the data.

1) Reaction Data

The recent review of fusion reaction data for fusion applications by G. Shuy[4] is relied on here heavily. A summary of reaction data is presented in Table IV where it is observed that a majority of the measurements for relevant reactions contain relatively large uncertainties. This is clearly an unsatisfactory situation as the search for attractive AF systems continues. On the other hand, the situation for select key reactions is not so serious. These include:

a) D-T, D-D, and D-³He reactions

While there has only been one measurement of the basic D-T reaction:[4]

since 1960, the integral data seem adequate from 0.01 to 15 MeV. However, as noted by Shuy [4], discrepancies in angular distributions exist above 5 MeV. These data could eventually become important and consequently deserve more attention. Further, due to the vital role of D-T in fusion, it would seem prudent to remeasure this reaction over the entire energy range in order to reduce the existing 10-20% uncertainty.

Measurements for the two D-D reactions

have been evaluated by Liskien and Paulsen [23] for the range of 0.013 to 10 MeV. Results appear adequate for fusion uses at this time.

The D-³He reaction,

has received no measurements since 1960. A fairly large uncertainty (25-35%) exists in the neighborhood of the 430 keV resonance. In view of its key position as an AF, this question deserves attention. Hale's review [19] suggests, however, that integral data is reasonably good up to 15 MeV.

b) p-Based Reactions

Considerable uncertainty exists for many of the multitude of p-based reactions. Two key fuel cycles that are of particular interest as candidates for almost "neutronless" fuels are p-⁶Li and p-¹¹B. The fact that these fuels can approach ignition[4] makes them especially attractive.

As indicated in Table V, a p-⁶Li fusion plasma would involve a number of reactions in addition to the basic reaction:

Recent measurements of the latter reaction by Elwyn[24] over the range 0.14-3 MeV appear fairly definitive, but as summarized in Table VI, many of the other p-⁶Li plasma reactions need careful attention. Indeed, recent measurements of the key ³He-⁶Li reaction[25] indicate that this cross section (with all decay channels included) is

lower than originally estimated. The result is that ignition of $p\text{-}^6\text{Li}$ for T_i below ~ 500 keV is now in doubt.[4]

Uncertainties in the $p\text{-}^{11}\text{B}$ reaction

drew strong attention in recent years as interest grew in this nearly ideal "neutronless" fusion fuel. The recent measurement by Davidson[26] over the range 0.08-1.4 MeV resolved some of the questions, although uncertainties in the region of higher lying resonances (7 pronounced resonances are observed up to 5 MeV) require more attention.

In addition to reaction cross sections (10), evaluation of parasitic gamma and neutron production requires, as indicated in Fig. 4, data for other reactions such as ^{11}C branching ratio and $^{11}\text{B}\text{-}^{11}\text{B}$ reactions. Norbeck[27] has reported recent measures of these cross sections. Indeed, as shown in Fig. 4, the corresponding reactivities are several orders of magnitude lower than for $p\text{-}^{11}\text{B}$ itself. Still, this is important since even low levels of radioactivity must be considered in evaluating this nearly ideal fuel.

2) Nuclear Elastic Scattering

As pointed out earlier, nuclear elastic scattering can become an especially important mechanism in AF plasmas due to the combination of high electron temperature and more energetic fusion products. (See, for example, Fig. 5.) In that case, hard collisions between energetic (MeV) fusion products and fuel plasma ions can "knock-up" the latter to relatively high energies, causing a bump on the tail of the otherwise Maxwellian ion distribution. Since ions in the tail of the distribution are major contributors to fusion reactions, this "bump" can result in an important enhancement in fusion reactivities, i.e., fusion rates. For example, the ratio of $\langle\sigma v\rangle_{\text{eff}}$ calculated for $p\text{-}^{11}\text{B}$ reactions including this effect normalized by the normal Maxwellian $\langle\sigma v\rangle$ is shown in Fig. 6. This result has led Shuy[4] to predict ignition against Bremsstrahlung losses is possible for $p\text{-}^{11}\text{B}$ with $T_i \sim 250$ keV and $T_e \sim 150$ keV.

Similar enhancements in $\langle\sigma v\rangle$ have been noted for D-D and D- ^3He plasmas. As illustrated in Table VII, in D-D and catalyzed-D plasmas, a variety of energetic

fusion products can undergo nuclear elastic effects. The tritium and ^3He can also undergo fast fusion events during slowing, although this contribution to fusion is generally small compared to fusion reactions that occur after they thermalize. As shown in Fig. 7, when "knock-up" ions due to nuclear elastic scattering are included, the reactivity is increased by $\sim 20\%$ at $T_i \sim 40$ keV where ignition occurs for catalyzed-D fusion.

As outlined in Table VIII, based on Shuy's review[4], data on nuclear elastic scattering is generally available for reactions through ^3He - ^3He . However, there are significant gaps in data involving heavier elements.

The most comprehensive data bank for nuclear elastic scattering is that compiled by Perkins and Cullen[13]. They have considered the 25 projectile-target combinations of the particles, p, D, T, ^3He , and α , based on data from about 100 references (the differential cross section data used were sent to the National Nuclear Data Center at BNL and are available from that center). They obtained nuclear (plus interference) elastic cross sections from these data by subtracting out calculated Coulombic interaction contributions. Results are presented for the following quantities integrated over the center-of-mass scattering cosine: reaction rate, average fractional energy loss per collision, average fractional energy loss per unit path length, and average laboratory scattering cosine. A typical plot of these results is shown in Fig. 8 for an alpha particle impinging on a tritium target. (This particular case has a sharp peak at an α energy of ~ 5 MeV while the behavior of other projectile-target combinations may be more or less smooth.

A basic problem encountered in the treatment of the nuclear elastic data is that the differential cross section $d\sigma/d\Omega_{\text{NE}}$ (including interferences) exhibits poles at the extreme scattering cosine (η) values, hence is nonintegrable. Consequently, Perkins and Cullen, in their analysis, define a new cross section:

$$\left(\frac{d\sigma}{d\Omega}\right)_E \equiv (1-\eta) \left(\frac{d\sigma}{d\Omega}\right)_{\text{NE}}, \quad (11a)$$

$$\text{where } \eta = \begin{cases} \geq 0 & \text{for like particles} \\ \geq -1 & \text{for unlike particles.} \end{cases} \quad (11b)$$

which is integrable over the entire range of interest. Then, the various quantities of interest can be obtained by direct integration. For example, the average energy loss per unit path length, $dE(E)/dx$, is simply:

$$\frac{1}{n_1} \frac{1}{E} \frac{dE(E)}{dx} = \frac{4\pi A_1 A_2}{(A_1 + A_2)^2} \int_{n_1}^{n_2} \left(\frac{d\sigma}{d\Omega} \right)_E d\Omega \quad (12)$$

where n_1 is the target-ion number density, A_1 is the atomic mass of the projectile of energy E incident on a stationary target of atomic mass A_2 and $n_1 = -1$ for unlike particles, $n_1 = 0$ for like particles, and $n_2 = 1$.

Likewise, the average fractional energy loss per collision is:

$$\frac{D(E)}{E} = \frac{4\pi A_1 A_2}{(A_1 + A_2)^2} = \frac{1}{\sigma_{NE}(E)} \int_{n_1}^{n_2} \left(\frac{d\sigma}{d\Omega} \right)_E d\Omega \quad (13)$$

where σ_{NE} is the total nuclear elastic (plus interference) cross section defined by

$$\sigma_{NE}(E) = 2\pi \int_{n_1}^{n_2} \frac{1}{(1-\eta)} \left(\frac{d\sigma}{d\Omega} \right)_E d\Omega, \quad (14a)$$

$$n_2 \equiv \max(n_+, n_{C0}) \quad (14b)$$

Here n_{C0} , representing the boundary between large-angle and small-angle scattering, is taken as $\sim 20^\circ$ (c.m. angle). The cosine n_+ corresponds to the point where the cross section (including interference effects) goes through zero. Indeed, for most cases $n_+ \sim n_{C0}$.

Expressions for the reaction rate and average laboratory scattering cosine can be derived in similar fashion (see Ref. 13).

As pointed out by Perkins and Cullen[13], results such as presented in Fig. 8 can be used to correct energy loss rates due to Coulomb scattering, or in more exact transport calculations, to account for large-angle nuclear scattering. A problem discussed later is that present trends in these calculations involve use of scattering matrix techniques, and convenient data forms are desirable for such approaches.

3) Nuclear Inelastic Scattering

Energetic ions from AF reactions can, in addition to nuclear elastic scattering, excite nuclear levels, losing energy by inelastic scattering. For example, for the 14-MeV proton from D-³He slowing against deuterium, the inelastic cross section is ~ 0.15 barns vs. ~0.65 barns for elastic events.[28] Thus, while inelastic scattering does not appear to be a dominant effect, it could be significant, especially in some AF cases where ignition is marginal.

Thus far, however, inelastic scattering has not been included in any burn calculations that the author knows of, nor does an adequate data base exist. Consequently, this represents an important area for future work.

DATA REDUCTION

To understand the type of data required for fusion plasma calculations, we review the typical AF burn code flow chart of Fig. 9. Basically this program requires reactivity data (as a function of ion temperature T_i), both nuclear elastic and inelastic scattering data, and fast fusion probabilities. AF codes now being developed typically use a multigroup energy approach to handle the variety of particles, interactions, and large energy range involved. Consequently, a format consistent with such an approach should be one of the options available from data banks.

Most calculations for magnetic confinement studies have been centralized on the computers available at the National Magnetic Fusion Energy Computer Center (NMFECC) at LLL. Future data compilations could take advantage of this by making files available through this center. (Alternate access would still be necessary since a few users and the ICF community do not yet use the NMFECC facilities.)

To date most data have been distributed through reports and a standard format has not been developed. Consequently, this appears to be an opportune time for compilers, evaluators, and users to set up guidelines for development of a national data bank and format for fusion applications.

CONCLUSIONS

Based on the review presented here, we conclude that:

- The existing data for the basic fusion fuel cycles are "adequate" for present calculations, but should be improved as the field matures.
- The growing interest in AF fuel introduces new needs due to gaps in both reaction rate and scattering cross sections for the variety of ion species and energy range of interest.
- Evaluations of the accuracy of charged-particle cross sections in the regime of interest to fusion have been "sparse" to date and should be intensified in the future.
- Thus far no attempt has been made to develop a guideline for presentation of data in a form that is most convenient to workers doing plasma calculations. The use of the NMFECC computer for files appears as an important opportunity in this respect. The variety of data and various averaged quantities of interest require careful consideration by both compilers and users.

In summary, the opportunity to establish a national data bank in the rapidly growing area of charged-particle cross sections for fusion represents an exciting challenge for the nuclear data community.

REFERENCES

1. G. H. MILEY, Fusion Energy Conversion, Am. Nuclear Society, LaGrange, Illinois (1976).
2. G. H. MILEY, "Status and Prospects for Advanced-Fuel Fusion," IASTED International Symposia on Modelling, Policy and Decision in Energy Systems, Montreal, Canada, May 28-30, 1980.
3. J. R. McNALLY, JR. and K. C. ROTHE, "Advanced Fusion Fuels - A Review," Second Int'l Conf. Emerging Nuclear Energy Systems, Lausanne, Switzerland, April 1980.
4. G. W. SHUY, "Advanced Fusion Fuel Cycles and Fusion Reaction Kinetics," Report UWFD-335, U of Wisc., Madison, Wisc, Dec. 1979.

5. R. CONN, et al., "Alternate Fusion Cycle Research," IAEA-CN-38/V5, 1980.
6. C. F. BARNETT, W. B. GAUSTER, and J. A. RAY, "Atomic and Molecular Collision Cross Sections of Interest in Controlled Thermonuclear Research," Report ORNL-3113, Oak Ridge National Laboratory, Oak Ridge, TN.
7. G. H. MILEY, et al., "Fusion Cross Sections and Reactivities," Report COO-2218-17, U of Illinois, Urbana, IL (June 1974).
8. B. H. DUANE, "Fusion Cross Section Theory," BNWL-1685, Battelle Northwest Laboratories, (1972).
9. N. JARMIE and R. SEAGRAVE (eds.), "Charged Particle Cross Sections," LA-2014, Los Alamos Scientific Laboratory (1957).
10. S. L. GREEN, "Maxwell-Averaged Cross Sections for Some Thermonuclear Reactions on Light Isotopes," UCRL-70522 (1967).
11. R. J. HOWERTON, "Maxwell-Averaged Reaction Rates $\langle\sigma v\rangle$ for Selected Reactions between Ions with Atomic Mass ≤ 11 ," Report UCRL-50400, Vol. 21, Pt. A, Lawrence Livermore Laboratory, Feb. 1979.
12. B. I. COHEN (ed.), "Status of Mirror Fusion Research 1980," UCAR 10049-80, Lawrence Livermore Laboratory (1980).
13. S. T. PERKINS and D. E. CULLEN, "Elastic Nuclear (Plus Interference) Cross Sections for Light Charged Particles," UCRL-83468, Lawrence Livermore Laboratory (January 1980).
14. D. E. CULLEN and S. T. PERKINS, "Multigroup Constants for Charged Particle Elastic Nuclear (plus Interference) Scattering of Light Isotopes," Lawrence Livermore Laboratory, Livermore, CA, UCID-17564 (1977).
15. S. T. PERKINS, "NSCAT - A Code to Obtain Charged Particle Nuclear (plus Interference) Differential Scattering Cross Sections from Experimental Data," Lawrence Livermore Laboratory, Livermore, CA, UCID-17608 (1977).
16. D. E. CULLEN and S. T. PERKINS, "Elastic Nuclear (plus Interference) Cross Sections for Light Charged Particles, Tables and Plots," to be published, Lawrence Livermore Laboratory, Livermore, CA (1980).
17. J. E. DEVANEY and M. L. STEIN, "Energy Loss by Nuclear Elastic Scattering," Nucl. Sci. Eng., 46, 323 (1971).

18. E. GREENSPAN, "Large Energy Transfer Reactions in Ion Slowing Problems," MATT-1235, Princeton Plasma Physics Laboratory (May 1976).
19. G. M. HALE and D. C. DODDER, "R-Matrix Analysis of Light-Element Reactions for Fusion Applications," LA-UR 79-2896, Los Alamos Scientific Laboratory (1979). Also see Int. Conf. on Nuclear Cross Sections for Technology, Knoxville, TN (Oct. 1979).
20. G. M. HALE, "R-Matrix Analysis of the Light Element Standards," NBS Special Publication 425, p. 302 (1975).
21. D. C. DODDER, et al., "Models Based on Multichannel R-Matrix Theory," JAERI-M 5984, p. 1 (1975).
22. G. M. HALE, "R-Matrix Methods for Light Systems," IAEA-90, Vol II, p. 1 (1976).
23. H. LISKIEN and A. PAULSEN, "An Evaluation for Cross Sections of the Reactions $T(D,n)^4\text{He}$, $D(D,n)^3\text{He}$ and $D(D,p)^3\text{H}$," Report EANDC(E)-144 "L", 1972.
24. A. ELWYN, R. E. HOLLAND, C. N. DAVIDS, L. MEYER-SCHUTZMEISTER, F. P. MOORING, and W. RAY, JR., "Cross Sections for the $^6\text{Li}(p,^3\text{He})^4\text{He}$ Reaction at Energies Between 0.1 and 3.0 MeV," Phys. Rev., C20, 1984 (1979).
25. A. ELWYN, et al., "Cross Sections for the $^6\text{Li}(^3\text{He},p)$ Reaction at Energies Below 2 MeV," submitted to Phys. Rev. (1980).
26. J. DAVIDSON, H. L. BERG, and M. M. LOWRY, "Low Energy Cross Sections for $p\text{-}^{11}\text{B}(p,3\alpha)$," Report LAP-165, Calif. Institute of Technology, Pasadena, CA (1978).
27. E. NORBECK, "Neutrons from $^{11}\text{B} + ^{11}\text{B}$ Compared with Other Sources of Neutrons from an $^{11}\text{B} + p$ Burn," Report 80-32, Univ. of Iowa, August 1980.
28. R. FRANK and J. GAMMEL, "Inelastic Scattering of Protons and Neutrons by Deuterons," Phys. Rev., 93, 463 (1954).

Table I
Some Key Advanced Fuel Reactions

<u>CONVENTIONAL D-T</u>		Q_F, MeV	f_c
$D + T \rightarrow n + \alpha$		17.6	0.2
<u>Advanced</u>			
Prime	$\left\{ \begin{array}{ll} \underline{D-D} & D+D \begin{cases} \nearrow n + {}^3\text{He} \\ \searrow p + T \end{cases} \\ \underline{D-{}^3\text{He}} & D + {}^3\text{He} \rightarrow \alpha + p \\ \underline{\text{CAT-D}} & \text{Burn product T \& } {}^3\text{He} \\ & \text{in situ} \end{array} \right.$	3.6	0.33
		18.3	1.0
		21.6	0.62
Exotic	$\left\{ \begin{array}{ll} \left\{ \begin{array}{l} p \\ D \end{array} \right\} + {}^6\text{Li} & \left\{ \begin{array}{l} p \\ D \end{array} \right\} + {}^6\text{Li} \rightarrow \left\{ \begin{array}{l} \alpha + {}^3\text{He} \\ p + {}^7\text{Li} + \dots \end{array} \right. \\ p + {}^{11}\text{B} & p + {}^{11}\text{B} \rightarrow 3\alpha \end{array} \right.$	<5.0	~0.9
		8.7	1.0

Note Q_F : total fusion energy released f_c : fraction of energy to charged particles

TABLE II
Data Requirements

Discussed here	<u>Fusion Cross Sections</u>	σ_f
	Reactivities (Maxwellian)	$\langle \sigma v \rangle_m$
	Beam-Target (Maxwellian Target)	$\langle \sigma v \rangle_b$
	Specialized Reactivities (j: non-Maxwellian distribution)	$\langle \sigma v \rangle_j$
	<u>High-Energy Scattering</u>	
	Coulombic	σ_s
	Nuclear Elastic	σ_{SE}
	Nuclear Inelastic	σ_{SI}

Charge-Exchange σ_{C-X}

Ionization σ_I

TABLE III

Evaluated Charged Particle Induced Reactions in
The LLL Evaluated Charged Particle Library (ECPL). Ref. 11

<u>Reaction</u>	<u>Q-Value (MeV)</u>	<u>Range (MeV)</u>	<u>Properties</u>
$D(d,n)^3\text{He}$	3.37	.001-20.	c/s, ang. dist. of n
$D(t,n)^4\text{He}$	17.59	.001-20.	c/s
$D(d,p)T$	4.034	.001-20	c/s
$T(p,n)^3\text{He}$	- 0.764	1.025-20.	c/s, ang. dist. of n
$T(d,n)^4\text{He}$	17.59	.001-20.	c/s, ang. dist. of n
$^3\text{He}(d,p)T$	18.354	.005-20.	c/s, ang. dist. of p
$^6\text{Li}(d,n)^7\text{Be}$	3.382	.001-20.	c/s
$^6\text{Li}(t,2n)^7\text{Be}$	- 2.87	4.31 -20.	c/s
$^6\text{Li}(d,p)^7\text{Li}$	5.027	.001-20.	c/s
$^6\text{Li}(\text{He}^3,d)$	0.11	.2 -20.	c/s
$^6\text{Li}(d,p+t)^4\text{He}$	2.558	.001-20.	c/s
$^6\text{Li}(d,^4\text{He})^4\text{He}$	22.374	.001-20.	c/s
$^7\text{Li}(p,n)^7\text{Be}$	- 1.64	1.88 -20.	c/s
$^7\text{Li}(p,2n)^7\text{Be}$	- 3.86	4.97 -20.	c/s
$^7\text{Li}(t,3n)^7\text{Be}$	-10.13	14.47 -20.	c/s
$^7\text{Li}(^3\text{He},t)^7\text{Be}$	- 0.88	1.25 -20.	c/s
$^{10}\text{B}(d,n)^{11}\text{C}$	6.47	.001-20.	c/s
$^{10}\text{B}(d,p)^{11}\text{B}$	9.23	.1 -20.	c/s
$^{10}\text{B}(p,^3\text{He}+2^4\text{He})$	- 0.44	.484-20.	c/s
$^{10}\text{B}(p,^4\text{He})^7\text{Be}$	1.15	.1 -20.	c/s
$^{10}\text{B}(d,3^4\text{He})$	17.914	.001-20.	c/s
$^{11}\text{B}(p,n)^{11}\text{C}$	- 2.77	3.02 -20.	c/s
$^{11}\text{B}(d,n)^{12}\text{C}$	13.73	.001-20.	c/s
$^{11}\text{B}(d,p)^{12}\text{B}$	1.14	.1 -20.	c/s
$^{11}\text{B}(p,3^4\text{He})$	8.683	.068-20.	c/s

TABLE IV

Overview of Fusion Reaction Data

	D	T	^3He	p
D	0.013-14 [†] (50-90)*	/	/	-
T	0.01 -15 (94-112,	0.04-2.2 (143-146)	/	1.1 -10 (31-45)
^3He	0.25-15 (117-125)	.15-1.9 (149-154)	0.06-2.2 (159-163)	-
^6Li	0.1 -1.0 (213-225)	0.3- 20 ^x (226-230)	1.2 -4.2 ^x (232-245)	0.14-12 (197-210)
^7Li	0.6 -2.6 ^x (287-300)	0.23-2.5 ^x (301-310)	0.8 -6.0 ^x (312-325)	0.8 -15 ^x (255-285)
^7Be	0.8 -1.7 ^x (331-332)	None ^x	None ^x	- ^x
^9Be	0.15-19 (351-370)	0.52-2.1 (371-372)	1.6-20 ^x (376-380)	0.028-2.0 (341-345)
^{10}B	0.14-12 ^x (394-415)	0.8-2.0 ^x (416)	2.0-19 ^x (424-430)	0.06-6.3 ^x (388-390)
^{11}B	0.3 -10 ^x (441-453)	1.0-2.1 ^x (454,455)	0.9-18 ^x (456-460)	0.17-10 ^x (434-440)

Based on data in Ref. 4.

[†]Energy range of measurements, MeV

*Reference numbers (keyed to listing in Ref. 4)

^xMeasurements insufficient and/or inconsistent

TABLE V

Summary of Key Reactions for the p-⁶Li Fuel CyclePrimary Secondary and Tertiary Reactions Other Reactions: over 30 side

reactions plus thirteen ⁶Li + ⁶Li
exothermic reactions

TABLE VI

Key Cross-Section Requirements for the p-⁶Li Reactor

REACTION	REASON FOR IMPORTANCE	ADEQUATE X-SECTION DATA
$^3\text{He} + ^6\text{Li} \rightarrow \text{d} + ^7\text{Be}$	A,B,	INCOMPLETE
$^3\text{He} + ^6\text{Li} \rightarrow \text{n} + ^8\text{Be}$	B	INCOMPLETE
$^3\text{He} + ^6\text{Li} \rightarrow \text{p} + 2\text{n}$	A,C,D	INCOMPLETE
$^6\text{Li} + ^6\text{Li} \rightarrow \text{p} + \alpha + ^7\text{Li}$	A,C,D	NO
" $\rightarrow ^3\text{He} + ^9\text{Be}$	A	NO
" $\rightarrow 2\text{p} + ^{10}\text{Be}$	A,B,C,D	NO
" $\rightarrow \text{n} + ^3\text{He} + 2\alpha$	A,B	NO
$\text{d} + ^7\text{Be} \rightarrow \text{p} + 2\alpha$	A,C,D	NO
$^3\text{He} + ^7\text{Be} \rightarrow 2\text{p} + 2\alpha$	A,C,D	NO
$\bar{\alpha} + ^3\text{He} \rightarrow \alpha + ^3\text{He}$	D	NO
$\bar{\alpha} + \text{t} \rightarrow \alpha + \bar{\text{t}}$	D	NO
$\text{d} + ^6\text{Li} \rightarrow 5 \text{ channels}$	A,B,C,D	NO DATA ABOVE 1 MeV
$^3\text{He} + ^3\text{He} \rightarrow 2\text{p} + \alpha$	A,C,D	NO DATA ABOVE 2.2 MeV

A - HAS IMPORTANT EFFECT ON EQUILIBRIUM PLASMA PARAMETERS THROUGH $\langle \sigma v \rangle_{\text{th}}$

B - NEUTRON AND RADIOACTIVE MATERIAL PRODUCTION

C - AFFECTS FAST FUSION PROBABILITY

D - NUCLEAR ELASTIC SCATTERING

TABLE VII

Energetic Fusion Products in D-D and Catalyzed-D Reactors*

*A bar signifies an energetic ion capable of undergoing nuclear elastic scattering. The tritium and ${}^3\text{He}$ can also undergo fast fusion.

TABLE VIII

Summary of Nuclear Elastic Scattering

	D	T	^3He	^4He	p
D	2.0 -20 [†] (46-49)*	/	/	0.3 -20 (164-178)	0.2 -30 (1-20)
T	0.013-10 (91-93,	1.58-2 (141-142)	/	1.2 -18.2 ^x (179-182)	0.05-8.3 (21-30)
^3He	0.38-20 (113-116)	5.0 -19 (147-148)	5.0 -20 (155-158,	1.72-20 (183-190)	0.1 -20 (126-140)
^6Li	2.0 -7 (211-213)	None ^x	8.0 -20 ^x (231)	2. -7.5 (246-250)	0.5 -16 (191-196)
^7Li	0.4 -1.8 ^x (286)	None ^x	10 - 11 ^x (311)	1.6 -20 ^x (326-330)	0.4 -20 ^x (251-254)
^7Be	No Measurement ^x				
^9Be	0.4 -7 (346-350)	0.6 -2.1 (371-372)	1.2-20 ^x (373-375)	1.4 -20 (381-384)	0.2 -10 (333-340)
^{10}B	1. -16 ^x (391-393)	1.5-3.3 ^x (416-418)	4.0-20 ^x (419-423)	2.0 -20 ^x (431-433)	0.15-10.5 ^x (385-387)
^{11}B	No Data ^x Reported				

Based on information in Ref. 4.

[†]Energy range of measurements, MeV

*Reference numbers (keyed to listing in Ref. 4)

^xData insufficient and/or inconsistent

Figure Titles

- Figure 1. Data Flow Chart
- Figure 2. Mirror Loss Cone Distribution. Results from two calculations, one using a modified Fokker-Planck (F-P) method and one using a semi-empirical fit (Kuo-Petravic) are shown for injection at ~ 78 keV into a conventional mirror with effective mirror ratio ~ 3 .
- Figure 3. Fast Fusion Probabilities for Protons Slowing in a ${}^6\text{Li}$ Plasma. (From McNally and Rothe, Ref. 3). Arrows on E_p axis indicate initial proton energies from various reactions.
- Figure 4. Reaction rates for ${}^{11}\text{B}$ reactions. The primary ${}^{11}\text{B} + p \rightarrow {}^3\text{He}$ reaction is given to facilitate comparison with the various nuisance reactions.
- Figure 5. Energy loss Rates for Test Ions in D-Plasma ($n_e = n_d = 10^{14}$ particles/cm³). From Ref. 3. Assumes $\ln A_{je} \sim \ln A_{ji} \sim 20$. Note that at higher energies where electron "drag" is the predominant Coulombic loss rate, nuclear elastic scattering is comparable in magnitude with electron drag.
- Figure 6. Effective reactivity for p - ${}^{11}\text{B}$ including a non-Maxwellian distribution due to hard collisions from nuclear elastic scattering of fusion products. (From Ref. 4).
- Figure 7. Ratio of $\langle\sigma v\rangle_{\text{eff}}$ to the Maxwellian value for the D-D cycle. (From Ref. 4).
- Figure 8. Evaluated Nuclear (plus Interference) Elastic Data From Scattering Integration Over the Center-of-Mass Scattering Cosine for an Alpha Particle Impinging on a Tritium Target. (Ref. 13).
- Figure 9. Flow Diagram for a Typical AF Burn Code.

FSL-80-118

FSL-80-355

ENERGY MESH - 100keV

Questions and Answers

Question: Tom Burrows

I believe that there have been several measurements for the D-D and D-T reactions (MeV range) since 1960.

Answer: I am glad to hear that. Also, one of the attendees at the meeting pointed out to me that some new measurements are in progress. Let me hasten to add that the literature review of this paper was simply done by me as a user to quickly survey the field. Indeed, for reaction rate data I largely depended on Shuy's excellent earlier survey (Ref. 4). Some important work may have been overlooked by me in this process. Still one purpose of having a user present this view was to find out what information is generally known by workers in the field. I would hope that this will provide an incentive to others to point out oversights.

Question: Bhat

Can you comment on the use of nuclear reaction for plasma diagnostics? Short time response?

Answer: Actually, atomic phenomena are most frequently involved in plasma diagnostics. Examples include detection of charge-exchange neutrals escaping the plasma and spectroscopic studies of radiation from partially ionized impurities and from fuel at the cold outer layer of the plasma. Two measurements involving nuclear reactions come to mind -- detection of alpha particles and also of neutrons from fusion reactions. In inertial confinement experiments, the use of magnetic spectrometer and time of flight measurements of the energy spectrum of alphas created by D-T reactions has enabled a measurement of fuel ion temperature, tamper pR, and the buildup of electrostatic potential on the target. Measurements of neutrons can also yield ion temperature data, either based on the spread of the D-T energy distribution or on the ratio of 2.54-MeV D-D neutrons to 14-MeV D-T neutrons. In conclusion, though, I would agree that more thought should be devoted to the possible use of nuclear reactions for diagnostics.

Question: Dhat

For $p+^{11}\text{B}$ reactions are the nuclear data reaction needs less for inertial confinement as opposed to plasma reactions?

Answer: The potential use of $p-^{11}\text{B}$ as a "neutronless" fuel was initially stressed by Wood and Weaver at LLL who were interested in its use in inertial confinement fusion (ICF) pellets. A major advantage of the ICF approach is that losses due to synchrotron radiation are eliminated since no confining magnetic fields are used. The disadvantage is the large input energy required to burn $p-^{11}\text{B}$ (assuming ignition is indeed possible). One approach that we have been considering at Illinois is the use of a small D-T "seed" in the center of the pellet that is shock heated to ignition. It then, in turn, heats a surrounding $p-^{11}\text{B}$ layer. This compromises some of the advantage of $p-^{11}\text{B}$ since neutrons are produced by the D-T seed. However, the neutron flux is still relatively low. To attempt to burn $p-^{11}\text{B}$ with magnetic confinement would require a very high β (plasma pressure/magnetic pressure) device such as the Surmacs under study at UCLA. Regardless of the approach, however, the nuclear data needs are much the same. As pointed out in the talk, continued refinement of data for the basic reaction as well as parasitic reaction data are needed. Distortion of the tail of the ion distribution function due to nuclear elastic scattering events is especially important, so refinement of scattering cross sections data also becomes crucial.

Question: O. Larsen

The importance of specification of and inclusion of variances and covariances in evaluation of neutron data has been stressed at this meeting. Are you considering inclusion of this information in charged-particle evaluations from the beginning of this effort?

Answer: I have not considered this possibility in any detail. Off-hand, however, its inclusion sounds good to me, speaking mainly as a user of the data. We are in a fortunate position since, compared to the area of neutron reaction data, we are just at the beginning of formulating charged particle data "banks" for fusion. Consequently, this is a good time to incorporate new procedures that take advantage of experience gained in the neutron area.