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A METHOD FOR DETERMINING FAST-ALPHA-PARTICLE CONFINEMENT IN TOKAMAK PLASMAS USING RESONANT NUCLEAR REACTIONS

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A Method for Determining Fast-Alpha-Particle Confinement in Tokamak Plasmas using Resonant Nuclear Reactions

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Abstract

The resonant nuclear reactions $D(\alpha,\gamma)^6Li$, $^6Li(\alpha,\gamma)^{10}B$, and $^7Li(\alpha,\gamma)^{11}B$ are examined as diagnostics of fast-alpha-particle confinement in tokamak plasmas. Gamma rays from these resonant reactions with energies from 2.1 MeV to 9.2 MeV may be used to infer the alpha-particle population between energies of 0.4 MeV and 2.6 MeV. The ratio of these alpha-burnup reactions to the reactions $T(D,\gamma)^5He$ and $^3He(D,\gamma)^5Li$ provides a technique for the measurement of alpha confinement.

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I. INTRODUCTION

The confinement of the 3.5 and the 3.7-MeV alpha particles from the D-T and D-^{3}He reactions in magnetic confinement fusion devices represents an abiding concern of the controlled fusion effort. A number of approaches to the problem of measuring the extent to which the alpha particles are confined have been proposed [1-3]. Most recently, Slaughter [4] has noted that the study of products from alpha-induced reactions on either the indigenous or artificially seeded ions in a plasma might yield important information on the spatial and energy distribution. We would like to point out the existence of a relatively small number of narrow resonances in (α,γ) reactions on light nuclei which are accessible to alpha particles with energies up to 3.7 MeV. These resonances offer a potential technique for studying the extent to which the fast alphas in fusion plasmas are confined. Specifically, the spectrometry of the gamma rays from these reactions will reflect the value of the alpha-particle distribution at the energy of the (α,γ) resonance. There are two advantages to this technique:

(i) the reaction cross sections can be quite large and

(ii) the narrowness of the resonance can be exploited to enhance the signal-to-noise ratio in the gamma-ray energy spectrum.

The technique is illustrated schematically in Fig. 1 which shows the resonant cross section of an (α,γ) reaction and also shows, schematically, two equilibrium alpha-particle-energy distributions. These distributions represent plasmas for which, on the one hand, the alpha-particles are very well confined and, on the other, are very poorly confined. The proposed technique distinguishes very simply between these two cases of confinement; to wit, the gamma ray associated with the resonant (α,γ) reaction whose cross section is indicated will be produced in the plasma with good alpha-particle confinement. The gamma ray will not be produced by the plasma with poor alpha confinement. A series of resonances with energies between zero and 3.5 MeV will allow the alpha-particle-energy distribution to be evaluated pointwise at these energies.

In the next section, general expressions for the gamma-ray yields and gamma-ray energies will be presented in terms of the parameters of the resonances. These expressions will be applied to the (α,γ) resonances on light nuclei accessible to alpha particles with energies up to 3.7 MeV. In addition, it will be shown that the recently measured [5,6] cross sections for the production of the 16.7-MeV and 16.6-MeV gamma rays from the D-T and D-^{3}He reactions at low energies permit an independent determination of the production rate of the 3.5-MeV and the 3.7-MeV alpha particles to be compared to the yields of the resonant gamma rays. In the following section, count rate estimates will be made and the problems associated with observing the resonant reaction gamma rays in the presence of harsh gamma and neutron backgrounds will be discussed. In the last section, several specific examples, including DT Q=1 plasmas on TFTR, will be examined.

II. GAMMA-RAY YIELDS AND ENERGIES

The energy of the emitted gamma ray from a particular resonant (α,γ) reaction depends upon the energy of the excited state in the alpha-target compound system. For decay to the ground state, the gamma-ray energy will equal the excitation energy. For decays to some intermediate state, the gamma-ray energy corresponds to the difference in excitation energies of the two states.

The excitation energy in the alpha-target system will be

$$E_X = Q + \frac{m_{tgt}}{m_\alpha + m_{tgt}} E_R \ , \tag{1}$$

where

$$Q = (m_\alpha + m_{tgt} - m_{final})\ c^2 \quad . \tag{2}$$

The subscripts refer to the alpha particle, the target nucleus and the final nucleus, and E_R is the laboratory kinetic energy of the alpha particle at which the resonance occurs. Thus, in the case of the reaction $^6Li(\alpha,\gamma)^{10}B$, Q = 4.460 MeV and the resonance which occurs at an alpha-particle energy of 1.175 MeV corresponds to the 5.166-MeV excited state in ^{10}B. This state decays primarily through the 2.154-MeV excited state and, thus, the energy of the primary gamma ray from the reaction will be 3.012 MeV [7]. These energetics are illustrated in Fig. 2. The alpha-particle laboratory kinetic energy at which the resonance occurs will be shifted if the target ions are in motion, but the excitation energy in the product nucleus, and hence the gamma-ray energy, will not be shifted. Thus, in the context of the present discussion, if the D-T or D-^{3}He plasma which is producing 3.5 or 3.7-MeV alpha particles is seeded with a certain level of ^6Li then, when the alpha particle has slowed to a laboratory kinetic energy of 1.175 MeV, there will be a nonzero probability of the $^6Li(\alpha,\gamma)^{10}B$ reaction taking place with the prompt emission of a 3.012-MeV gamma ray. Since the excited state through which the reaction resonates has an intrinsic finite width Γ, the total yield of gamma rays per unit volume from a given resonance is given by an energy integral over the width of the state:

$$Y_\gamma = n_{tgt} \int \sigma(E)\, n_\alpha(E)\, v_\alpha dE \;, \tag{3}$$

where n_{tgt} is the target density, E and v are the alpha-particle energy and velocity, and $n_\alpha(E)$ is the alpha-particle-energy distribution.

If we neglect the normally small nonresonant contribution to the cross section, (typically one or two orders of magnitude down) then the energy dependence of the cross section assumes the well-known Breit-Wigner form:

$$\alpha(E) = \frac{\sigma_R\ (\Gamma^2/4)}{(E-E_R)^2 + \Gamma^2/4} \;, \tag{4}$$

where σ_R is the value of the cross section at the peak of the resonance. Assuming the alpha-particle-energy distribution to be constant over the width of the resonance, the total yield of gamma rays from a given resonance per unit volume is:

$$Y_\gamma = [n_{tgt}\ n_\alpha(E_R)\ v_\alpha] \int \sigma(E)\ dE \quad . \tag{5}$$

With the expression for $\sigma(E)$ in Eq. (4), the integral in Eq. (5) may be evaluated analytically; thus,

$$Y_\gamma = n_{tgt}\ n_\alpha(E_R)\ v_\alpha \pi\ \sigma_R\ \Gamma/2 \quad . \tag{6}$$

In the literature the quantity $\omega_\gamma = \pi\ \sigma_R\ \Gamma/\lambda^2$, with $\lambda = h/p$ being the de Broglie wavelength of the alpha particle, is often used to characterize a resonance. In terms if ω_γ, we may then use Eq. (6) to calculate the yield of a given resonant gamma ray:

$$Y_\gamma = n_{tgt}\, n_\alpha(E_R)\, v_\alpha \omega_\gamma \lambda^2/2 \quad . \tag{7}$$

The resonances in the D-α, the ^{6}Li-α, and the ^{7}Li-α reactions which are accessible to alpha particles with energy up to 3.7 MeV are tabulated in Table 1, along with the resonance parameters [7,8]. It should be stressed that the 2.109-MeV resonance in the D-α reaction is the only resonant nuclear reaction which an alpha particle of energy less than 3.7 MeV will undergo with the primary plasma constituents, i.e., deuterons, tritons or ^{3}He ions, of the early generation fusion devices. Both the ^{3}He-α [9] and the T-α [10] cross sections rise smoothly to values of about 4 μb at E_α = 3 MeV. The gamma rays associated with these capture reactions will, therefore, be produced with continua of energies. From Eq. (1) it is seen that for the T-α reaction, the gamma-ray energy will vary between 2.7 and 4.0 MeV as the alpha-particle energy varies between 0.5 and 3.5 MeV. From the ^{3}He-α reaction, the gamma-ray energy will vary between 1.7 and 3.0 MeV as the alpha-particle energy varies between 0.5 and 3.5 MeV. These gamma rays will, accordingly, be difficult to measure in the presence of high neutron and gamma-ray backgrounds. In addition, it should be stressed that there are no reported resonances for (α,γ) reactions with low-energy alpha particles on light nuclei other than ^{6}Li and ^{7}Li. This exclusivity can be understood partly in terms of the neutron decay thresholds, which for ^{10}B and ^{11}B are well above the alpha-decay threshold, whereas, for other alpha-capture products, such as ^{13}C, ^{14}N, or ^{15}N, the neutron-decay threshold is well below the alpha-decay threshold.

Although Eq. (7) relates the production of a given resonant gamma ray to the alpha-particle-energy distribution, an independent measure of the alpha production rate is needed if the quality of the alpha confinement is to be addressed. In the case of D-T plasmas, the total alpha production rate will be equal to the total production rate of 14.7-MeV neutrons. There are well-established techniques for measuring this neutron production rate [11]. In the case of D-^{3}He plasmas, counting the escaping 15-MeV protons associated with the alpha production has been suggested [12] as a technique for inferring the alpha production rate. The recently measured cross sections for the $T(D,\gamma)^5He$ and $^3He(D,\gamma)^5Li$ capture reactions at low energies [5,6] are such that it may be possible to measure the total alpha production rate for plasmas where, in general, both the 3.5-MeV alphas from the D-T reaction and the 3.7-MeV alphas from the D-^{3}He reaction are being created.

Since the intrinsic widths of the 16.6-MeV gamma ray from the D-^{3}He capture reaction and the 16.7-MeV gamma ray from the D-T capture reaction are relatively large (1.5 MeV and 0.5 MeV, respectively), the two gamma rays will not be resolved. However, the total yield of gamma rays with energies between about 16 and 17 MeV can be determined with standard gamma-ray spectrometric techniques. The total gamma yield will be the sum of the yields from the D-T and D-^{3}He capture reactions:

$$Y_\gamma = \int [n_d \, n_t \, \langle\sigma v\rangle_{dt\gamma} + n_d \, n_{^3He} \, \langle\sigma v\rangle_{d^3He\gamma}] \, d^3x \; , \tag{8}$$

where the integral is carried out over the volume of the plasma. This yield may be expressed in terms of the gamma-to-alpha branching ratios $(\Gamma_\gamma/\Gamma_\alpha)$ for the D-T and D-^{3}He reactions:

$$Y_\gamma = \int [(\Gamma_\gamma/\Gamma_\alpha)_{dt} n_d \, n_t \langle\sigma v\rangle_{dt} + (\Gamma_\gamma/\Gamma_\alpha)_{d^3He} \, n_d \, n_{^3He} \langle\sigma v\rangle_{d^3He}] d^3x \quad . \tag{9}$$

Since both the D-T and D-^{3}He gamma-alpha branching ratios are, to within measurement uncertainties, equal [5, 6], we may factor their averaged value out of the integral in Eq. (9):

$$Y_\gamma = (\Gamma_\gamma/\Gamma_\alpha)_{av} \int [n_d\, n_t\, \langle\sigma v\rangle_{dt} + n_d\, n_{^3He}\, \langle\sigma v\rangle_{d^3He}]\, d^3x \quad . \tag{10}$$

But the integral in Eq. (10) is just the total production rate for the 3.5-MeV alphas from the D-T reaction and the 3.7-MeV alphas from the D-^{3}He reaction. Thus, the yield of gamma rays between about 16 and 17 MeV is simply related to the total alpha yield:

$$Y_\gamma = (\Gamma_\gamma/\Gamma_\alpha)_{av}\, Y_\alpha \quad . \tag{11}$$

A single gamma-ray spectrum may, therefore, be used to infer both the alpha production rate (from the yield of gamma rays between 16 and 17 MeV) and the alpha-particle-energy distribution (from the yields of the resonant gamma rays) [13].

III. COUNT RATES AND BACKGROUNDS

In this section, we present estimates of the count rates which might be expected if the (α,γ) resonances described in the preceeding section were to be utilized to study the alpha-particle confinement in D-T or D-^{3}He fusion devices. The yield of a specific resonant gamma ray (per unit volume) in the plasma is given by Eq. (7). These gamma rays can be measured with a detector, emplaced outside the plasma vacuum vessel, collimated to view a given volume of plasma, and shielded from the neutron flux associated with the plasma. For purposes of making estimates of the count rates and backgrounds associated with such measurements, a simplified gamma-ray energy spectrum is shown in Fig. 3. In this figure, the peak associated with the specific (α,γ) resonant gamma ray must be counted in the presence of a broad continuous gamma-ray background extending up to some energy E_{max}. In terms of the total isotropic flux Φ_B of uncollimated background gamma rays in the vicinity of the detector location, the total number T of gamma rays per second which will be recorded in the spectrum will be:

$$T = \Phi_B \, [A_c/(4\pi \ell_c^2)] \, A_D \, e^{-\mu x} \, \varepsilon_\gamma \, , \qquad (12)$$

where ε_γ is an average detector efficiency for gamma rays up to E_{max} and μ is an average gamma-ray absorption coefficient of the neutron shield with thickness x. A_c and ℓ_c are the aperture area and length of the collimator and A_D is the area of the front face of the detector. The background counts per second B under the width of the peak will be:

$$B = [\Delta E/E_{max}] \, T \, , \qquad (13)$$

where ΔE is the width of the peak. This width will, in principle, be limited by the intrinsic width Γ of the resonance but, in practice, will be limited, at least for the narrow resonances listed in Table 1, by the Doppler broadening of the gamma rays due to the alpha-particle motion. The yield per second P of the peak will be:

$$P = Y_\gamma \, V_{obs} \, [A_D/(4\pi r_D^2)] \, e^{-\mu x} \, \varepsilon_\gamma \, , \qquad (14)$$

where f_γ is given by Eq. (7), V_{obs} is the volume of the plasma observed by the collimator, and r_D is the distance from the detector to the center of the plasma. In Eq. (14), we obviously assume the yield Y_γ to be constant over the observed volume of the plasma.

The accuracy of the value of the inferred alpha-particle-energy distribution n_α at the resonance energy E_R will be limited by the statistical accuracy in the net peak counts N_p in the gamma-ray-energy spectrum for a total counting time t. Assuming simple counting errors, the fractional error in the peak counts will be:

$$\Delta N_p/N_p = [(B+P)t]^{1/2}/(P\ t) \quad . \tag{15}$$

We may thus calculate the time t_f required in order to make a measurement of the peak yield with a fractional error $f = \Delta N_p/N_p$:

$$t_f = (B+P)/[P^2\ f^2] \quad . \tag{16}$$

IV. EXAMPLES

It is instructive to consider a specific example in an effort to evaluate the viability of the proposed technique. For such an example, we consider the proposed Q=1 DT plasmas on Princeton's Tokamak Fusion Test Reactor (TFTR). These plasmas are expected to produce 10^{19} alphas per second. For this example, we will calculate, using Eq. (16), the time required to make a measurement of the 4.825 MeV gamma ray from the 0.985 MeV resonance in the ^{7}Li-α reaction to a statistical accuracy of 25%. Such a measurement obviously requires a seeding of the plasma with ^{7}Li. We will restrict our considerations to ^{7}Li concentrations in the 1-10% range.

As seen from Eq. (16), the time t_f required to carry out a measurement of the peak yields P to a given accuracy f is directly proportional to the background counts B. From Eqs. (12) and (13), this background B is directly proportional to the total, uncollimated background Φ_B. The gamma ray background Φ_B which is expected during the heating of D-D and D-T plasmas has been the subject of extensive calculation [14]. On TFTR, for example, for D-T plasmas with a total neutron production rate of 10^{19} neutrons/sec, a total prompt gamma ray background Φ_B of about 10^{12} gammas/(cm^2-sec) is expected at a radius of 8 m from the vacuum vessel. This background is expected to be roughly constant with energy up to a maximum value of about 10 MeV. These calculations will be used as the basis for our counting time estimates for prompt counting during steady-state plasma conditions

It should be noted that, in addition to the continuum gamma ray background discussed above, discrete gamma rays may be expected which would interfere with observing the gamma rays from the (α,γ) reaction. For example, the 2.224 MeV gamma ray from the thermal neutron capture on hydrogen which is expected in the proximity of hydrogenous shielding material will lie precariously close to the 2.186 MeV gamma ray from the $D(\alpha,\gamma)^6$Li reaction. More insidious still will be the gamma rays from (n,n') reactions in borated shielding materials which are identical in energy to those from the (α,γ) reactions on the ^{6}Li and ^{7}Li leading, respectively, to excited states of ^{10}B and ^{11}B. It would be incumbent upon the experimenter to check for the presence of these intruders by measuring the gamma ray spectrum without the lithium seeding of the plasma.

Calculations of the resonant gamma ray production rates presume a knowledge of the alpha-particle-energy distribution. If we assume that the alphas are perfectly confined, then we may estimate the alpha-particle-energy distribution n_α to be used in calculating the resonant gamma ray yields from Eq. (7). Following Post et al. [2] we assume that

$$n_\alpha(E) = n_\alpha(E_0)\ (E_0/E)^{1/2}\ (E_0^{3/2} + E_c^{3/2})/(E^{3/2} + E_c^{3/2}) \quad , \tag{17}$$

where $n_\alpha(E_0) = Y_\alpha\ t_s/(V\ E_0)$ and where Y_α is the total alpha-particle production rate; t_s is the total alpha-particle slowing down time, (which we take to be about 400 msec for the conditions being considered); V is the active alpha emission volume, for TFTR about 10 m^3; and E_0 is the initial alpha-particle energy (3.5 or 3.7 MeV for D-T or D-^{3}He plasmas, respectively). The cut-off energy E_c we take to be about 400 keV. Thus, for example, for an alpha production rate of 10^{19} alphas per second, we estimate a confined alpha-particle-energy distribution at E_α = 1 MeV to be about of 1.3×10^{12} cm^{-3} MeV^{-1}. For this value of the alpha particle energy distribution, we would like to calculate the counting times t_f for the 4.825 MeV gamma ray from the ^{7}Li-α resonance for two detector configurations and for two counting scenarios.

The two detector configurations are:

i) A single detector. We assume a 20 cm × 20 cm NaI detector in a 4 m long collimator which has a 10 cm × 10 cm aperture.

ii) A 10 × 10 array of detectors; each of the type described above.

The two counting scenarios are:

(i) Prompt counting during plasma heating. In this scenario we assume a neutron shield thickness of 3.5 m.

(ii) Delayed counting after plasma heating is turned off. In this scenario we assume a neutron shield thickness of 0.5 m.

(i) Single detector; prompt counting.

Starting with Eq. (7) $Y_\gamma = 940\ cm^{-3}\ sec^{-1}$; where we have taken $n_{tgt} = 1 \times 10^{12}\ cm^{-3}$ (i.e., a 1% concentration of ^7Li) and $n_\alpha = 1.3 \times 10^{12}\ cm^{-3} - MeV^{-1}$. It is worth noting parenthetically that this yield is greater by about two orders of magnitude than the yield of the 5.5 MeV gamma ray from the $D(p,\gamma)^3He$ reaction which was observed (in a low neutron background) in an earlier study of fusion gamma rays from D-III [15]. The above estimate of 940 cm^{-3}-sec^{-1} will result, using Eq. (14) and the detector parameters given above in a peak yield P = 0.74 counts-sec^{-1}. We have assumed that the detector is viewing an observed plasma volume of 0.45 m^3 from a distance of 12 m. From Eq. (12), the total prompt count rate in the detector will be T = 790 kHz. The background under the peak is given in Eq. (13), and is equal in this example to B = 3900 counts-sec^{-1}. The counting time required to make a measurement of the peak to an accuracy of 25% is given by Eq. (16) and is equal in this example to an unacceptably long counting time $t_f = 1.1 \times 10^5$ sec.

(ii) Detector array, prompt counting.

One parameter which can be adjusted in order to reduce the counting time to an acceptable value is the detector area. An array of detectors can have the effect of increasing the detector area without increasing the count rate in any one detector. Naturally, the signals will have to be processed individually and summed _ex post facto_. For the 10 × 10 array proposed above and for the parameters assumed in example (i), a counting time of 1100 sec is estimated. Again, this is an unacceptably long counting time. Another variable which could be varied in an effort to reduce the counting time is the concentration of the seeded ^{7}Li. By increasing the ^{7}Li concentration to 1×10^{13} cm^{-3} (10% assuming a D and T density of 1×10^{14} cm^{-3}), this counting time of 1100 sec could be reduced to 11 sec [see Eqs. (7) and (16)]. Such a ^{7}Li density must, however, be regarded as a significant perturbation on the plasmas conditions since it will result in a $Z_{eff} = 1.5$. Under present conditions, a counting time of 11 seconds would correspond to summing over several shots.

(iii) Single detector and delayed counting.

Another potential method for decreasing the count time is to reduce the neutron produced gamma ray background. Since there will be a significant time lag between when an alpha particle is produced and when it slows down to one of the resonance energies, a significant reduction in gamma ray background might be achieved by measuring the gamma ray spectra after the plasma heating is turned off. For example, for $T_e = 10$ keV and $n_e = 10^{14}$ the time for an alpha particle to slow down from 3.5 to 1 MeV is about 0.3 sec, whereas the neutron decay time $\tau_n \leq 30$ msec for an incident neutral deuterium beam energy of 120 keV [16]. Thus, at 0.3 sec after the heating is turned off, we may expect the neutron background, and the associated gamma ray background to have dropped off by more than four orders of magnitude. This decreased background will be used as the basis of our delayed counting estimates to be presented below. By virtue of this decreased neutron and gamma ray background, the thickness of the neutron shield can be reduced from the 350 cm used in the above example to 50 cm with no increase in the background. With this reduced shield thickness and with all other parameters as in the example above, the counting time can be reduced to 18 msec. This phenomenal decrease in counting time results largely from a thousand fold increase in the peak yield from 0.74 counts-sec^{-1} to 1300 counts-sec^{-1} [see Eq. (16)]. The total count rate in the detector during the delayed counting period will be 140 kHz.

(iv) Detector array, delayed counting.

By combining the increased area of the detector array with the reduced background expected in the delayed counting mode, the counting time will be further decreased. For a ^{7}Li density of 1×10^{12}, the 10×10 detector array proposed above will have a counting time of $t_f = 1.8 \times 10^{-4}$ sec for delayed counting. As in example (ii) above, the total count rate in each of the 10 detectors will be 140 kHz.

From the four examples considered above, we may draw two conclusions regarding the applicability of the proposed diagnostic to TFTR Q=1 plasmas:

(i) A carefully shielded and collimated 10 × 10 array of detectors should be able to observe the ^{7}Li-α resonant gamma ray within an 1 sec steady-state counting time for a 10% ^{7}Li concentration. As noted above, this will result in a Z_{eff} = 1.5, about the same as a 1% contamination of oxygen.

(ii) A single detector should be able to observe the gamma ray using the delayed counting technique within an 18 msec counting time for a 1% ^{7}Li concentration.

The proposed diagnostic technique should be applicable to the study of alpha particle confinement in plasmas other than the TFTR DT Q=1 scenario discussed above. Two specific cases are:

(i) D-^{3}He plasmas. D-^{3}He plasmas will produce 3.7 MeV alpha particles from the D(^{3}He,p)^{4}He reaction. For ICRF-heated plasmas with high concentrations of ^{3}He, the neutron production rate from the D-D reaction should be significantly less than the alpha production rate. This would allow the alpha particle confinement to be examined using the proposed technique in an environment where the gamma ray background is significantly reduced compared to the D-T situation examined above. In this example, the alpha production rate could be increased with decreasing the neutron background by polarizing the nuclei in the plasma [17].

(ii) P-^{6}Li plasmas. P-^{6}Li plasmas will produce 1.8 MeV alpha particles from the reaction $P(^6Li, ^3He)^4He$. The confinement of these alpha particles can be examined using the proposed technique (by virtue of the α-^6Li reactions presented in Table 1) with virtually no neutron generated gamma ray background.

In conclusion, the proposed diagnostic technique should prove useful in the study of confined alpha particles in Q=1 DT plasmas as well as other situations involving lower neutron backgrounds.

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Table 1. Resonant Reactions and Parameters.

Reaction	E_R(MeV)	E_γ(MeV)	ω_γ(keV)	Γ(keV)	σ_R(μb)
α-^2H	2.109	2.186	1.012	24	0.15
α-^6Li	1.085	5.112	0.059	1.63	21
	1.175	3.012	0.259	<0.5	292
	2.435	5.992	0.19	10	5.16
	2.605	6.024	0.34	0.08	1079
α-^7Li	0.401	8.920	0.01	<1	16.5
	0.819	4.736	0.31	0.003	8.3×10^4
	0.958	9.275	0.29	7	28
	0.958	4.825	1.2	7	117

FIGURE CAPTIONS

FIG. 1. Comparison of resonant cross section with (a) the alpha-particle-energy distribution in a plasma in which the alpha particles are well confined and (b) the alpha-particle-energy distribution in a plasma in which the alpha particles are poorly confined.

FIG. 2. Level diagram of ^{10}B showing relative energy of $^{6}Li + {}^{4}He$. An additional 0.706 MeV is needed in the Li-He system in order that it resonate with the 5.166-MeV level in ^{10}B. The 5.166-MeV level gamma decays 65% of the time to the 2.154-MeV level with the emission of a 3.012-MeV gamma ray.

FIG. 3. Schematic of an energy spectrum showing a narrow peak on a broad continuous background which extends up to a maximum energy E_{max}. There are P counts in the peak and B counts in the background region beneath the peak.

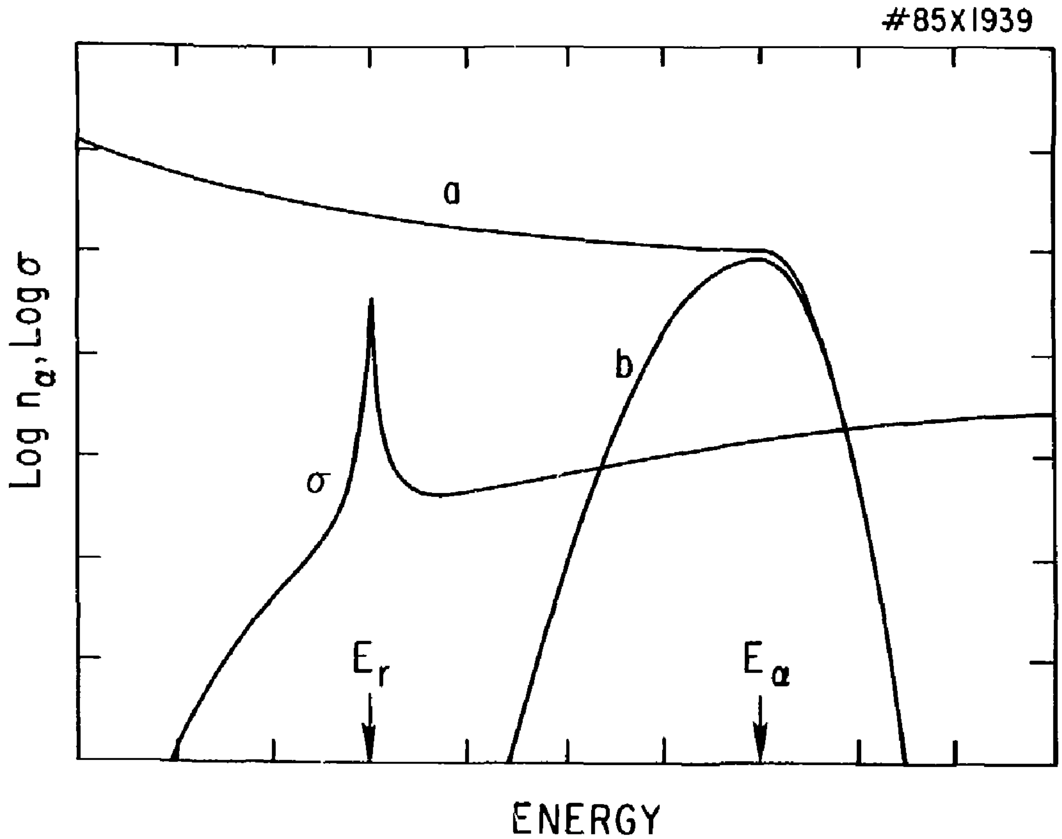

Fig. 1

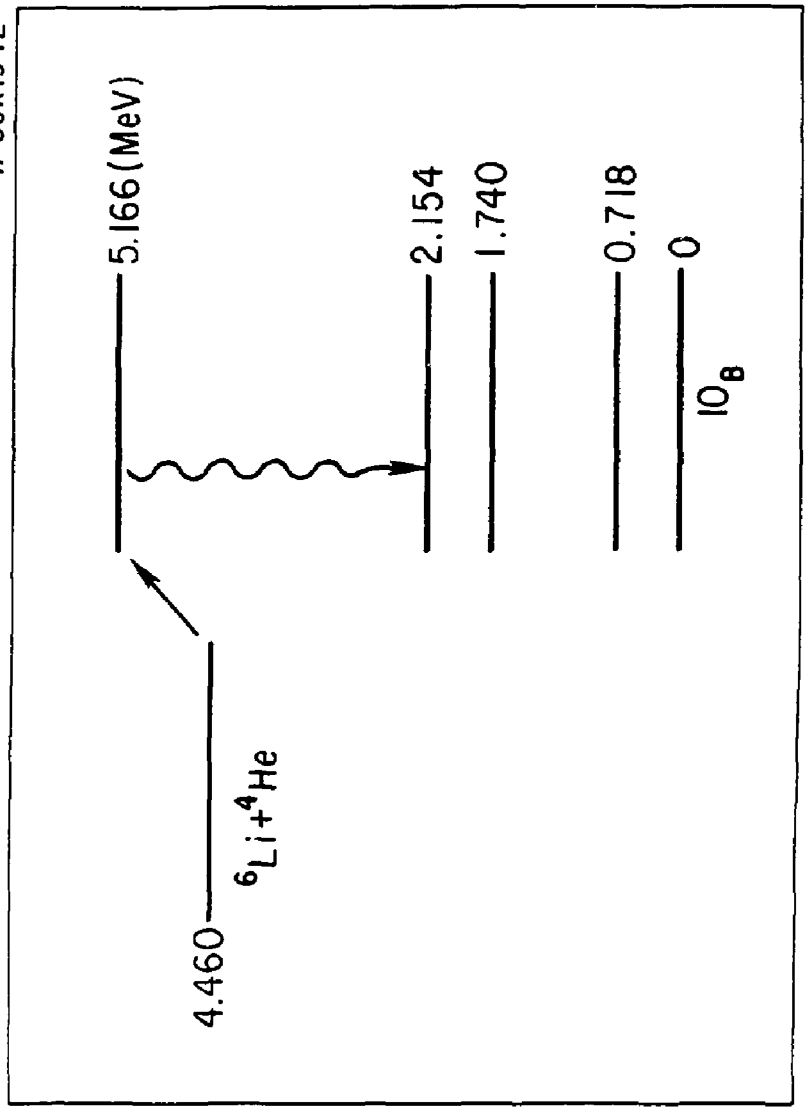

Fig. 2

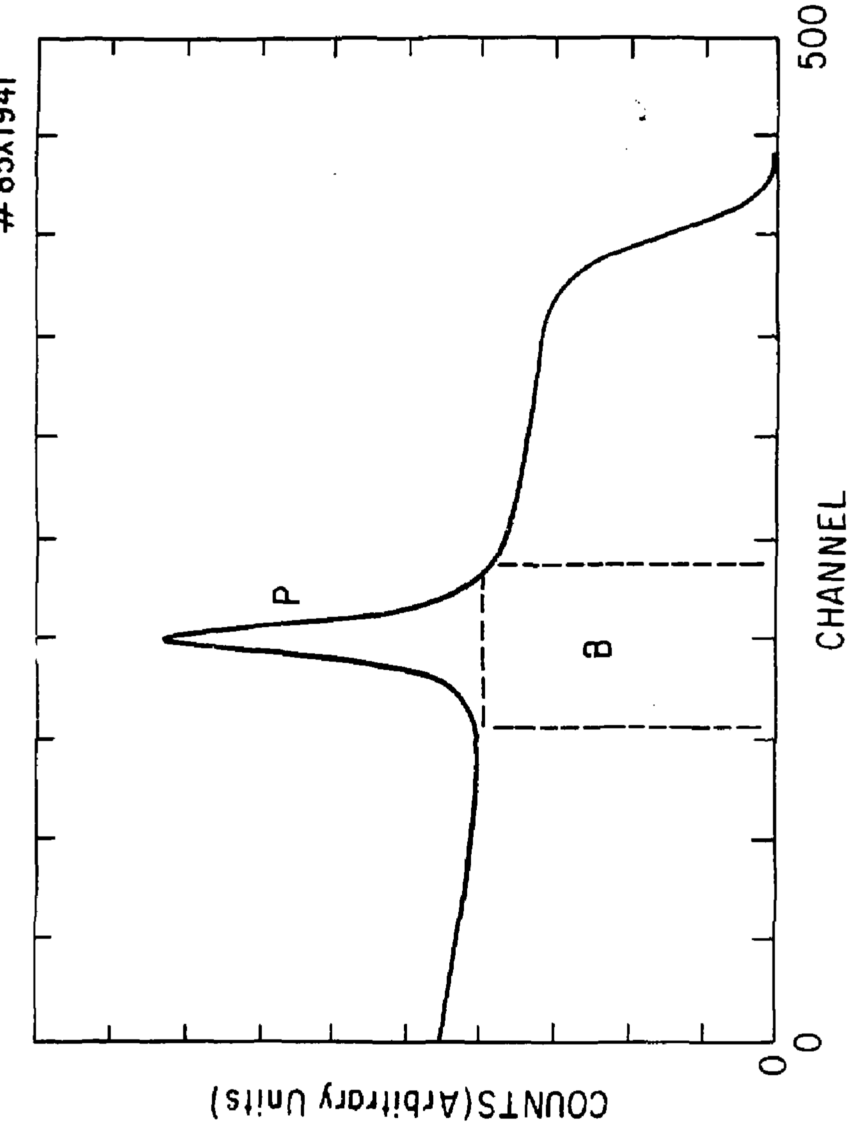

Fig. 3

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