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FUSION GAMMA DIAGNOSTICS FOR D-T AND D-^{3}He PLASMAS

By

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FUSION GAMMA DIAGNOSTICS FOR D-T AND D-^{3}He PLASMAS

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Abstract

Nuclear reactions of interest in controlled thermonuclear fusion research often possess a branch yielding prompt emission of gamma radiation. In principle, the gamma emission can be exploited to provide a new fusion diagnostic offering measurements comparable to those obtained by the well established neutron diagnostics methods. The conceptual aspects for a fusion gamma diagnostic are discussed in this paper and the feasibility for application to the Tokamak Fusion Test Reactor during deuterium neutral beam heating of a D-T plasma and minority ion cyclotron resonance heating of a D-^{3}He plasma is examined.

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I. INTRODUCTION

The branching ratios of the prompt gamma emission channels for the nuclear reactions of importance fusion reactors are generally several orders of magnitude below those for the well-known neutron and charged particle producing reactions. Thus, until recently, fusion reaction rates attained in experimental devices have not been adequate to exploit the fusion gamma emission for diagnostic purposes. New results on present experiments [1,2] and predictions for next-generation machines [3] strongly suggest fusion reaction rates sufficiently high to yield diagnostically useful gamma ray fluxes in spite of the small branching rations [4-6].

As will be discussed further in Section II, of the candidate gamma producing reactions the two that are of particular interest for near-term application of fusion gamma diagnostics are the $T(d,\gamma)$ ^5He and the $^3He(d,\gamma)^5Li$ reactions. Both reactions yield 16.7 MeV prompt gamma emission over a relatively broad resonance which is around a deuterium energy of 107 keV for the D-T reaction and 450 keV for the D-^{3}He reaction. The $T(d,\gamma)^5He$ reaction is accessible in the Tokamak Fusion Test Reactor (TFTR) during injection of 120 keV deuterium neutral beams into a tritium plasma. In this case, gamma diagnostics offer an independent corroboration of the conventional 14-MeV neutron diagnostic measurements which are crucial in determining achievement of the TFTR fusion break-even mission. D-^{3}He plasmas are of interest both at the present time in Ion Cyclotron Resonance Heating (ICRH) experiments where wave power couples to the ^{3}He minority in a bulk deterium plasma as well as in the future for reactor concepts based on the D-^{3}He advanced fuel cycle. In this case, the D-^{3}He reaction does not yield neutrons and fusion gamma diagnostics becomes the only direct method to measure the D-^{3}He fusion reaction rate.

A simple analysis supporting the feasibility of applying fusion gamma diagnostics to TFTR plasmas is given in Section III, followed by a summary in Section IV.

II. CANDIDATE REACTIONS FOR FUSION GAMMA DIAGNOSTICS

Before discussing particular reactions producing prompt gamma emission, it is useful to review the possible reactants and to define the criteria on which the selection of candidate reactions for diagnostic use is based. Three catagories of reactants are identified as: 1) thermalized bulk plasma ions comprised of the reactor fuel species, 2) non-thermalized, energetic ion populations resulting from auxiliary heating or from fusion reaction products, and 3) impurity ions which may be either indigenous or injected for diagnostic purposes. Thus a plethora of reactions involving species such as H, D, T, ^{3}He, ^{4}He, C, O, and others with energies ranging from several keV to ~ 15 MeV could be examined for diagnostically useful gamma production [4]. In order to realize the highest possible fusion gamma production rate under experimental conditions that can be envisaged at present or in the near future, we consider only reactions involving species having a population of ~ 5% or more of the plasma density and having reaction resonances at energies below 500 keV. Within the above constraints, two reactions are of particular interest for near-term application of fusion gamma diagnostics.

At relatively low energies, the reaction [7]

$$D + T \rightarrow {}^{5}He + \gamma \ (16.7 \text{ MeV}) \qquad (1)$$

is dominated by a resonance at a deuterium energy of E_d = 107 keV in laboratory coordinates which yields 16.7 MeV prompt gamma emission. Although the reaction cross sections [8,9,10] are not well known, available data indicates that the ratio [11] of the cross section for emission of 16.7 MeV gamma rays, $\sigma_{T(d,\gamma)}$, to that for emission of 14 MeV neutrons, $\sigma_{T(d,n)}$, has a value of $\sigma_{T(d,\gamma)}/\sigma_{T(d,n)} = 2.1 \pm 0.6 \times 10^{-4}$ quantum/neutron which is approximately constant over a deuteron energy range of E_d = 25-100 keV. Above the resonance, the branching ratio decreases rapidly: at a deuteron energy of $E_d = 1025 \pm 2.7$ keV the ratio is 2.3×10^{-5} [12]. The cross section data for the $T(d,\gamma)^{5}He$ reaction compiled from published results are shown in Fig. 1.

The reaction [7]

$$D + {}^{3}He \rightarrow {}^{5}Li + \lambda \ (16.7 \text{ MeV}) \qquad (2)$$

is of special interest to potential fusion gamma diagnostic applications because of the high energy of the prompt gamma emission and the absence of the $^{3}He(d,n)$ reaction. The 16.7 MeV prompt gamma emission is isotropic in the region of a broad resonance at a deterium energy of E_d = 450 keV. The total cross section at resonance is 21 ± 4 μb. The existing cross section measurements [13] are shown by the data points in

Fig. 2. To estimate the branching ratio of the $^3He(d,\gamma)^5Li$ reaction to the $^3He(d,p)^4He$ reaction we use an analytic fit to the (d,p) reaction of the form [14]

$$\sigma(E) = \left[E\left\{\exp\left(a_1 E^{-1/2}\right)-1\right\}\right]^{-1} \times \left[a_2\left\{1 + \left(a_3E - a_4\right)^2\right\}^{-1} + a_5\right] \qquad (3)$$

where E(eV) is the energy of the projectile in the laboratory coordinate system and the values of the constant are

$a_1 = 2823\ (eV^{1/2})$
$a_2 = 259 \times 10^5$ (eV barn)
$a_3 = 398 \times 10^{-8}\ (eV^{-1})$
$a_4 = 1.297$
$a_5 = 647 \times 10^3$ (eV barn).

The ^3He (d,p) ^4He cross section as a function of deuteron energy is shown by the solid curve in Fig. 2, while the dashed curve corresponds to the $D(^3He, p)\ ^4He$ rection as a function of ^3He energy. From the plot, the $^3He(d,\gamma)\ ^5Li$ to $^3He(d,p)\ ^4He$ branching ratio is determined to be $\sigma_{^3He(d,\gamma)}/\sigma_{^3He(d,p)} \sim 2 \times 10^{-4}$ in the region of the resonance. Unfortunately, data to confirm this branching ratio at lower energies ($\lesssim$ 200 keV) of diagnostic interest are lacking.

A literature search of gamma producing reactions for light projectiles on light-to-medium mass target nuclei [15,16,17] did not reveal any <u>prompt</u> gamma reactions for the common light plasma impurities (carbon and oxygen, for example) at proton or deuteron energies of $\lesssim$ 200 keV.

Since nuclear reactions with charged particles are hindered by the repulsive Coulomb interaction with the nucleus, significant gamma yields for higher masses ($A \gtrsim 25$) are less likely (with the possible exception of some radioactive isotopes) and were not surveyed. However, potentially useful reactions exist for some light elements which do not usually occur as plasma impurities, but which might be used to seed the plasma for the purpose of investigating light ion impurity pheonomena. The possibility of such diagnostics is interesting because in the core of fusion plasmas the light impurities are fully ionized and therefore not amenable to conventional spectroscopy measurements, but might be diagnosed by fusion gamma methods. Of possible interest in this connection is the reaction [17, 18, 19]

$$^{11}B + p \rightarrow {}^{12}C + \gamma \tag{4}$$

which has a resonance at a proton energy of E_p = 163 keV yielding gamma rays of energies 16.11, 11.68, and 4.42 MeV with an emission percentage [20] per reaction of 3.5, 96.5, and 96.5, respectively, and a total cross section of 157 μb. In passing, it is of interest to note that the $^{11}B(p, 2{}^4He)\,{}^4He$ reaction is one of the candidates being considered for advanced reactor fuel cycles in which fusion reactions yield only charged particle products. For this fusion cycle, as for the D-^{3}He cycle mentioned earlier, fusion gamma diagnostic appears to be the only method which would be capable of direct measurement of the fusion reaction rate.

Another "seeded impurity" reaction having potential application is the reaction [21]

$$ {}^{7}\mathrm{Li} + p \rightarrow {}^{8}\mathrm{Be} + \gamma \qquad (5) $$

which has a resonance at a proton energy of E_p = 441 keV yielding 15-and 18-MeV gamma rays with a cross section at the resonance peak of 7.2 mb.

III. EXPERIMENTAL CONSIDERATIONS

The application of fusion gamma diagnostics will be discussed in the context of the TFTR machine, since this represents the most promising near-term test bed. Furthermore, attention is focused on the $T(d,\gamma)^5He$ reaction since the copious 14 MeV neutron background and associated induced gamma radiation presents a more severe diagnostic environment than for the $^3He(d,\gamma)^5Li$ reaction.

A crucial experimental consideration in applying fusion gamma diagnostics is the selection of a suitable detector. During high power tritium operation, the TFTR diagnostic area is bathed in a neutron and gamma radiation background with a broad energy spectrum ranging from $\sim$ 14 MeV to thermal at total flux densities of the order of 2×10^{11} cm^{-2} sec^{-1} for both neutrons and gammas. Radiation dose levels are estimated to be 100 rad (Si) sec^{-1} per discharge and 4×10^5 rad (Si) over the operational life of the tokamak. For general utility, a detector with the following characteristics is desired:

1. Detector Efficiency: the 16.7 MeV gamma detection efficiency should be high ($\gtrsim 10^{-2}$) while the response to $E \lesssim 14$ MeV neutrons should be low ($\lesssim 10^{-4}$).

2. Time Response: a scintillator decay time of $\lesssim$ 10 nsec is required in order to obtain good counting statistics (10^2 - 10^3 counts) within a measurement time resolution of 1-10 msec while avoiding detector pulse pile-up or saturation due to extraneous neutron and gamma counts.

3. Energy Resolution: only a modest detector energy resolution of $\lesssim$ 15% is required since the 16.7 MeV fusion gamma emission lies well above the 14 MeV neutron energy and the concomitant gamma background.

4. Radiation Damage: the detector must operate without suffering radiation damage or significant performance degradation at a cumulative dose level of up to 4×10^5 rad (Si).

The high count rate requirement ($\lesssim 10^6$ cps) during a tokamak discharge precludes use of sophisticated electronic signal processing techniques such as coincidence counting and pulse shape discrimination to reject neutron events and pulse pile-up. Under the most interesting tokamak experimental conditions, therefore, the only viable signal processing method appears to be simple counting with pulse amplitude discrimination. During low yield discharges, however, the more sophisticated techniques noted above may be advantageous.

The standard gamma ray scintillation detector, NaI(Tℓ), satisfies the above requirements except for time response. Even in the relatively benign environment of accelerator experiments investigating the $T(d,\gamma)^5He$ reaction [23], pulse pile-up of low energy ($\lesssim$ 8 MeV) gammas as a consequence of the slow decay time (230 nsec) of NaI(Tℓ) produces a background that interferes seriously with the 16.7 MeV gamma energy region of interest. Likewise, bismuth germinate ($Bi_4Ge_3O_{12}$) exhibits good gamma detection properties in a neutron field [23], but also has an unacceptably long decay time of ~ 300 nsec. The most suitable detector appears to be NE226, a hexafluorobenzene based liquid scintillator which has a decay time of 3.3 nsec and a light output of 20% relative to anthracene [24]. In the energy range of 0.5-10 MeV, Ewen and Gonsior [25] found that the gamma ray and neutron efficiencies of NE226 were 25% and 0.4% respectively relative to NaI(Tℓ). The gamma emission due to neutron capture in NE226 occurs predominantly at energies below 10 MeV [26] which enables use of pulse amplitude discrimination to further suppress neutron interference with the ~ 16.7 MeV gamma energies of interest provided detector saturation is avoided.

Proper design of the gamma collimator and detector shielding against unwanted neutron and gamma background radiation is another important factor in applying fusion gamma diagnostics. Although such a design is beyond the scope of this paper, some general aspects of detector shielding are discussed. First, it is noted that the neutron and gamma backgrounds for TFTR are similar both in energy distribution as well as intensity. Second, the NE226 detector permits both intrinsic and electronic discrimination against neutron detection. The detector shielding, therefore, should primarily address background gamma attenuation with neutron shielding being of secondary importance. A conceptual shielding configuration is shown schematically in Fig. 3. The outer layer is 60 cm thick paraffin loaded with boron (25% B_2O_3 by weight) which provides a neutron attenuation of $\sim 5 \times 10^{-3}$ and a gamma attenuation of $\sim$ 0.4. The inner shield is 40 cm thick lead which provides a gamma attenuation of $\sim 5 \times 10^{-7}$ and a neutron attenuation of $\sim 10^{-2}$. The collimating nozzle consists of a lead shroud with a central plug of $\sim$ 120 cm length boron-loaded paraffin which provides an attenuation of direct flight neutrons to the detector of $\sim 3 \times 10^{-5}$ with a gamma attenuation of $\sim$ 0.20. A thinner lead disc in front of the NE226 detector serves to attenuate low energy gamma flux entering through the collimator. The combined shielding gives an estimated background attenuation of $\lesssim 5 \times 10^{-5}$ for neutrons and $\lesssim 2 \times 10^{-7}$ for gammas. Thus for background and aperture streaming neutron levels of 2×10^{11} cm^{-2} sec^{-1}, the attenuated neutron flux at the detector is $\lesssim 10^{7}$ cm^{-2} sec^{-1} which combined with a conservative neutron detection efficiency of 10^{-4} [27] yields a neutron induced count at the detector of $\lesssim 10^{3}$ cm^{-2} sec^{-1}. At a background gamma level of 2×10^{11} cm^{-2} sec^{-1}, the shielded intensity at the detector is $\lesssim 2 \times 10^{4}$ cm^{-2} sec^{-1}. Since the gamma radiation is primarily produced by neutron collisions with massive structures in the tokamak environment, an aperture streaming gamma level well below that for neutrons is expected by arranging the gamma collimator nozzle to view the plasma through a minimum of structural material.

An estimate of the 16.7 MeV prompt fusion gamma count rate at the NE226 detector is obtained using:

$$S = R \cdot \frac{d\Omega}{4\pi} \cdot V \cdot \xi_A \cdot \xi_D \qquad (1)$$

where $d\Omega$ =solid angle subtendend by the detector at the plasma (steradians)

V = plasma volume viewed (cm^3)

ξ_A = attenuation losses in the collimator

ξ_D = detector efficiency

and R = reaction rate for 16.7 MeV gammas (cm^{-3} sec^{-1}).

For convenience, the reaction rate R is expressed as the product of the dominant particle production rate and the 16.7 MeV gamma branching ratio with respect to the particles. Thus for the $T(d,\gamma)^5He$ reaction

$$R_{DT} = R_n \frac{\sigma_{T(d,\gamma)}}{\sigma_{T(d,n)}} \qquad (2)$$

where R_n is the 14 MeV neutron reaction rate and for the $^3He(d,\gamma)^5Li$ case

$$R_{D^3He} = R_p \frac{\sigma_{^3He(d,\gamma)}}{\sigma_{^3He(d,p)}} \qquad (3)$$

where R_p is the 14.7 MeV proton reaction rate. Choosing a detector of radius r = 10 cm located a distance L = 500 cm from the plasma gives $d\Omega = \pi r^2/L^2 = 1.3 \times 10^{-3}$ sr. The viewed plasma volume is taken to be a cylinder of radius 20 cm and length 40 cm giving $V = 5 \times 10^4$ cm^3. For 16.7 MeV gamma rays, the collimator attenuation as discussed above is $\xi_A = 0.2$ and the NE226 detector efficiency is taken to be $\xi_D = 10^{-2}$. Combining the above values in Eq. (1) along with the branching ratio, $\sigma_{T(d,\gamma)}/\sigma_{T(d,n)} = 2.1 \times 10^{-4}$ yields a detector count rate of $S = 2 \times 10^{-6} R_n$ sec^{-1}.

The 14 MeV neutron reaction rate per unit volume shown in Fig. 4 is obtained from code calculations [28] for 20 MW injection of 120 keV dueterium into a TFTR tritium plasma of density $n_e \sim 7 \times 10^{13}$ cm^{-3} as a function of plasma temperature ($T_e = T_i$). The spread in reaction rate reflects a range of anticipated plasma parameters (such as impurity concentration and energetic particle loss rate due to charge exchange) which affect the beam slowing-down and loss processes and hence the neutron yield. Beam-beam and plasma thermal contributions to the neutron production rate are not included. Since these contributions are the order of 20%, Fig. 4 provides a conservative value of the $T(d,\gamma)^4$He 14 MeV neutron yield. For exemplary purposes, a value of $R_n \simeq 4 \times 10^{11}$ neutrons/cm^3/sec corresponding to $T_i \sim 5$ keV is taken from Fig. 4 which results in an estimated detector count rate for 16.7 MeV gammas of $S = 2 \times 10^{-6} R_n = 8 \times 10^5$ sec^{-1}. Thus even for modest TFTR performance conditions, the experimental configuration described above predicts 16.7 MeV gamma count rates suitable for good fusion gamma measurement statistics with adequate spatial resolution and time resolution of the order of 1-10 msec. From the earlier discussion of background suppression by detector shielding, signal-to-noise ratios in the range of $\gtrsim$ 100 appear to be attainable. However, such a favorable signal-to-noise ratio is not essential because the choice of a fast scintillator would permit background count rates which exceed the 16.7 MeV signal by two or three orders of magnitude provided the background pulse height is below $\sim$ 10 MeV gamma equivalent to permit rejection by simple pulse amplitude discrimination.

Application of fusion gamma diagnostics is examined for a D-^{3}He plasma in which an energetic ^{3}He minority species is created by Ion Cyclotron Resonance Heating (ICRH). In PLT, direct ion cyclotron damping on ^{3}He minority species in a deuterium plasma [29] has demonstrated efficient heating at power levels exceeding 1 MW and similar experiments are being planned for the TFTR at power levels comparable to that provided by neutral beam injection. Such heating generates two sources of energetic ^{3}He particles: 1) ^{3}He pumped by absorption of wave power to energy levels of $\sim$ 200 keV or more depending on the confined energetic particle orbits, and 2) ^{3}He born in the D(d,n)^{3}He fusion reaction with an energy of 820 keV. ^{3}He(d,p)^{4}He reaction rates in excess of 10^{12} sec^{-1} have been observed in PLT by detection of the unconfined 14.7 MeV protons during heating of D -^{3}He plasmas both by ICRH and injection of $\sim$ 40 KeV, 2.2 MW deuterium neutral beams [30]. Under suitable conditions, use of gamma diagnostic techniques in principle would allow observation of the slowing-down and confinement of fusion born ^{3}He as the particles pass through the reaction resonance energy, similar to measurements reported [31] for the confinement of fusion-produced tritium by 14-MeV neutron diagnostics of deuterium plasmas heated by deuterium neutral beam injection in PLT. We also note that comparison of the ^{3}He(d,γ) and the D(d,n) reaction rates using fusion gamma and neutron diagnostics, respectively, would provide a measurement of the approach to plasma ignition when the relative densities of D and ^{3}He are known, as is expected.

The ^{3}He(d,γ)^{5}Li reactivity per deuteron for an ICRH induced energetic ^{3}He distribution shown in Fig. 5 is obtained from code calculations [32] for the following plasma conditions: $T_d = T_e = 1.5$ keV and $n_e = 4 \times 10^{13}$ cm^{-3} with a 10% ^{3}He minority density. The reactivity is plotted as a function of the truncation energy of the energetic ^{3}He distribution which reflects the fast ion containment conditions. Curves are shown for plasma ICRH power density deposition values of 0.5, 1.0, and 1.5 W cm^{-2}. Taking a reasonable reactivity value of 10^{-7} sec^{-1} per deuteron for ICRH in TFTR at a deuteron density of 4×10^{13} cm^{-3} gives a proton reaction rate of $R_p = 4 \times 10^6$ cm^{-3} sec^{-1} for the ^{3}He(d,p)^{5}Li reaction. Using the same branching ratio in Eq. (3) as for the T(d,γ)^{5}He case (as predicted under the hypothesis of charge independence of nuclear forces) as well as the same experimental configuration leads to a 16.7 MeV count rate at the detector for the ^{3}He(d,γ)^{5}Li reaction of $S = 2 \times 10^{-6}\ R_p = 8$ sec^{-1}. This count rate is obviously inadequate and indicates that a different experimental arrangement is required for ^{3}He(d,γ)^{5}Li reaction diagnostics. For D-^{3}He plasmas, both the energy and intensity of the neutron and gamma radiation background is relatively benign since only modest yields of 2.5 MeV neutrons are produced by plasma thermal D(d,n)^{3}He reactions and the collision induced gamma level for 2.5 MeV neutrons is small compared with 14 MeV neutrons. This in turn permits a significant reduction in shielding and collimation requirements which allows positioning the detector closer to the plasma thereby increasing the product of the solid angle and viewed plasma volume by orders of magnitude, albeit at the expense of spatial resolution. Also use of a NaI(Tℓ) detector may be advantageous in this case since high gamma efficiency is more important than the issue of neutron detection efficiency [33] and the lower anticipated count rates relax the scintillator response time requirements compared with the $T(d,\gamma)^5He$ application.

Though the experimental considerations presented above are admittedly rough, the results indicate that fusion diagnostics based on the measurement of prompt 16.7 MeV gamma emission from the $T(d,\gamma)^5He$ and $^3He(d,\gamma)^5Li$ reactions merit further investigation. A fusion gamma diagnostic development effort is underway at the Princeton Plasma Physics Laboratory for application to the TFTR fusion breakeven experiments in the mid-1980 time frame. The program includes assessment of NE226 detector characteristics for 14 MeV neutron and 16.7 MeV gamma radiation using the PPPL Neutron Generator Facility.

IV. SUMMARY

The concept of fusion gamma diagnostics which exploits, for example, the prompt emission of 16.7 MeV gamma radiation from the $T(d,\gamma)^5He$ and $^3He(p,\gamma)^5Li$ reactions, offers a new and potentially powerful technique for fusion reaction rate measurements. In near-term experiments and first generation reactors based on D-T burning, fusion gamma diagnostics offers independent corroboration of fusion rate measurements obtained using standard neutron diagnostics. For future reactors utilizing "neutron-free" advanced fuel cycles, fusion gamma diagnostics becomes the only direct method to measure fusion reaction rates.

The evaluation and application of fusion gamma diagnostics is hampered at the present time due to nonexistent or discordant data on cross sections and/or branching ratios for the fusion gamma reactions of interest. In particular, reliable data is required for the $T(d,\gamma)^5He$ and the $^3He\ (d,\gamma)^5Li$ reactions in the 10-1000 keV energy range.

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FIGURE CAPTIONS

Fig. 1 $T(d,\gamma)^5He$ Cross Sections for 16 MeV Gamma Production. Data from: O[11], Δ[9], and [] [12].

Fig. 2 Cross Sections for Proton [14] and Gamma [13] production in D-^3He Reactions.

Fig. 3 Schematic Experimental Arrangement for Fusion Gamma Diagnostics on the Tokamak Fusion Test Reactor (TFTR). The indicated scale is approximate.

Fig. 4 $T(d,n)^4He$ - 14 MeV neutron flux density for 20 MW - 120 keV deuterium injection $n_e \equiv 7 \times 10^{13}$ cm^{-3} TFTR tritium plasma. Data corresponds to beam-plasma interactions only with data spread reflecting variation of beam slowing-down and loss factors. [Courtesy of Harry H. Towner].

Fig. 5 $D(^3He,p)^4He$ Reactivity per deuteron for ^3He Minority Ion Cyclotron Resonance Heating at $n_e = 4 \times 10^{13}$ cm^{-3} with a 10% ^3He Minority Density plotted as a function of ^3He Truncation Energy.

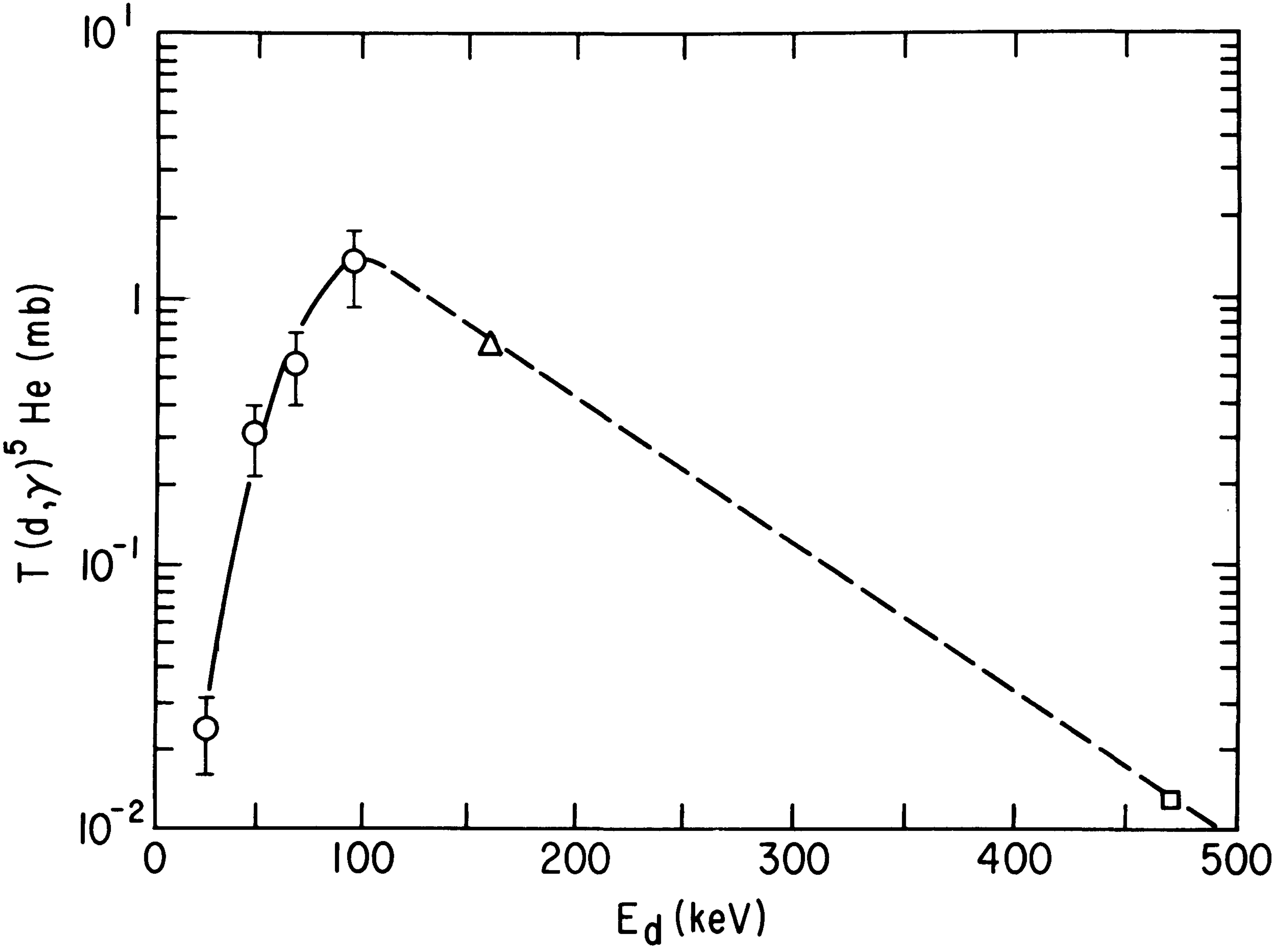

FIG. 1

#81X0240

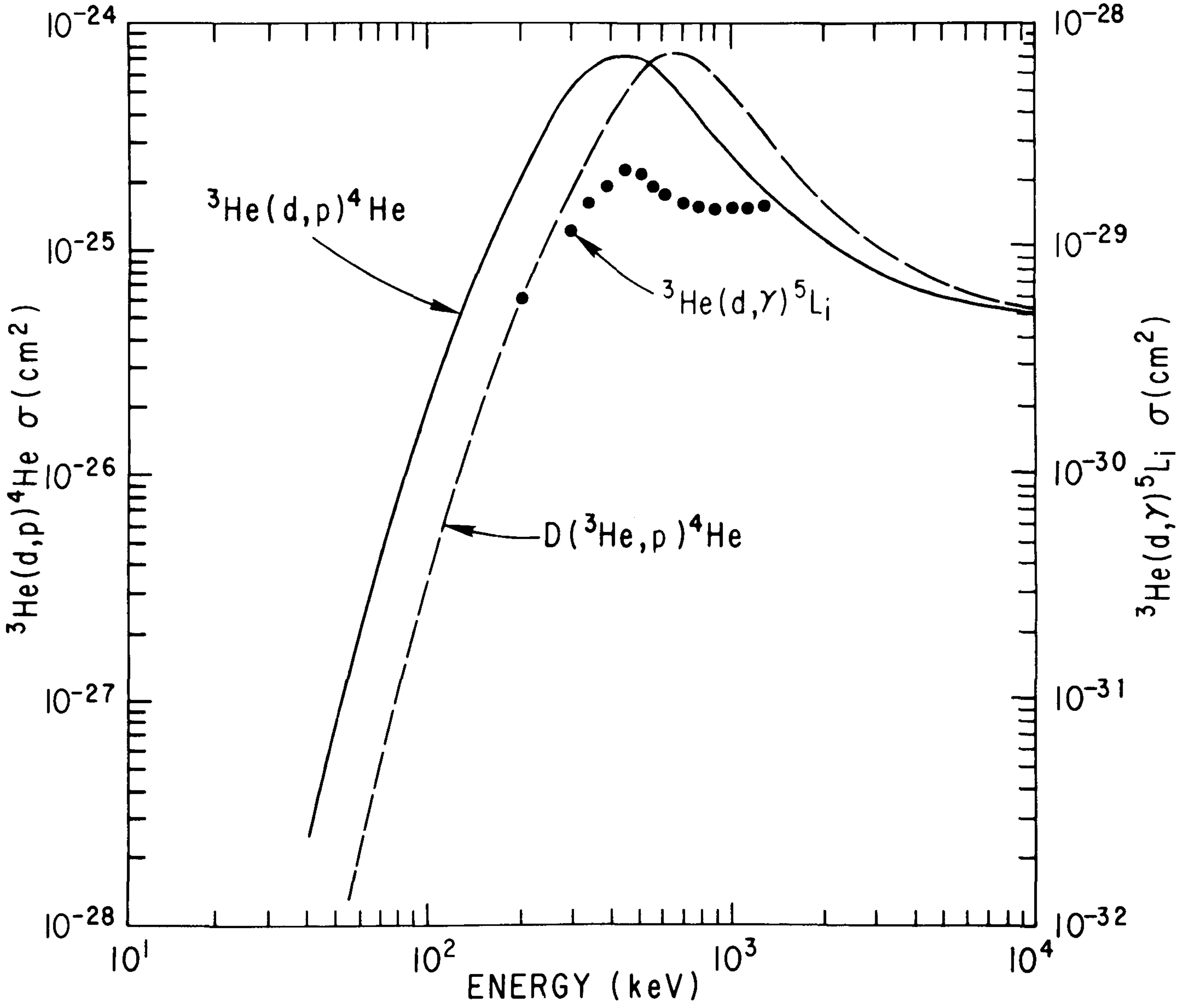

FIG. 2

#82X0827

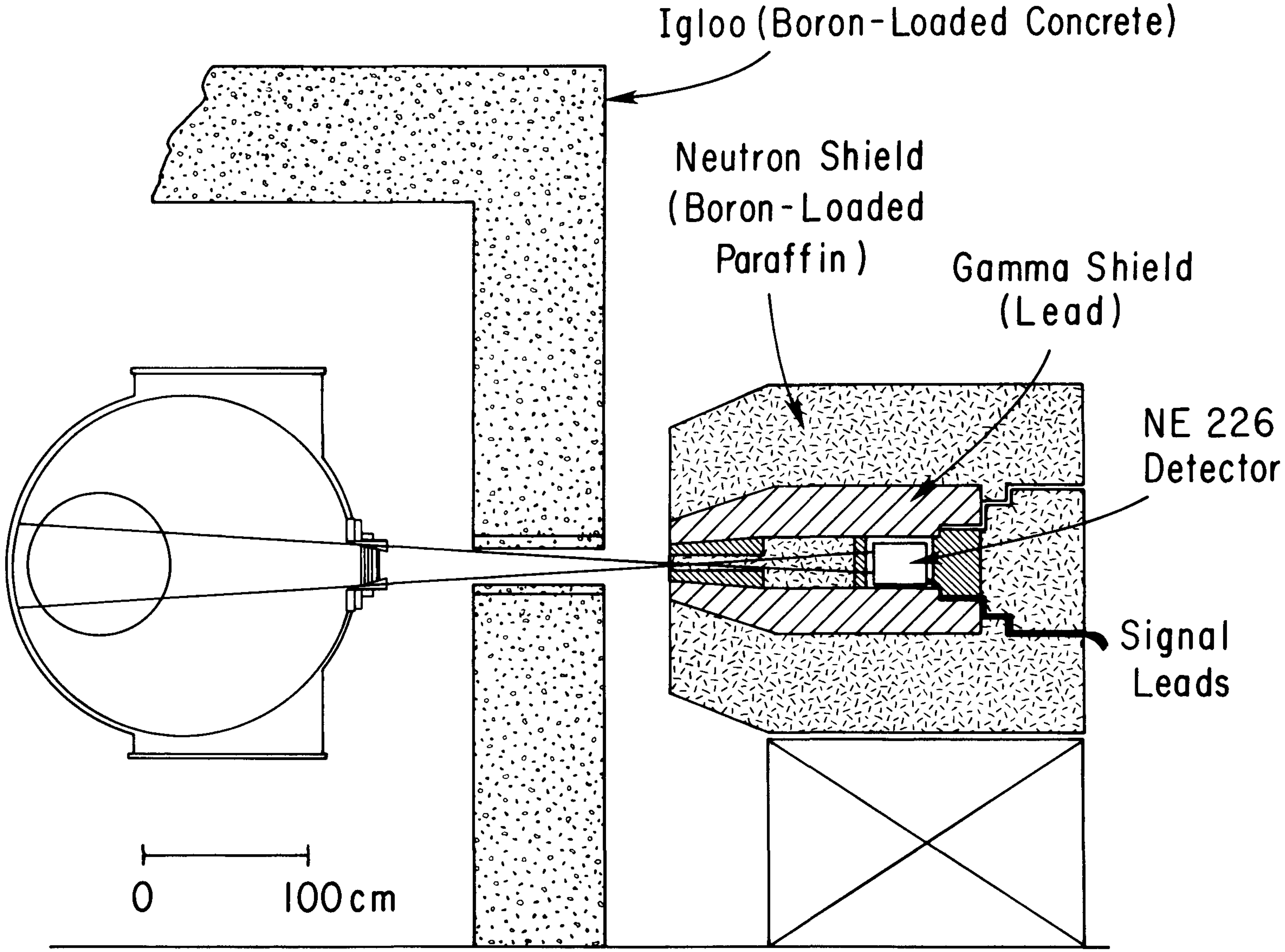

FIG. 3

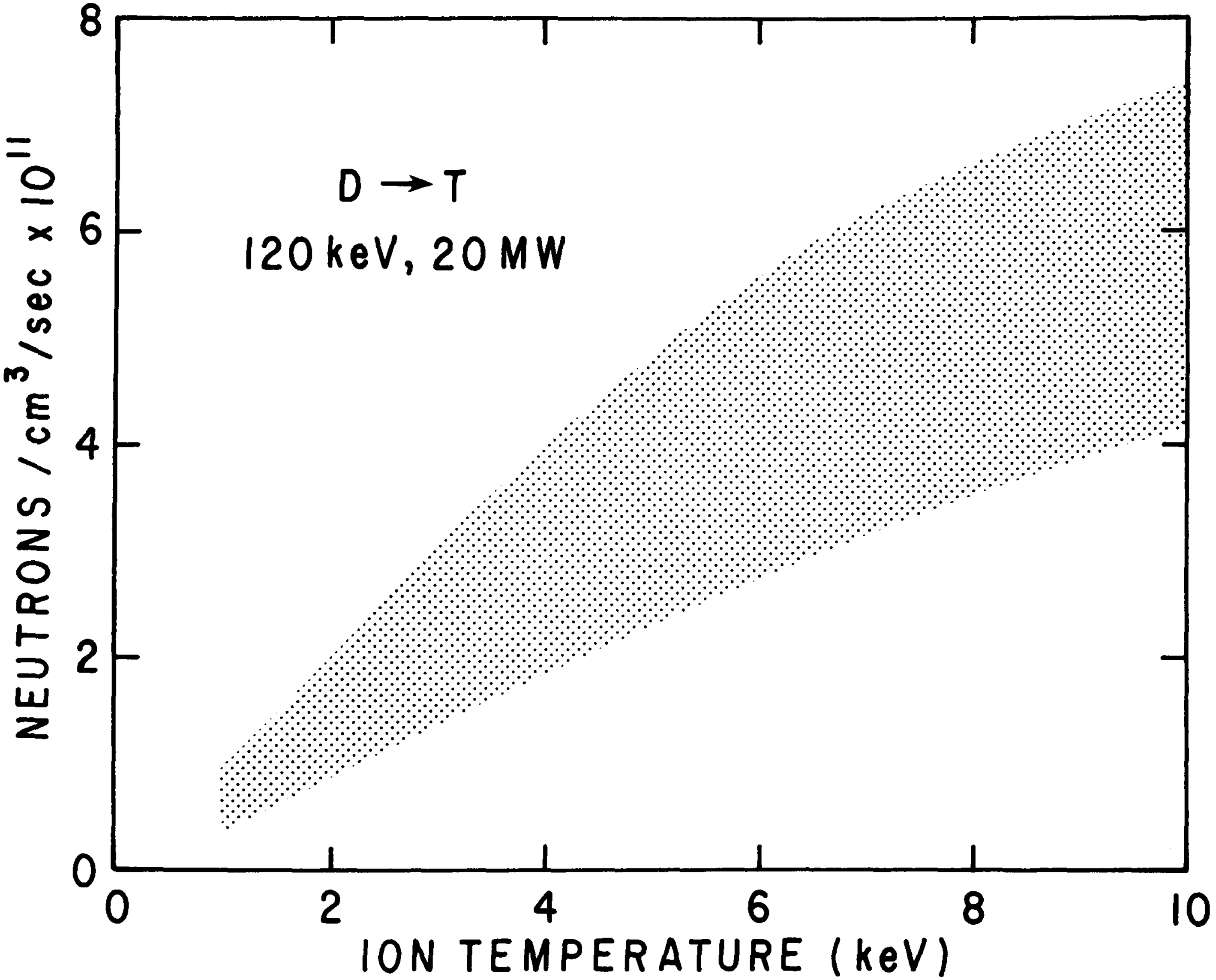
D → T
120 keV, 20 MW
NEUTRONS /cm³/sec x 10¹¹
ION TEMPERATURE (keV)
0
2
4
6
8
0
2
4
6
8
10

FIG. 4

#81X0241

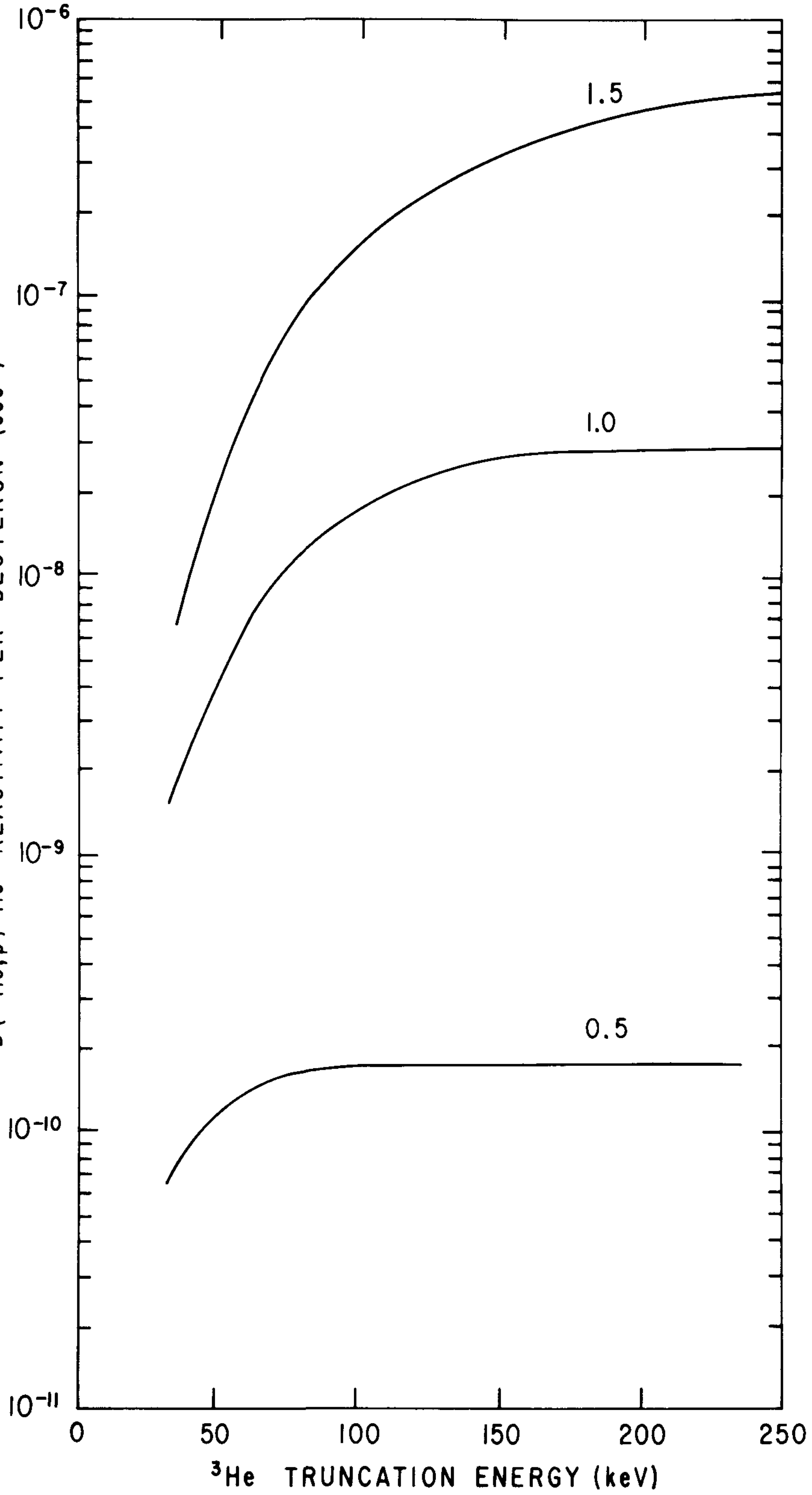

FIG. 5

DO NOT MICROFILM

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