CHARGED PARTICLE CROSS SECTION REQUIREMENTS FOR ADVANCED FUSION FUEL CYCLES

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Charged particle cross sections required for advanced fusion fuel cycle calculations are discussed. Reactions important for the d-d, d-^{3}He, d-^{6}Li, p-^{6}Li and p-^{11}B cycles are described. The importance of nuclear elastic scattering is emphasized. Important fusion cross sections and the energy range where data is required are identified. Of particular interest for the propagating p-^{6}Li cycle is the ^{6}Li(^{3}He,p)^{8}Be reaction where the ^{8}Be can be in different energy states. The reactivity of the catalyzed d-d reaction at T_i = 75 keV can be increased by 25% at T_e = 50 keV to 75% at 100 keV relative to the reactivity neglecting nuclear elastic scattering. The result is due to fusion events between fast deuterons produced by elastic scattering with the background ions. The fraction of energy given to electrons is likewise influenced by nuclear elastic scattering. The fraction of a 14.5 MeV proton's energy given to electrons at 100 keV decreases from 85% when only coulomb scattering is assumed to 50% when coulomb plus nuclear scattering is included.

[Fusion, d-d, d-^{3}He, d-^{6}Li, p-^{6}Li, p-^{11}B fuel cycles; charged particle cross section needs; fusion reactivity]

Introduction

Fusion devices utilizing the d-t-Li cycle will certainly be the first to demonstrate energy breakeven and also very likely will be the first cycle for commercial fusion reactors. Nevertheless, fusion reactors with tritium fuel should be viewed as an intermediate step in fusion power development. The ultimate goal is to achieve a reactor based on either hydrogen or deuterium to insure both an inexhaustible fuel supply and systems with minimum radioactivity. To preserve this potential, it is essential to maintain efforts to develop advanced fuel cycle fusion power based on d-d, d-^{3}He, d-^{6}Li or proton based cycles such as p-^{11}B and p-^{6}Li. Minimizing the plasma deuterium content is a key to a minimum neutron producing reactor. A proper determination of the potential of each cycle requires cross section data for the basic reactions and for nuclear elastic and inelastic scattering among the nuclei with A less than 12.

Required Nuclear Data

The nuclear data required to analyze advanced fuels include fusion reaction cross sections, reaction rate parameters such as $\langle\sigma v\rangle$, reaction probabilities for fast fusion products to react with various elements in the background plasma, and nuclear elastic and inelastic cross sections to determine the energy transfer from the energetic fusion products to the background ions and electrons. The reaction rate, R, for two reacting species, a and b, is

$$R = \int d\bar{v}_a \int d\bar{v}_b \, f_a(\bar{v}_a) f_b(\bar{v}_b) \sigma(u) u \tag{1}$$

where R is the number of reactions per unit volume per unit time, f_a and f_b are the distribution functions, σ is the reaction cross section, and u is the relative velocity, $u = |\bar{v}_a - \bar{v}_b|$. It is convenient to write R as $n_a n_b \langle\sigma v\rangle$, where the density of species a and b (n_a and n_b) are found from

$$n_i = \int f_i(\bar{v}_i) d\bar{v}_i \qquad (i = a,b). \tag{2}$$

The reaction rate parameter, $\langle\sigma v\rangle$, depends on the form of the normalized distribution functions $\hat{f}_i(\bar{v}_i) = \frac{1}{n_i} f_i(\bar{v}_i)$:

$$\langle\sigma v\rangle = \int d\bar{v}_a \int d\bar{v}_b \, \hat{f}_a(\bar{v}_a) \hat{f}_b(\bar{v}_b) \sigma(u) u. \tag{3}$$

If $\hat{f}_i(\bar{v}_i)$ is the Maxwellian distribution,

$$\hat{f}_i(\bar{v}_i) = \left(\frac{m_i}{2\pi KT}\right)^{3/2} \exp(-m_i v_i^2/2KT), \tag{4}$$

the integral in Eqn. (3) can be expressed as:

$$\langle\sigma v\rangle = 4\pi \int_0^\infty u^2 du \left(\frac{\mu}{2\pi KT}\right)^{3/2} \exp\left(\frac{-\mu u^2}{2KT}\right) \sigma(u) u, \tag{5}$$

where μ is the reduced mass. Using $E = \frac{1}{2}\mu u^2$, Eqn. (5) becomes

$$\langle\sigma v\rangle = \sqrt{\frac{8}{\pi\mu}} \left(\frac{1}{KT}\right)^{3/2} \int_0^\infty E\sigma(E) \exp(-E/KT) dE. \tag{6}$$

The ion temperature in advanced fuel cycle fusion plasmas may reach 500 keV. One clearly would like to know the reaction cross section, $\sigma(E)$, up to an energy of at least 4KT (or 2 MeV in the most extreme case) to analyze fusion reactions among species with a Maxwellian distribution. In addition, nuclear scattering events between energetic fusion products and the background Maxwellian can transfer significant energy (>1 MeV) to the struck particle thereby promoting it to higher energy where it is typically more reactive. In short, cross sections are required not just to an energy of 4-5 KT but to the energy of fusion reaction products. The p-^{6}Li cycle is particularly useful to demonstrate this point.

The primary reactions of this fuel cycle are

$$p + {}^6Li \rightarrow {}^3He(2.3\text{ MeV}) + \alpha(1.7\text{ MeV}) \tag{7}$$

$${}^3He + {}^6Li \rightarrow p(11.3\text{ MeV}) + 2\alpha(2.813\text{ MeV}) \tag{8a}$$

$$\rightarrow p + {}^8Be(\text{various nuclear levels}) \tag{8b}$$

$$\rightarrow d(.088\text{ MeV}) + {}^7Be(.026\text{ MeV}) \tag{8c}$$

Secondary and tertiary reactions include:

$$d + {}^6Li \left\{ \begin{array}{ll} n + {}^7Be(.42\text{ MeV}) & (9a) \\ p(4.4\text{ MeV}) + {}^7Li(.63\text{ MeV}) & (9b) \\ p(1.6\text{ MeV}) + t + \alpha & (9c) \\ n + {}^3He + \alpha & (9d) \\ 2\alpha(11.2\text{ MeV}) & (9e) \end{array} \right.$$

$$d + {}^{3}He \rightarrow p(14.6\ MeV) + \alpha(4.7\ MeV) \quad (10)$$

$$d + d \begin{cases} \rightarrow n + {}^{3}He(.82\ MeV) & (11a) \\ \rightarrow p(3MeV) + t(1.01\ MeV) & (11b) \end{cases}$$

$$d + {}^{7}Be \rightarrow p(11.2\ MeV) + 2\alpha(2.8\ MeV) \quad (12)$$

$$d + t \rightarrow n + {}^{4}He(3.5\ MeV) \quad (13)$$

$$t + {}^{3}He \begin{cases} \rightarrow d(9.6\ MeV) + \alpha(4.8\ MeV) & (14a) \\ \rightarrow p + n + \alpha & (14b) \end{cases}$$

$${}^{3}He + {}^{3}He \rightarrow 2p(5.7\ MeV) + \alpha(1.4\ MeV) \quad (15)$$

$${}^{3}He + {}^{7}Be \rightarrow 2p(4.5\ MeV) + 2\alpha(1.1\ MeV) \quad (16)$$

$$t + {}^{7}Be \rightarrow p(4.2\ MeV) + 2\alpha \quad (17)$$

$$d + {}^{7}Li \rightarrow n + 2\alpha(2.52\ MeV) \quad (18)$$

In addition, there are at least thirty side reactions and thirteen ^{6}Li + ^{6}Li exothermic reactions which produce elements from H to ^{12}C and neutrons. Many of the fusion reaction products are energetic and may react with elements in the background plasma prior to completely slowing down (fast fusion or two-component fusion events). Including these fast fusion events is crucial, particularly for cycles that are either propagating or chain events. Some important propagating fusion reaction sequences in the p-^{6}Li cycle (the fast particle has a bar over the element's designation) include

$$\left\{ \begin{array}{l} \bar{p} + {}^{6}Li \rightarrow {}^{3}\overline{He} + \alpha \\ {}^{3}\overline{He} + {}^{6}Li \rightarrow \bar{p} + 2\alpha \\ \bar{p} + {}^{6}Li \rightarrow {}^{3}\overline{He} + \alpha \\ \vdots \end{array} \right\} (19) \qquad \left\{ \begin{array}{l} \bar{p} + {}^{6}Li \rightarrow {}^{3}\overline{He} + \alpha \\ {}^{3}\overline{He} + d \rightarrow \bar{p} + \alpha \\ \bar{p} + {}^{6}Li \rightarrow {}^{3}\overline{He} + \alpha \\ \vdots \end{array} \right\} (20)$$

$$\left\{ \begin{array}{l} \bar{p} + {}^{6}Li \rightarrow {}^{3}\overline{He} + \alpha \\ {}^{3}\overline{He} + {}^{6}Li \rightarrow \bar{d} + {}^{7}Be \\ \bar{d} + {}^{6}Li \rightarrow \bar{p} + {}^{7}Li \\ \bar{p} + {}^{6}Li \rightarrow {}^{3}\overline{He} + \alpha \\ \vdots \end{array} \right\} (21) \qquad \left\{ \begin{array}{l} \bar{p} + {}^{6}Li \rightarrow {}^{3}\overline{He} + \alpha \\ {}^{3}\overline{He} + {}^{6}Li \rightarrow \bar{d} + {}^{7}Be \\ \bar{d} + {}^{7}Be \rightarrow \bar{p} + 2\alpha \\ \bar{p} + {}^{6}Li \rightarrow {}^{3}\overline{He} + a \\ \vdots \end{array} \right\} (22)$$

and there are many others.

Nuclear elastic scattering of the energetic products with the background plasma produces additional energetic particles which can undergo fast fusion and further propagate the reaction. Therefore, the reaction cross section for the various channels and nuclear elastic scattering cross sections are required up to about 20 MeV.

In general, the nuclear scattering cross section is 1 barn or greater when the incident energy is in the range, 1 to 15 MeV. As an example, the proton-deuterium nuclear elastic scattering cross section is shown in Fig. 1 as a function of proton energy. The coulomb scattering cross section has been subtracted prior to plotting the result.

The average energy transfer per collision is large. For example, counting only collisions which transfer 1 MeV or more, a 3 MeV proton in a deuterium plasma with a 75 keV ion temperature is found to transfer ~30% of its energy to the energetic deuterons when the electron temperature is 60 keV. This fraction increases to ~50% when T_e is 100 keV. The fast fuel ions produced from this process undergo fusion while slowing down thereby enhancing the reactivity and the effect of propagating reaction. In Figs. 2 and 3, we show the fraction of energy transferred from fast alphas and fast protons to produce energetic deuterons with an energy greater than 1 MeV. The effect is smaller for alphas at 3 to 4 MeV than for protons at either 3 MeV or 14.5 MeV because of the larger coulomb cross section for alphas.

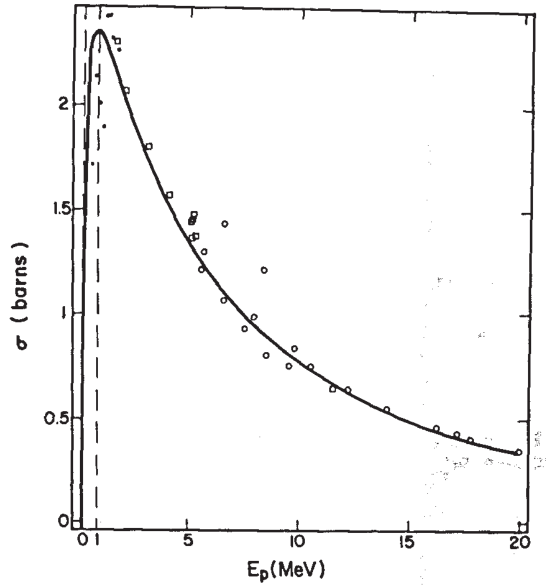

Fig. 1. The elastic scattering cross section for protons with deuterons after subtracting the coulomb scattering from the angular distributions.

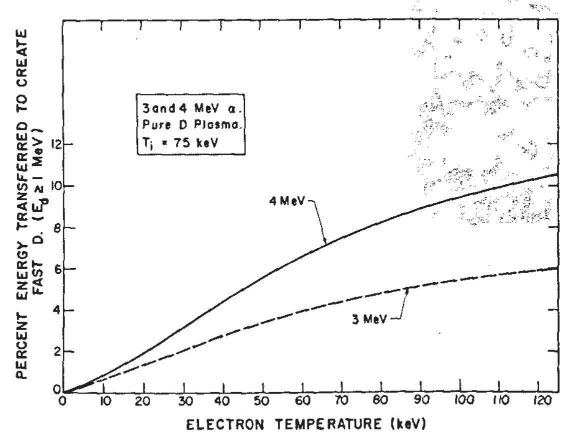

Fig. 2. Percentage of initial energy transferred from fast alphas to produce energetic (>1 MeV) deuterons.

The catalyzed d-d fuel cycle can be used to elaborate on the role of nuclear elastic scattering and propagating effects. The major reactions for this cycle are:

$$d + d \begin{cases} \rightarrow n(2.45\ MeV) + {}^{3}\overline{He}(.87\ MeV) & (23a) \\ \rightarrow \bar{p}(3.01\ MeV) + \bar{t}(1\ MeV) & (23b) \end{cases}$$

$$d + t \rightarrow n(14.06\ MeV) + \bar{\alpha}(3.5\ MeV) \quad (24)$$

$$d + {}^{3}He \rightarrow \bar{\bar{p}}(14.68\ MeV) + \bar{\alpha}(3.67\ MeV). \quad (25)$$

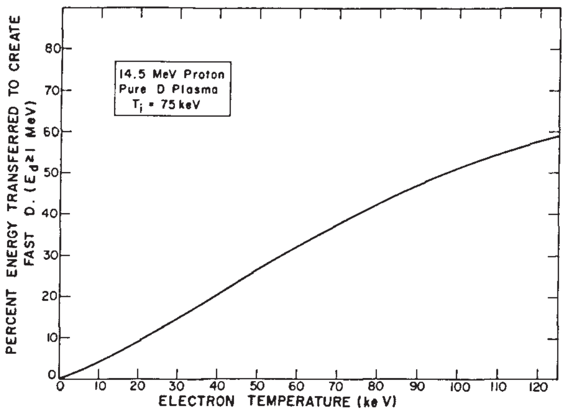

Fig. 3. Percentage of energy transferred from a fast proton to produced deuterons with an energy exceeding 1 MeV.

The overbars denote fast charged particles. Nuclear elastic events such as

$$\bar{p} + d \rightarrow p + \bar{d} \tag{26}$$

$$\bar{\alpha} + d \rightarrow \alpha + \bar{d}\ . \tag{27}$$

$$\vdots$$

promote fast deuterons from the background Maxwellian distribution. Some of the propagating sequences in this cycle are:

$$\left\{\begin{aligned} & d + d \rightarrow \bar{p} + \bar{t} \\ & \bar{p} + d \rightarrow \bar{d} + p \\ & \bar{d} + d \rightarrow \bar{p} + \bar{t} \\ & \quad\vdots \end{aligned}\right\} \tag{28}$$

$$\left\{\begin{aligned} & d + d \rightarrow \overline{^3He} + n \\ & {}^3\overline{He} + d \rightarrow \bar{\bar{p}} + \bar{\alpha} \\ & \bar{\bar{p}} + d \rightarrow \bar{d} + p \\ & \bar{d} + d \rightarrow {}^3He + n \\ & \quad\vdots \end{aligned}\right\} \tag{29}$$

$$\left\{\begin{aligned} & d + \bar{d} \rightarrow \bar{t} + \bar{p} \\ & \bar{t} + d \rightarrow \bar{\alpha} + n \\ & \bar{\alpha} + d \rightarrow \bar{d} + \alpha \\ & \bar{d} + d \rightarrow \bar{t} + p \\ & \quad\vdots \end{aligned}\right\} \tag{30}$$

$$\left\{\begin{aligned} & d + d \rightarrow \overline{^3He} + n \\ & \overline{^3He} + d \rightarrow \bar{\alpha} + \bar{\bar{p}} \\ & \bar{\alpha} + d \rightarrow \bar{d} + \alpha \\ & \bar{d} + d \rightarrow {}^3He + n \\ & \quad\vdots \end{aligned}\right\} \tag{31}$$

and there are more. As an example, the propagating sequence indicated in set (28) produces fast protons; the fast proton promotes the deuteron out of the thermal bath; the energetic deuteron then reacts before slowing down, producing a fast proton; and so on.

The inclusion of these effects increases the reactivity of the catalyzed d-d cycle at T_i = 75 keV by 25% when T_e is 50 keV and by 75% when T_e is 100 keV. The results are shown in Fig. 4. These increases are measured relative to a standard calculation in which propagating reactions are neglected.

An additional effect is that nuclear knock-on events alter the fraction of energy given to electrons and ions by energetic fusion products. The energy transferred to electrons by various fast particles (a 4 MeV alpha, a 3 MeV proton, and a 14.5 MeV proton) is shown in Fig. 5, 6 and 7 as a function of electron temperature. The dashed curve in each figure is the fraction of the initial energy received by electrons when only the coulomb interaction is assumed. The dash-dot curves in each figure give the analogous result when both coulomb and nuclear elastic scattering are included. Finally, the solid curve properly includes the effect of fast ion production by nuclear scattering and the subsequent slowing down of those ions with background ions and electrons. The background plasma in all cases is electrons and deuterium ions. The ion temperature is fixed at 7.5 keV. The difference in the results is small for the 4 MeV alphas but substantial for both the 3 MeV and 14.5 MeV protons, and the differences become more important as the electron temperature increases. Accounting for both nuclear elastic scattering and subsequent slowing down of knock-on ions, a 14.5 MeV proton in a 75 keV ion temperature deuterium plasma will transfer 79% of its energy to 50 keV electrons compared to 93% when only coulomb scattering is assumed. At an electron temperature of 100 keV, the percentage of energy transferred to electrons decreases to 51% compared to 85% with coulomb interactions only. The effect is clearly important to a plasma energy balance calculation. Overall, the net result is that lower $n\tau_E$ values are required to meet either the Lawson or ignition condition for the catalyzed d-d cycle.

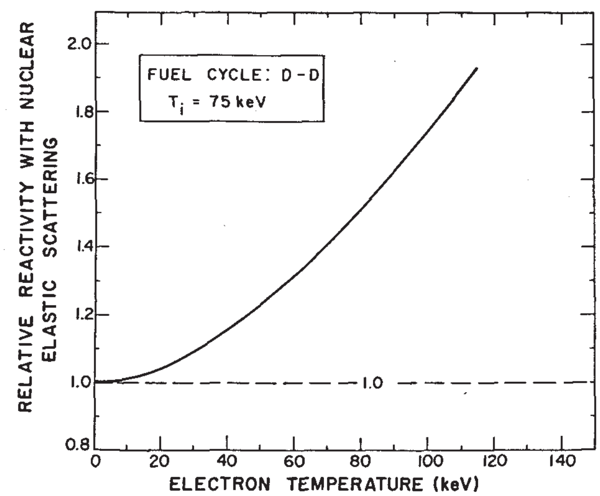

Fig. 4. Increase in d-d reactivity due to promotion and propagation effects measured relative to the reactivity of a pure Maxwellian at T_i = 75 keV.

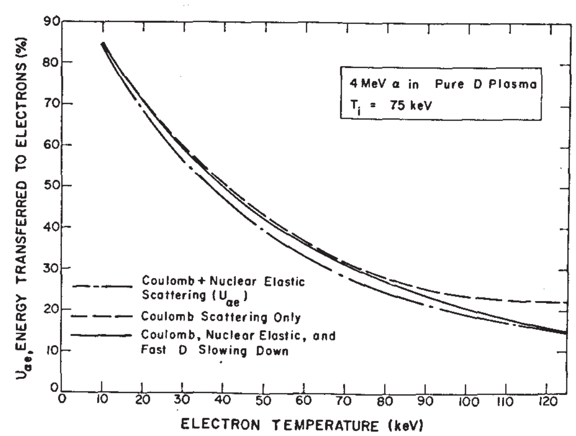

Fig. 5. Calculations of the fraction of energy given to electrons by a 4 MeV alpha. The solid curve includes all effects properly.

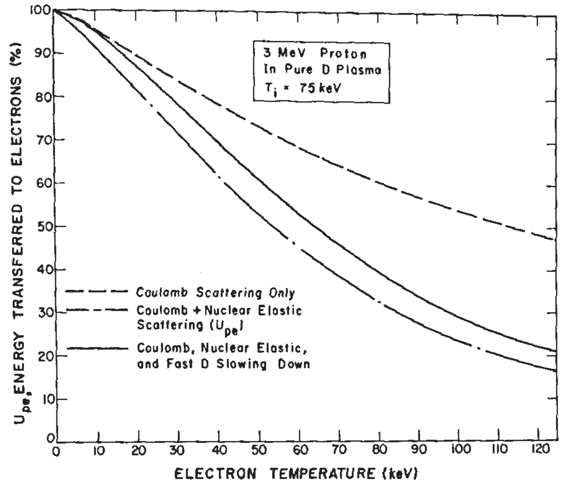

Fig. 6. Fraction of energy given to electrons by a 3 MeV proton.

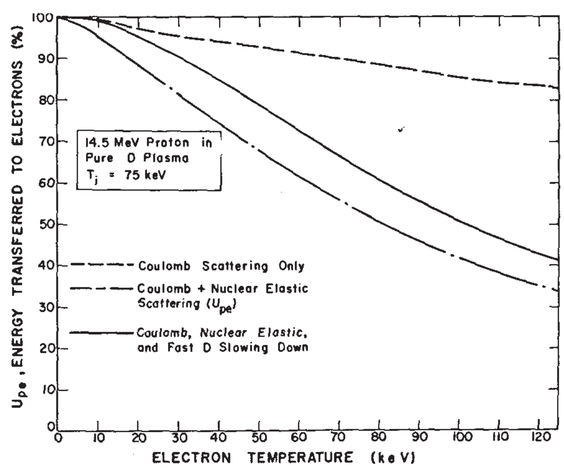

Fig. 7. Fraction of energy given to electrons by a 14.5 MeV proton.

The examples, while not inclusive, show the need in the analysis of advanced fusion fuel cycles for reaction cross section data to various final channels and for nuclear elastic and inelastic scattering cross sections up to about 20 MeV.

Status of Nuclear Data for Advanced Fusion Fuel Cycle Analysis

The literature has been examined through October 1979. The list of references in this paper is a partial one because of the very large number of works reported. All data for a given reaction were examined for consistency. In general the uncertainties or inconsistencies ranged from 10% to as much as an order of magnitude. Cross sections for some of the reaction branches have either been partially measured or not measured at all. In the reactions of ^3He-^6Li and d-^7Be, for example, the total reaction cross section may be 10 to 50 times larger than reported values. For other reactions, such as ^3He with ^7Be, data do not exist.

The status of the nuclear data is summarized in matrix form in Tables 1, 2, and 3. The asterisk (*) indicates the reaction is important for fusion fuel cycle analysis; the check (✓) indicates the data for that reaction are reasonably consistent; while the cross (X) indicates the existing data are either inconsistent or have large error bars. References are given in the parentheses. The numbers followed by MeV give the energy range over which data have been measured. A literature search for nuclear inelastic cross sections is in progress and is not included in this paper. Comments are as follows:

1. The d-d Reactions

$$d + d \rightarrow n + {}^3He \qquad Q = 3.269\ \text{MeV} \qquad (33)$$

$$d + d \rightarrow p + t \qquad Q = 4.033\ \text{MeV} \qquad (34)$$

Liskien and Paulsen[461] have summarized and evaluated the cross section measurements for E_d = 0.13 - 10 MeV. The data and evaluation are shown in Fig. 8. This is adequate for fusion fuel cycle analysis.

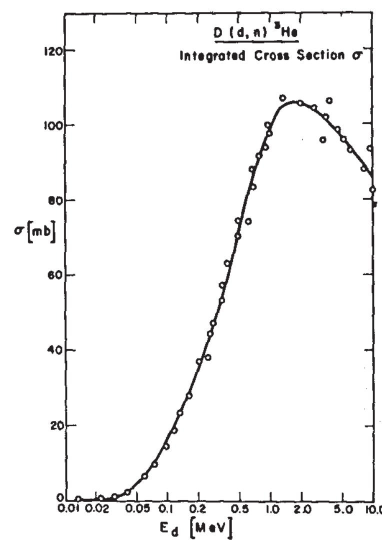

Fig. 8. Data and evaluation for the d-d reaction.

2. The p-t Reaction

$$t + p \rightarrow n + {}^3He \qquad Q = -.764\ \text{MeV} \qquad (35)$$

Cross section measurements have been evaluated by Liskien and Paulsen.[462] The angular distribution measurements are inconsistent with one another. Most of the integrated cross section measurements are within 15% of the recommended values. Experimental and recommended values for E_p = 1.0-10 MeV are shown in Fig. 9. This data is adequate for fusion fuel cycle analysis.

3. The d-t Reaction

$$t + d \rightarrow n + \alpha \qquad Q = 17.590\ \text{MeV} \qquad (36)$$

There has been only one measurement since 1960. The cross section measurements have been evaluated[463] and indications are that a number of reported angular distributions are not satisfactory at energies above 5 MeV. Most of the integrated cross section measurements are within 10% of the recommended values. In general, the data is adequate for fusion fuel cycle analysis.

TABLE

	p	d	t	^{3}He	^{4}He
d	ELASTIC (1 - 20) σ (E, θ) 0.2 - 30. MeV * ✓ REACTION (———) ———	ELASTIC (46 - 49) σ (E, θ) 2. - 20. MeV * ✓ REACTION (50 -90) σ (E) or σ (E, θ) 0.013 - 14. MeV	S	S	ELASTIC (164 - 178) σ (E, θ) 0.3 - 20. MeV * ✓ REACTION (———) ———
t	ELASTIC (21 - 30) σ (E, θ) 0.05 - 8.3 MeV * ✓ REACTION (31 - 45) σ (E) or σ (E, θ) 1.0 - 10. MeV	ELASTIC (91 - 93) σ (E, θ) 0.013 - 10. MeV * ✓ REACTION (94 - 112) σ (E) or σ (E, θ) 0.01 - 15. MeV	ELASTIC (141 - 142) σ (E, θ) 1.58 - 2. MeV X REACTION (143 - 146) σ (E) or σ (E, θ) 0.04 - 2.2 MeV	S	ELASTIC (179 - 182) σ (E, θ) 1.2 - 18.2 MeV * X REACTION (———) ———
^{3}He	ELASTIC (126 - 140) σ (E, θ) 0.1 - 20. MeV * ✓ REACTION (———) ———	ELASTIC 113 - 116 σ (E, θ) 0.38- 20. MeV * ✓ REACTION (117 - 125) σ (E) or σ (E, θ) 0.25 - 15. MeV	ELASTIC (147 -148) σ (E, θ) 5. - 19. MeV X REACTION 149 - 154 σ (E) or σ (E, θ) .15 - 1.9 MeV	ELASTIC (155 - 158) σ (E, θ) 5. - 20. MeV * ✓ REACTION (159 - 163) σ (E) or σ (E, θ) 0.06 - 2.2 MeV	ELASTIC (183 - 190) σ (E, θ) 1.72 - 20. MeV * X REACTION (———) ———

TABLE 2

	p	d	t	^{3}He	^{4}He
^{6}Li	ELASTIC (191 - 196) σ (E, θ) 0.5 - 16. MeV * ✓ REACTION (197 - 210) σ (E, θ) 0.14 - 12. MeV	ELASTIC (211 - 213) σ (E, θ) 2. - 7. MeV * ✓ REACTION (213 - 225) σ (E, θ) 0.1 - 1. MeV	ELASTIC (———) No measurement X REACTION (226 - 230) σ (E, θ) 0.3 - 20. MeV	ELASTIC (231) σ (E, θ) 8. - 20. MeV * X REACTION 232 - 245 σ (E, θ) or σ (E) 1.2 - 4.2 MeV	ELASTIC (246 - 250) σ (E, θ) 2. - 7.5 MeV REACTION (———) ———
^{7}Li	ELASTIC (251 - 254) σ (E, θ) 0.4 - 20. MeV X REACTION (255 - 285) σ (E, θ) or σ (E) 0.8 - 15. MeV	ELASTIC (286) σ (E, θ) 0.4 - 1.8 MeV X REACTION (287 - 300) σ (E) or σ (E, θ) 0.6 - 2.6 MeV	ELASTIC (———) No measurement X REACTION (301 - 310) σ (E, θ) 0.23 - 2.5 MeV	ELASTIC (311) σ (θ) 11. MeV X REACTION (312 - 325) σ (E, θ) 0.8 - 6. MeV	ELASTIC (326 - 330) σ (E, θ) 1.6 - 20. MeV REACTION (———) ———
^{7}Be	ELASTIC (———) No measurement X REACTION (———) ———	ELASTIC (———) No measurement * X REACTION (331-332) σ (E, θ) 0.8 - 1.7 MeV	ELASTIC (———) No measurement X REACTION (306) No measurement $\langle \sigma V \rangle$ Estimated	ELASTIC (———) No measurement * X REACTION (306) No measurement $\langle \sigma V \rangle$ Estimated	ELASTIC (———) No measurement REACTION (———) ———

TABLE 3

	p	d	t	^3He	^4He
^9Be	ELASTIC (333 - 340) $\sigma(E,\theta)$ 0.2 - 10. MeV ✓ REACTION (341 - 345) $\sigma(E,\theta)$ 0.028 - 2.0 MeV	ELASTIC (346 - 350) $\sigma(E, 90^o)$ 0.4 - 7. MeV ✓ REACTION (351 -370) $\sigma(E)$ or $\sigma(E,\theta)$ 0.15 - 19. MeV	ELASTIC (371, 372) $\sigma(E,\theta)$ 0.6 - 2.1 MeV ✓ REACTION (371, 372) $\sigma(E,\theta)$ 0.52 - 2.1 MeV	ELASTIC (373 - 375) $\sigma(E, 45^o)$ or $\sigma(E,90^o)$ 1.2 - 20. MeV X REACTION (376 - 380) $\sigma(E,\theta)$ 1.6 - 20. MeV	ELASTIC (381 - 384) $\sigma(E,\theta)$ 1.4 - 20. MeV REACTION (———) ———
^{10}B	ELASTIC (385 - 387) $\sigma(E,\theta)$ 0.15 - 10.5 MeV X REACTION (388 - 390) $\sigma(E,\theta)$ 0.06 - 6.3 MeV	ELASTIC (391 - 393) $\sigma(E,\theta)$ 1. - 16. MeV X REACTION (394 - 415) $\sigma(E)$ or $\sigma(E,\theta)$ 0.14 - 12. MeV	ELASTIC (416 - 418) $\sigma(E,\theta)$ 1.5 - 3.3 MeV X REACTION (416) $\sigma(E)$ 0.8 - 2.0 MeV	ELASTIC (419 - 423) $\sigma(E,\theta)$ 4. - 20. MeV X REACTION (424 - 430) Excitation function 2. - 19. MeV	ELASTIC (431 - 433) Excitation function 2. - 20. MeV REACTION (———) ———
^{11}B	ELASTIC (———) No data reported * X REACTION (434 - 440) $\sigma(E)$ or $\sigma(E,\theta)$ 0.17 - 10. MeV	ELASTIC (———) No data reported X REACTION (441 - 453) $\sigma(E)$ or $\sigma(E,\theta)$ 0.3 - 10. MeV	ELASTIC (———) No data reported X REACTION 454, 455 $\sigma(E,\theta)$ 1.0 - 2.1 MeV	ELASTIC (———) No data reported X REACTION (456 - 460) Excitation function or $\sigma(E)$ 0.9 - 18. MeV	ELASTIC (———) No data measurered below 27. MeV REACTION (———) ———

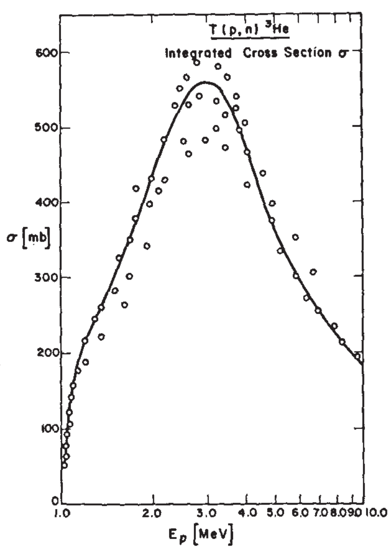

Fig. 9.

4. The d-^{3}He Reaction

$$^3He + d \rightarrow p + \alpha \qquad Q = 18.35 \text{ MeV} \qquad (37)$$

There have been no measurements since 1960. A pronounced resonance occurs at E_d = 430 keV with $\Gamma \sim 450$ keV. The experimental data disagree in the neighborhood of this resonance (~25%). However, analysis by Hale[464] suggests that the recommended values are very good. Thus, the cross sections are adequate for fusion fuel cycle analysis.

5. The ^{3}He-^{3}He Reactions

$$^3He + {^3He} \rightarrow p + {^5Li} \qquad Q = 10.890 \text{ MeV} \qquad (38)$$
$$\quad\quad\quad \hookrightarrow p + \alpha$$
$$^3He + {^3He} \rightarrow 2p + \alpha \qquad Q = 12.860 \text{ MeV} \qquad (39)$$

A study of the proton spectrum indicates that the reaction proceeds mainly via a direct mechanism and the ^{5}Li channel. However, the branching ratio is not firmly established, particularly at low energy.

6. The p-^{6}Li Reaction

$$^6Li + p \rightarrow {^3He} + \alpha \qquad Q = 4.023 \text{ MeV} \qquad (40)$$

The cross section measurements for E_p = .14-3 MeV by Elwyn et al.[197] appear to be definitive. The earlier measurements are inconsistent with one another as shown in Fig. 10. Cross section measurements for E_p = 3 to 12 MeV have been made recently by Gould et al.[198] The measurements for E_p = 62 to 188 keV deviate from an S-wave Gamow plot above ~130 keV.

7. The d-^{6}Li Reactions

$$d + {^6Li} \rightarrow n + {^7Be} \qquad Q = 3.380 \text{ MeV} \qquad (41)$$
$$\rightarrow p + {^7Li} \qquad Q = 5.026 \text{ MeV} \qquad (42)$$
$$\rightarrow p + t + \alpha \qquad Q = 2.561 \text{ MeV} \qquad (43)$$
$$\rightarrow n + {^3He} + \alpha \qquad Q = 1.796 \text{ MeV} \qquad (44)$$
$$\rightarrow 2\alpha \qquad Q = 22.374 \text{ MeV} \qquad (45)$$

The recent measurements for E_d = .1-1 MeV by Elwyn et al.[214] are definitive. Other measurements differ sharply with one another, even in recent experiments.[218] Cross section measurements for $E_d > 1$ MeV are needed for a complete analysis.

8. The ^{3}He-^{6}Li Reactions

$$^6Li + {^3He} \rightarrow p + {^8Be}(g.s.) \qquad Q = 16.787 \text{ MeV} \qquad (46)$$
$$\hookrightarrow 2\alpha$$
$$\rightarrow p + {^8Be}(2.94) \qquad Q = 13.847 \text{ MeV} \qquad (47)$$
$$\hookrightarrow 2\alpha$$
$$\rightarrow p + {^8Be}(11.4) \qquad Q = 5.387 \text{ MeV} \qquad (48)$$
$$\hookrightarrow 2\alpha$$

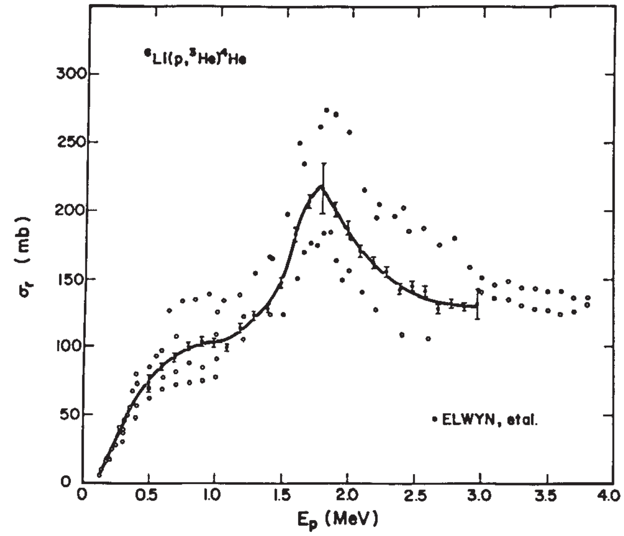

Fig. 10

$$\rightarrow p + {}^8Be(16.63) \quad Q = .157 \text{ MeV} \quad (49)$$
$$\quad \hookrightarrow 2\alpha$$
$$\rightarrow p + {}^8Be(16.92) \quad Q = -.1325 \text{ MeV} \quad (50)$$
$$\quad \hookrightarrow 2\alpha$$
$$\rightarrow p + {}^8Be(17.64) \quad Q = -.853 \text{ MeV} \quad (51)$$
$$\rightarrow p + 2\alpha \quad Q = 16.88 \text{ MeV} \quad (52)$$
$$\rightarrow \alpha + {}^5Li \quad Q = 14.91 \text{ MeV} \quad (53)$$
$$\quad \hookrightarrow p + \alpha$$
$$\rightarrow d + {}^7Be \quad Q = .1126 \text{ MeV} \quad (54)$$
$$\rightarrow d + {}^7Be(.43) \quad Q = -.317 \text{ MeV} \quad (55)$$
$$\rightarrow 2p + {}^7Li \quad Q = -.468 \text{ MeV} \quad (56)$$

A measurement is in progress by A. Elwyn et al. at the Argonne National Laboratory.(465) The earlier measurements are not complete. At least 5 nuclear levels in ^{8}Be can be excited. It is expected that the reaction cross section to all branches will be at least a factor of 10 larger than those now known. For example, at $E_{^3He}$ = 3.5 MeV, Gould et al.(245) measured $\sigma_r \approx$ 10-12 mb for the ^{8}Be(g.s.) branch, $\sigma_r \approx$ 55 mb for the ^{8}Be(2.94 MeV) branch, and estimated $\sigma_r \approx$ 42 mb for the continuum breakup reaction, Elwyn et al. indicates values could be $\sigma_r \approx$ 30-50 mb for the ^{8}Be(16.63 MeV) branch, $\sigma_r \approx$ 20-40 mb for the ^{8}Be(16.9 MeV) branch and $\sigma_r \approx$ 400 mb for the d + ^{7}Be branch.

9. The d-^{7}Be Reactions

There have been no measurements since 1960. d + ^{7}Be reacts via the same compound nucleus as ^{3}He + ^{6}Li. Therefore, it will have the same reaction channels as ^{3}He + ^{6}Li except for eqns. (54) and (55). Since the existing data are only for the eqn. (46) and (47) branches, measurements for each branch stated above are required. However, a standard 9-nucleon R-matrix calculation can give good estimated values, provided that the cross sections of each branch of ^{3}He + ^{6}Li reaction are given.

10. The p-^{11}B Reactions

$$^{11}B + p \rightarrow \alpha + {}^8Be \quad Q = 8.590 \text{ MeV} \quad (57)$$
$$^{11}B + p \rightarrow 3\alpha \quad Q = 8.682 \text{ MeV} \quad (58)$$

The most recent cross section measurements for E_p = 0.08-1.4 MeV by Davidson et al.(434) appear to be definitive. There are 7 pronounced resonances in the range, E_p = .1-5 MeV. The energy of the resonances, the cross sections at each resonance peak, and the width of each resonance are summarized in Table 4. The cross sections are uncertain above 2 MeV and should be measured again.

Table 4

Parameters for p-^{11}B Resonances

Resonance Energy E_p (MeV)	Cross Section at Resonance Peak (mb)	Resonance Width Γ (keV)
.172	28	10
.64	800	300
1.39	180	1160
1.98	113 - 132	100
2.62	200 - 347	320
3.75	200 - 348	1100
4.93	130 - 210	180

Conclusions

As described in the previous sections, propagating effects in an advanced fusion fuel cycle analysis are important. Data for both nuclear reactions and nuclear elastic scattering up to 20 MeV are required. For example, with the inclusion of propagating effects, the reactivity of the catalyzed d-d reaction at T_i = 75 keV can be increased from 25% at T_e = 50 keV to 75% at 100 keV relative to the reactivity neglecting nuclear elastic scattering. The result is due to fusion events between fast deuterons produced by elastic scattering and the background ions. The fraction of energy given to electrons is likewise influenced by nuclear elastic scattering. The fraction of a 14.5 MeV proton's energy given to electrons at 100 keV decreases from 85% when only coulomb scattering is assumed to 50% when coulomb plus nuclear scattering is included.

In addition, charged particle cross sections required for advanced fusion fuel cycle calculations have been discussed. Reactions important for the d-d, d-^{3}He, d-^{6}Li, p-^{6}Li and p-^{11}B cycles have been described. The importance of nuclear elastic scattering has been emphasized. Important fusion cross sections and the energy range where data is required have been identified.

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