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ESTIMATIONS OF THE EFFECT OF ALPHA PARTICLES ON A REFUELLING PELLET

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ABSTRACT

The effect of the α-particle from the D(T,n)α reaction on a 3 mm solid deuterium pellet was studied by disregarding the optimum of the refuelling process and limiting attention to the feasibility of pellet refuelling alone. A comparison of the refuelling period required with the slowing-down time of the α-particle in a D^+,e plasma corresponding to a 2.5 GW(e) reactor showed that the pellet is first subjected to the direct impact of α-particles of around 2-3 MeV energy. The penetration depth of these particles in the pellet is comparable to that of a 20 keV electron. If the temperature of the ablated cloud created around the pellet is about 1 eV, a cloud radius of about 20 cm is required for the subsequent thermalization of the α-particles.

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1. INTRODUCTION

The injection of a solid D_2 (or DT) pellet has long been suggested as a possible means of refuelling a fusion reactor[1, 2]. In the 2.5 GW(e) reactor envisaged by Hancox[3] (plasma temperature, kT = 20 keV, plasma density, $n = 1.8 \times 10^{14}$ cm^{-3}), the particle flux N_e and the energy flux F_e of the thermal electrons are 4.26×10^{23} cm^{-2} sec^{-1} and 2.73×10^{9} Watt-cm^{-2}, respectively. As a comparison, the corresponding fluxes for the 3.52 MeV α-particles from the $D(T,n)\alpha$ reaction, at a burn-up factor $f_b = 3\%$[4], are $N_\alpha \approx f_b \frac{n}{2} V_\alpha = 3.5 \times 10^{21}$ cm^{-2} sec^{-1} and $F_\alpha = f_b \frac{n}{2} V_\alpha E_\alpha = 1.98 \times 10^{9}$ Watt-cm^{-2}, respectively, ($V_\alpha = 1.298 \times 10^{9}$ cm/sec at $E_\alpha = 3.52$ MeV). We observe that although the particle flux of the α-particles is two orders of magnitude less than that of the thermal electrons, their energy flux is comparable to that of the thermal electrons. Accordingly, questions were raised regarding the part that the 3.52 MeV α-particles might play in the ablation of a refuelling pellet[5].

A correct answer clearly depends on many other factors involved in the successful operation of a fusion reactor. Among them are the production and loss rate of α-particles[6,7,8], the energy spectrum of the escaping α-particles[9], the possible introduction of a suitable radiant, and the efficient use of a divertor[10]. Most of these problems are related more closely to the optimum of the refuelling process than to the feasibility of pellet refuelling. To avoid complexity in this paper, we shall adopt a simplified model and make some plausible estimations of the effect of α-particles on pellet ablation.

In the model considered here it is assumed that the α-particles are continuously produced in the central core of the reactor only and that they diffuse outward, lose their energy and become thermalized through collisions with plasma ions and electrons. We ask now as the pellet enters, near the outer region of the reactor, what can be the average impact energy of the α-particles and what can be their effect on the ablation of the pellet?

To analyze the problem, we shall first use the binary collision approximation[11,12], estimate the average impact energy of the α-particle after being slowed down by the reactor plasma, and then use the stopping power argument to estimate its penetration depth and energy deposition in the pellet itself[13]. Subsequently, we shall estimate the further attenuation of the α-particle energy in the dense cloud created during the direct impact phase. Finally, a discussion is given of the effect of the magnetic field.

As basis for the analysis, we shall take the plasma parameters corresponding to the 2.5 GW(e) reactor mentioned previously[3]. For simplicity, the plasma is assumed to be homogeneous throughout the reactor.

To compare with this rather conservative estimation, the following section presents an alternative case in which it is assumed that the pellet is always injected at a time when the α-particles are already thermalized.

2. PENETRATION DEPTH OF THERMALIZED α-PARTICLES IN THE SOLID DEUTERIUM

When α-particles produced from the D(T,n)α reaction are thermalized to the same temperature as the reactor plasma, their average energy will be around 20-30 keV. The penetration depth of 20 keV α-particles in solid deuterium calculated from the tabulated data of Ziegler is approximately 1.56×10^{-6} m[14]. Comparing this depth with the penetration depth of 20 keV electrons of 30×10^{-6} m, extrapolated from the experimental data of Schou and Sørensen[15], it is about a factor of 20 smaller. We conclude, therefore, that if α-particles are already thermalized during the injection of the pellet, their effect can be neglected.

3. SLOWING DOWN OF THE 3.52 MeV α-PARTICLES BY THE REACTOR PLASMA

The rate of energy loss of α-particles in a plasma can be written as

$$\frac{dE}{dt} = \left(\frac{dE}{dt}\right)_N + \left(\frac{dE}{dt}\right)_R$$

where $(\frac{dE}{dt})_N$ is the loss rate due to binary collisions of α-particles with their closest neighbours, and $(\frac{dE}{dt})_R$ is the loss rate due to the polarization of the plasma caused by the α-particle. (For simplicity of notation, we shall omit the subscript α for the energy E and velocity v of the α-particle in the subsequent treatment).

To determine the maximum impact parameter, p_{max}., for the binary collision, and thus the dividing distance between the two regions, we employ the concept of adiabatic collision, i.e. energy transfer due to binary collisions is negligible when

$$\omega_p \tau > 1 \tag{1}$$

where ω_p is the plasma frequency, and τ is the effective collision time taken approximately as

$$\tau = 2\, p_{max}/u. \tag{2}$$

Here u is the relative impact velocity between an α-particle and a target particle (electron or deutron), and it can be taken as

$$u = (3\, kT/\mu)^{\frac{1}{2}} \tag{3}$$

where μ is the reduced mass for the appropriate collision partners under consideration.

Using eqs. (2) and (3), and recalling the relationship that

$$\omega_p \lambda_D = w, \tag{4}$$

where λ_D is the Debye length and $w = (8\, kT/\pi m)^{\frac{1}{2}}$ is the thermal velocity of the target particle, it can be shown that eq. (1) is satisfied if we take

$$p_{max} \gtrsim \lambda_D. \tag{5}$$

a) Energy loss due to close encounters

Using the notations of reference 11, the energy loss rate of α-particles through binary collisions with plasma electrons and ions can be written as

$$\left(\frac{dE}{dt}\right)_N = \frac{-4\pi n_e z_\alpha^2 e^4}{v} \sum_{s=e,i} \frac{\Lambda_s}{m_s} F(\xi_s,\beta_s)$$

where

$$\xi_s = b_s v = \left(\frac{m_s}{2kT_s}\right)^{\frac{1}{2}} v, \quad \beta_s = m_s/m_\alpha$$

$$F(\xi_s,\beta_s) = \Phi(\xi_s) - (1+\beta_s)\xi_s\Phi'(\xi_s)$$

$\Phi(\xi_s)$ is the error integral and

$$\Lambda_s = \ln(p_{max}/p_{min})_s = \ln(\lambda_D/p_{min})_s$$

is the Coulomb logarithm. The proper value of the minimum impact parameters p_{min} is to be chosen as the larger one of

$$p_{min}^{cl} = \frac{z_\alpha e^2}{\mu u^2} = \frac{2e^2}{3kT}$$

and

$$p_{min}^{q} = \frac{\hbar}{\mu u} = \frac{\hbar}{(3\mu kT)^{\frac{1}{2}}}$$

It can be shown that for α-D^+ collisions, p_{min}^{cl} should be used, while for α-e collisions, p_{min}^{q} should be chosen.

b) Energy loss due to remote collisions

For large impact parameters, $p \gtrsim p_{max}$, the collective effect of the plasma must be taken into account. By treating the plasma as a dielectric medium, the energy loss of the α-particle due to the polarization effect can be written as[16)]

$$(\frac{dE}{dt})_R = - \frac{4\pi n_e z_\alpha^2 e^4}{m_e v} [\Phi(\xi) - \xi\Phi'(\xi)] \ln(k_o\lambda_D) \quad (7)$$

where

$$\xi = (\frac{m_e}{2kT_e})^{\frac{1}{2}} v$$

and k_o is the maximum wave number that can be excited by the moving α-particle.

Comparing eq. (7) with the electron component of the energy loss due to close encounters eq. (6), one notices that the two expressions have an identical appearance except for the expressions of the logarithm term. Owing to the uncertainty of k_o, the exact contribution of the loss rate as a result of remote encounters is difficult to assess. However, from the range of

$$\omega_{pe}/v < k_o < 1/p_{min}, \quad (8)$$

or using the relationship that $\lambda_D = w_e/\omega_{pe}$, we have

$$w_e/v < k_o\lambda_D < {}_D/p_{min}. \quad (8a)$$

In other words, the contribution resulting from the collective effect in our case could be at least 11%, and at most about the same amount as that resulting from binary collisions. As this uncertainty appears in the argument of the logarithm, it can hardly affect the estimation of the slowing-down time by any order of magnitude.

c) The slowing-down time

To investigate the slowing-down time, eq. (6) can be rewritten as the following

$$\frac{d}{dt} (\frac{E}{kT}) = - \frac{3}{t_S} (\frac{m_\alpha}{m_e}) G(y)$$

where

$$G(y) = \frac{\sqrt{\pi}}{2}\,\frac{F(y,\beta_e)}{y}\left\{1 + \frac{m_e\Lambda_i}{m_i\Lambda_e}\;\frac{F\left[\left(\frac{m_i}{m_e}\right)y,\beta_i\right]}{F\,y,\beta_e}\right\}$$

$$y = \left(\frac{m_e}{m_\alpha}\,\frac{E}{kT}\right)^{\frac{1}{2}}, \qquad t_S = \frac{3\pi}{128}\,\frac{m_e m_p}{e^4 n_e}\,\frac{w_e^3}{\Lambda_e}\,. \tag{9}$$

The slowing-down time

$$\tau(E) = \int_{E_o}^{E} dE/\left(\frac{dE}{dt}\right)$$

is then given by

$$\tau = \frac{2t_S}{3}\int_{y}^{y_o}\frac{y\,dy}{G(y)}\,. \tag{10}$$

The result is shown in fig. 1 for a D^+-e plasma at kT = 20 keV and $n_e = 1.8 \times 10^{14}\ cm^{-3}$. In the figure, $E_{th} = \frac{3kT}{2}$ and

$$E_c = \frac{m_\alpha}{m_e}\left[\frac{3\sqrt{\pi}}{4}\,\frac{m_e}{m_D}\cdot\frac{\Lambda_D}{\Lambda_e}\right]^{2/3} kT \tag{11}$$

is the critical energy for the slowing-down process (= 0.84 MeV), i.e. the average energy of the α-particle at which the loss rates to the electron and to the ion component of the plasma are equal. Observations show that it takes about 3/4 sec for the α-particles to come into thermal equilibrium with the background plasma.

For the 2.5 GW(e) reactor previously mentioned[3)], the total number of particles in the reactor amounts to $N_R = 3 \times 10^{23}$. If we wish to keep the number of particles, N_p, contained in a pellet of radius r_p below $N_p = 0.02\ N_R$, and in the meantime satisfy the required refuelling rate $\dot{N} = 6.42 \times 10^{22}\ sec^{-1}$, we may inject pellets of 3 mm radius at intervals of 71 msec. Comparing this time with the slowing-down time τ(E) shown in fig.1, we notice that in all likelihood the pellet will be bombarded by α-particles of around 2-3 MeV energy.

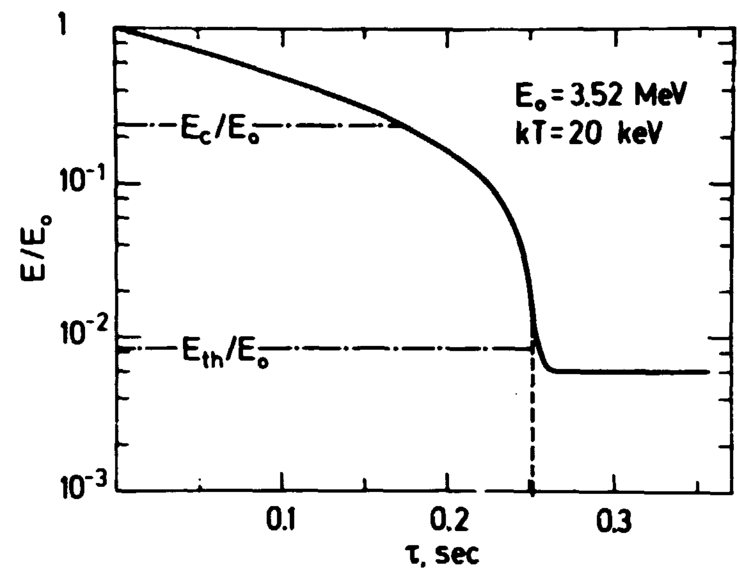

Fig. 1. Slowing-down time, τ, of a 3.5 MeV α-particle in a D^+-e plasma at kT = 20 keV and $n_e = 1.8 \times 10^{14}$ cm^{-3}.

4. INTERACTION OF 3 MeV α-PARTICLES WITH A DEUTERIUM PELLET

The interaction at 2-3 MeV of α-particles with the pellet can be approximately divided into two stages; (a) direct impact phase, and (b) attenuation of α-particle energy in the dense and cold (?) ablated plasma surrounding the pellet.

a) Range and expected impact phenomena of 3 MeV α-particles in solid deuterium

From the tabulated date of Ziegler[14)], we expect the range in solid D_2 for 3 MeV α-particles to be around 0.06 mm. (In comparison, the range of a 20 keV electron is around 0.03 mm[15)]. For a 3 mm pellet, the energy of the α-particle will be deposited in a thin shell. According to Lindhard et al.[13)], for incident ions at high energy, the energy deposited in the atomic motion tends to a limiting value and is inversely proportional to the electronic stopping number. Extrapolating the data calculated by Sigmund et al.[17)], we expect that only 1/1000 of the total energy carried by the α-particles will be deposited in the atoms. Most of the energy will be spent in causing excitation and ionization of the bound electrons. Assuming the average energy of electrons produced by the primary impact to be around 400 ev, using the data of Schou and Sørensen[15)], their range $R = 3.62 \times 10^{-6}$ cm. Because of the straggling effect of electrons, we may assume their path length to be $S = 3R$. Assuming furthermore a constant deceleration process, it will take only about 10^{-14} sec for the electrons to be thermalized. This, in turn, causes the temperature rise of the pellet and the possible formation of a dense, cold cloud around the pellet (taking approximately another 0.6×10^{-12} sec, the reciprocal of the Debye frequency).

b) Slowing down of the α-particle in the ablated cloud surrounding the pellet

The further slowing down of a 3 MeV α-particle in the ablated cloud clearly depends on the plasma parameters T_1 and n_1 of the cloud (we assume $T_{e1} = T_{i1} = T_1$). Although the exact values of these parameters depend on the interaction mechanism of the 3 MeV α-particles with the pellet, an estimation of their range can be made based on some reasonable guess of these paramters.

Assuming that the electron temperature kT_1 is not likely to exceed 10 ev, the thermal velocity w_e of the ablated plasma is about an order of magnitude smaller than the velocity v of the 3 MeV α-particle. Consequently, the plasma can be considered as cold, i.e. $F(\xi_s, \beta_s) \simeq 1$ in eq. (6). The stopping power formula simplifies to

$$\frac{dE}{dS} \simeq - 32\pi n_1 e^4 \left(\frac{m_p}{m_e}\right) \frac{1}{E} \ln \left(\frac{\lambda_D}{p^q_{min}}\right) .$$

Under the stated condition $w_e < v$, we may take

$$p^q_{min} \simeq \frac{\hbar}{m_e v} .$$

Finally, the stopping power formula reduces to

$$\frac{dE}{dS} = -16\pi n_1 e^4 \left(\frac{m_p}{m_e}\right) \frac{\ln(\xi E)}{E}$$

where (12)

$$\xi = \left(\frac{m_e}{e\hbar}\right)^2 \frac{kT_1}{8\pi m_p n_1}$$

The range $R = \int_{E_o}^{o} dE/\left(\frac{dE}{dS}\right)$ is then given by

$$R(\xi) = \frac{E_i^*[\ln(\xi E_o)]}{8\pi n_i e^4 \left(\frac{m_p}{m_e}\right) \xi^2}$$

where

$$E_i^*(x) = \int_{-\infty}^{x} \frac{e^t}{t} dt \ . \qquad (13)$$

By assuming a pressure balance at the boundary of the ablated cloud, the electron number density n_1 can be related to the temperature kT_1 of the ablated cloud by

$$2n_1 kT_1 = 2n_e kT_e + f_b \frac{n_e}{2} kT_\alpha . \qquad (14)$$

Taking $n_e = 1.8 \times 10^{14}$, $kT_e = 20$ keV, $kT_\alpha = 3$ MeV and a burn up factor, $f_b = 0.03$, we obtain

$$kT_1(\text{ev})\ n_1(\text{cm}^{-3}) = 7.65 \times 10^{18} . \qquad (14a)$$

Using eq. (14a) to eliminate n_1 that appeared in eq. (12), the range R can be expressed as a unique function of the ablated plasma temperature, kT_1. The result is shown in fig. 2. (The line ab in the figure indicates the region below which the plasma becomes nonideal[18]; the result of the present analysis might require modification). The result of the analysis shows that if the ablated plasma temperature is not too cold, e.g. above 5 ev, the cloud surrounding the plasma will not be able to thermalize the energetic α-particles around 2-3 MeV. On the other hand, if the ablated cloud is cold enough, i.e. below 1 ev,

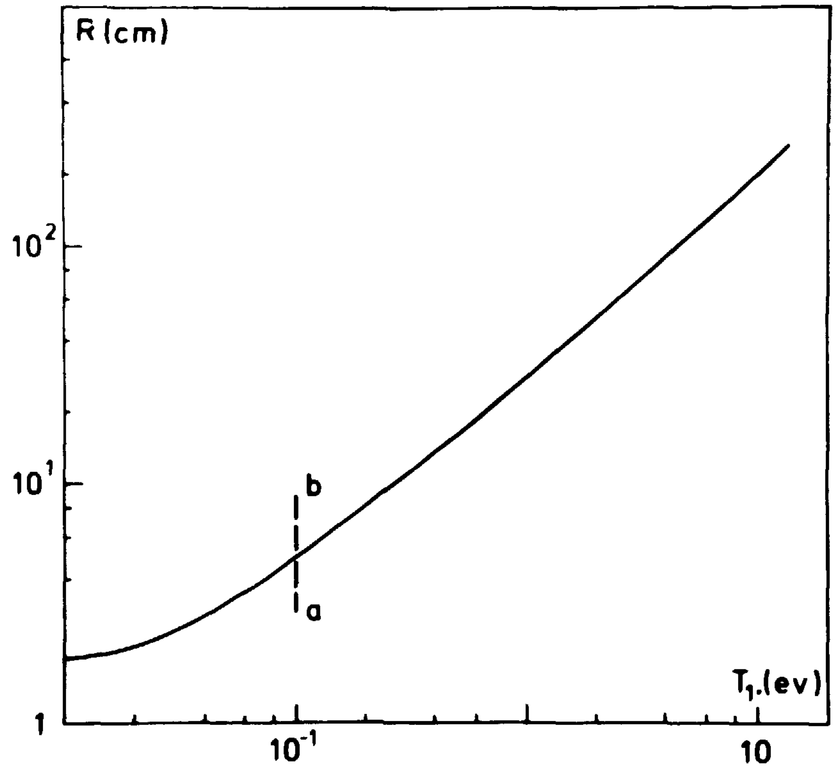

Fig. 2. Radius of the cloud surrounding the pellet required for the thermalization of a 3 MeV α-particle vs. the cloud temperature, T_1.

the energetic α-particles may become thermalized if the ablated cloud has a radius around 20 cm.

5. EFFECT OF THE MAGNETIC FIELD

In considering the slowing down of the α-particle energy we have hitherto treated the plasma only as a homogeneous, non-magnetized medium. To estimate the effect of the magnetic field, we shall confine our attention to the simple case where the plasma is permeated by a homogeneous field of a strength corresponding to the main confining field. For the previously mentioned 2.5 GW(e) prototype reactor, we take $B = B_T$ (= 75 kG)[3]. The corresponding gyrofrequency and gyroradius of a 3.52 MeV α-particle are

$$\Omega_c = 3.59 \times 10^8 \text{ sec}^{-1}$$

$$\rho_c = 3.62 \text{ cm},$$

respectively. As the Debye length of the plasma considered is $\lambda_D = 7.83 \times 10^{-3}$ cm, we expect, for close encounters, that the effect of the magnetic field can be neglected.

In principle, the presence of a magnetic field causes the medium to behave anisotropically. As a result, the dielectric property of the plasma changes drastically. However, some simplifications can be obtained, as stated by Akhiezer et al.[16], if the angle α between the particle velocity and the magnetic field satisfies the condition

$$\sin\alpha >> \frac{\Omega_c}{\max\{\omega_{pe},\omega_{ce}\}} \tag{15}$$

where ω_{ce} is the electron cyclotron frequency. For our case, $\omega_{ce} = 1.32 \times 10^{12}$ sec^{-1}, $\omega_{pe} = 7.57 \times 10^{11}$ sec^{-1}, eq. (15) reduces to

$$\sin\alpha >> 2.72 \times 10^{-4}. \tag{16}$$

This implies that condition (15) is satisfied for nearly all angles of α ($\neq 0$). Following the similar argument presented in reference 16, we may expect the additional energy loss rate resulting from the presence of the field for $v < w_e$ to be

$$\left(\frac{dE}{dt}\right)_B = \frac{4\sqrt{2\pi}}{3m_e v} n_e z_\alpha^2 e^4 \left(\frac{v}{w_e}\right)^3 f(\eta,\alpha)$$

where

$$\eta = \frac{\sin^2\alpha}{4} \;(\neq 0), \qquad a = \omega_{ce}/\omega_{pe}.$$

For $a > 1$, we have

$$f(\eta,a) \simeq \eta\,\{1 + \ln(\frac{\eta}{a^2})\} + \ln a\,. \tag{18}$$

From the definition of η and eq. (16), the range of η is limited to

$$2 \times 10^{-8} < \eta \leq 0.25 .$$

We observe that in the range of η concerned, $f(\eta,a)$ is a monotonically decreasing function, i.e.

$$f(\eta,a) \stackrel{<}{\sim} \ln a \ (= 0.556). \qquad (19)$$

Therefore, the presence of the field in the case considered slightly reduces the loss rate. Considering $\max\{-f(\eta,a)\} \simeq -\ln\left(\frac{\omega_{ce}}{\omega_{pe}}\right)$ as another "Coulomb logarithm", we have

$$\ln(\lambda_D/p_{min})_e \Big/ \left[\ln\left(\frac{\lambda_D}{p_{min}}\right)_e - \ln\left(\frac{\omega_{ce}}{\omega_{pe}}\right)\right]$$
$$= 17.70/(17.70-0.556) = 1.032.$$

We notice that the neglect of the magnetic field may lead to an overestimate of the energy loss rate of the α-particle to the electron component of the plasma of approximately 3% at the most.

6. CONCLUDING REMARKS

By disregarding the optimum of the refuelling process and restricting attention to the feasibility of pellet-refuelling alone, the possible effect of the 3.52 MeV α-particle from the $D(T,n)\alpha$ reaction on a refuelling deuterium pellet is estimated. It is shown that if the pellet is always injected at a time when the α-particle is already thermalized, its effect compared with that of the thermal electrons ($kT_e \simeq 20$ keV) is negligible. Alternatively, by comparing the slowing-down time of the 3.52 MeV α-particle in a plasma corresponding to that of a 2.5 GW(e) prototype fusion reactor with the required refuelling period for a 3 mm pellet, it is shown that the pellet will probably first be subject to the direct bombardment of α-particles of around 2-3 MeV energy. The possibility of the α-particle being subsequently thermalized in the dense cloud created around the pellet depends on the electron temperature, T_1, of the cloud.

At an electron temperature $T_1 = 1$ ev, a cloud radius of around 20 cm is required.

The present study also showed that the slowing-down time of the α-particle can be reasonably estimated with respect to its order of magnitude by considering the binary collision process alone. This is because the inclusion of the collective effect can only amount to an uncertainty in the argument of the Coulomb logarithm. Besides, this collective effect is partly compensated by the presence of a strong magnetic field.

As a final word of caution, we would like to emphasize that as a result of the simplified model used the present work was only intended to give an order-of-magnitude estimate. Implicitly, we have assumed that the α-particle is only (but instantaneously) produced when the fresh fuel enters the core of the reactor. The medium is assumed to be a homogeneous plasma without any anomalous loss processes.

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