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NEW APPLICATION OF POLARIZED IONS

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ABSTRACT

Recent improvement and newly proposed idea of the polarized ion sources have aroused practical interest in new application of the polarized ions. Two new possible application are discussed. The first one is a polarized fuel fusion in which enhancement or suppression of the fusion reaction rate is expected. The second one is a compact 14 MeV neutron generator for the radiotherapy.

1. Introduction

By means of the presently known techniques it may be possible to produce $\vec{H}^+$ and $\vec{D}^+$ beam intensities of mA range whereas $\vec{H}^-$ and $\vec{D}^-$ currents of a few 100μA. The new methods, however, which are based on the optical pumping proposed by Happer et al.[1] , and another one which select the electron spin state by very high magnetic field and very low temperature proposed by Kleppner et al.[2] are promissing to produce more than mA or even Amp of polarized ions. From these technological development,Kulsrud et al.[3] have proposed a use of spin polarized ions in magnetic confinement fusion. As is well known, the most commonly considered reaction for fusion reactor, D + T $\longrightarrow$ ^{4}He + n, goes almost entirely through the channel spin 3/2 state at low energy. Because the deuteron and triton have spin 1 and 1/2, respectively, and orbital angular momentum of two nuclei colliding with a sufficiently small impact can be neglected at fusion reactor energies, this implies that these two nuclei will fuse most frequently when their spins are aligned with one another. Therefore, controlling the relative orientation of the spin angular momentum of the nuclei just prior to a collision, the total angular momentum of the system can be controlled and the nuclear reaction can be modified (enhancement or suppression) to some extent. Could the spin polarization be retained during fusion plasma confinement time? The magnetic field that confines the plasma in the fusion reactor, whoes direction is the quantization axis for the nuclear spin vector, is so strong that the various depolarization mechanisms in the fusion reactor have to be examined in detail. Kulsrud et al.[4] have made extensive studies over these conseivable depolarization mechanisms and reached the conclusion that a polarized D-T, D-D or D-^{3}He plasma would maintain its polarization against collisions at better than 95 % for about a few seconds in a magnetic fusion reactor which are considerably larger than the plasma confinement time. Thus, once the nuclei of the fusion plasma are all polarized in the desired manner relative to internal field of the fusion reactor ($\vec{B}$), they may be considered to remain polarized.

Besides the fusion reaction rate modification, the angular distribution of the emitted neutrons and α-particles becomes proportional to $\sin^2\theta$ or $1+3\cos^2\theta$ depending on the selection of the spin state and direction of injecting polarized ions with respect to $\vec{B}$. These directional confinements of neutrons may reduce the radiation damage of the surrounding apparatus and the confined α-particles may also contribute further heating of the plasma.

As the second unusual application, we will discuss a possibility of constructing a compact 14 MeV neutron generator for neutron therapy by installing the polarized deuteron source instead of ordinary ion source. The D-T reaction caused by the tensor polarized deuteron and unpolarized triton target placed in a magnetic field may deliver 14 MeV neutrons distributed proportionally to $1+3\cos^2\theta$, thus reducing the amount of the heavy neutron shield material in the forward direction.

2. Theoretical aspect

From the practical viewpoint for realizing a controlled fusion reactor, the D-T reaction is considered to have the advantage of lower barrier for satisfying the Lawson's criterion i.e. $n\tau \gtrsim 10^{14}$ sec·cm^{-3} (n:the plasma density, τ:the confinement time) for fusion temperature T=10 keV (10^4 K), which is smaller about two order of magnitude than that of the D-D reaction. The D-T reaction is practical to use owing to its large cross section σ_{max}=5 b at a deuteron lab. energy 107 keV. In the following, therefore, we calculate the characteristics of the fusion reaction cross section and the differential cross section resulting from the polarized D-T reaction.

In a s-wave low energy region mentioned above, the probability f that the D-T reaction proceeds through the resonant $J=3/2^+$ intermediate state of ^{5}He is considered to be 0.95<f<1, the other (1-f), which is a small amount of contribution to the reaction, is induced by the $J=1/2^+$ state. The total cross section for the D-T reaction is given by

$$\sigma_T = W(J=\tfrac{3}{2})\cdot\sigma_T(J=\tfrac{3}{2}) + W(J=\tfrac{1}{2})\cdot\sigma_T(\tfrac{1}{2}). \qquad (1)$$

The statistical weights w(J) for the reaction cross section $\sigma_T(J)$ are expressed by

$$W(J) = \sum_{m_D, m_T} |\langle j_D\, j_T\, m_D\, m_T | JM\rangle|^2 \cdot N(m_D)\cdot N(m_T)/N(J), \qquad (2)$$

where m_D and m_T indicate the nuclear spin states of D and T (j_D=1 and j_T=1/2), respectively, with respect to the direction of the magnetic field in the D-T fusion reactor, and N the fractional populations of the respective spin states. Using the definition of the degree of polarizations we obtain

$$W(J=\tfrac{3}{2}) = \tfrac{1}{3}(2+P_Z^D\cdot P_Z^T) \text{ and } W(J=\tfrac{1}{2}) = \tfrac{2}{3}(1-P_Z^D\cdot P_Z^T), \qquad (3)$$

where P_Z^D and P_Z^T are the vector polarizations of deuterons and tritons, respectively. As the total cross section $\sigma_T(J)$ can be written by

$$\sigma_T(J=\tfrac{3}{2}) = \tfrac{3}{2}f\cdot\sigma_{unpol} \text{ and } \sigma_T(J=\tfrac{1}{2}) = \tfrac{3}{2}(1-f)\cdot\sigma_{unpol} \qquad (4)$$

we will obtain the total cross section for the D-T reaction by substituting eqs.(3) and (4) to eq.(1) as

$$\sigma_T = \left[f\ (1+\tfrac{1}{2}P_Z^D\cdot P_Z^T) + (1-f)\cdot(1-P_Z^D\cdot P_Z^T)\right]\cdot\sigma_{unpol} \qquad (5)$$

It can be seen from eq.(5) that the total cross section for D–T reaction depends only on the vector polarization of deuteron and triton and is independent of the tensor polarization.

If the D–T reaction goes purely through the $J=3/2^+$ state, f would be unity, then eq.(5) can be converted to the simple form

$$\sigma_T/\sigma_{unpol} = 1+\frac{1}{2}P_Z^D\cdot P_Z^T \quad . \qquad (6)$$

In the following, we restrict ourselves to the case of f=1 for the sake of simplicity. The differential cross section for the D–T reaction is represented by

$$\frac{d\sigma(\theta)}{d\Omega} = \left(\frac{d\sigma(\theta)}{d\Omega}\right)_{unpol}\left[1+\frac{1}{2}P_{ZZ}^D\cdot A_{ZZ}+\frac{3}{2}P_Z^D\cdot P_Z^T\cdot C_{Z,Z}\right] , \qquad (7)$$

where A_{zz} is a tensor analyzaing power given by $A_{zz} = -(3\cos^2\theta-1)/2$ and $C_{z\cdot z}$ a spin-correlation coefficient described by $C_{z\cdot z} = -(2/3)A_{xx} = -(3\cos^2\theta-2)/3$. Therefore, we will obtain the differential cross section for the D–T reaction (f=1) as

$$\frac{d\sigma(\theta)}{d\Omega}/\left(\frac{d\sigma(\theta)}{d\Omega}\right)_{unpol} = 1-\frac{3}{4}(P_{ZZ}^D+P_Z^D\cdot P_Z^T)\cos^2\theta+\frac{1}{4}(P_{ZZ}^D+4P_Z^D\cdot P_Z^T), \qquad (8)$$

where P_{zz}^D is the tensor polarization of deutron. The results of the total and differential cross sections described above are equivaleut to those of Kulsrud et al.[3)]

3. Practical application

3.1. The D–T reaction

By using the results of theoretical considerations, we represent some examples of the application of the polarized ions in a magnetic field $\vec{B}$ of fusion reactor. In the following, we put f=1 for simplicity.

(a) A case of both D and T nuclei polarized along $\vec{B}$ ($\vec{D}$, $\vec{T}\parallel\vec{B}$): The polarization degree becomes $P_{zz}^D=+1$ and $P_z^D\cdot P_z^T=+1$ as far as the above condition ($P_z^D=+1$, $P_z^T=+1$ or $P_z^D=-1$, $P_z^T=-1$) is fulfilled. Thus, we have from eqs.(6) and (8)

$$\sigma_T/\sigma_{unpol} = \frac{3}{2} \text{ and } \frac{d\sigma(\theta)}{d\Omega}/\left(\frac{d\sigma(\theta)}{d\Omega}\right)_{unpol} = \frac{9}{4}\sin^2\theta. \qquad (9)$$

We find from eq.(9) that if both D and T nuclei are polarized either parallel or antiparallel to $\vec{B}$, we can expect the 50 % enhancement in the reaction rate as compared to an unpolarized case and the strongly orientated angular distribution of reaction products (neutrons and α-particles appearing opposite direction each other), showing a peak at the perpendicular direction to $\vec{B}$. This case, therefore, has the benefit for a mirror fusion reactor resulting in the advantage of decreasing the radiation damage of the complicated magnet systems installed along $\vec{B}$.

(b) A case of only the D nuclei polarized perpendicular to $\vec{B}$

($\vec{D}\perp\vec{B}$): In this case P^D_{zz}=-2 and $P^D_z \cdot P^T_z$=0 because of P^D_z=0, irrespective of the value of P^T_z, we abtain from eqs.(6) and (8)

$$\sigma_T/\sigma_{unpol} = 1 \text{ and } \frac{d\sigma(\theta)}{d\Omega}/(\frac{d\sigma(\theta)}{d\Omega})_{unpol} = \frac{1}{2}(1+3\cos^2\theta). \qquad (10)$$

Although we cannot expect any gain from eq.(10) in the reaction rate, we have the possibility of controlling the direction of emitting neutrons and α-particles showing the strong angular distribution preferentially along $\vec{B}$. Accordingly, this case benefits a Tokamak fusion reactor for confining both neutrons and α-particles along $\vec{B}$. Thus, we can expect the reduction of the radiation damage due to neutrons and furthermore the increase of the plasma heating by confined α-particles.

3.2. The D-^{3}He and D-D reactions

As T and ^{3}He are mirror nuclei, the D(^{3}He,p)^{4}He reaction is easily understood by analogy with the D(T,n)^{4}He reaction except for the difference of the higher resonance energy 450 keV at a $3/2^+$ state of ^{5}Li. Thus, the formalism of the total and differential cross sections of the D-^{3}He reaction having different values of σ_{unpol} and f is identical to that of the D-T reaction. This leads to the somewhat smaller enhancement in the D-^{3}He reaction rate than in the D-T reaction. The angular distribution of the reaction products, protons and α-particles, could tend to be less preferential. The D-^{3}He reaction has the possibility to be used as a neutron free fusion reaction. However, the injected deuterons produce neutrons colliding with already deposited deuterons. Since the spin dependence of the cross section in the D-D reaction is less known than that of the D-T or D-^{3}He reacion, there exist contradictory discussions about the cleanliness. According to the results of the D(D,p)T reaction evaluated by Ad'yasevich et al.[5] one can expect the increase of σ/σ_{unpol} more than a factor 2 at low energies by polarizing the D nuclei perpendicular to $\vec{B}$, and substantial suppression for all the D nuclei polarized parallel to $\vec{B}$. On the other hand, another results based on the R-matrix analysis by Hale and Dodder [6] have shown smaller enhancement of the total cross section, for instance, about 1.3 and 1.5 in the D(D,p)T and D(D,n)^{3}He reactions at 200 keV, respectively, and also small suppression under the same polarization conditions as Ad'yasevich et al's. Recently, Hofmann and Fick [7] have presented the results supporting the predictions of Hale and Dodder by using the refined resonating-group model and shown the difficulty of realizing a neutron free D-^{3}He fusion reactor.

3.3. 14 MeV neutron generator with polarized deuteron source installed.

Since 14 MeV neutrons produced by D-T reaction are high LET(linear energy transfer) particles, these neutrons have been used for certain kind of cancer treatment. The problems inherent in this neutron generator are the fact that D-T reaction produces isotropically distributed neutrons. Therefore, heavy, complicated collimator system for the irradiation and large amount of shielding material for unwanted neutrons to protect the patient and other technical people are needed. If we could use tensor polarized deuterons and inject them perpendicular to the magnetic field ($\vec{B}$) wherein T-target is located, the neutron distribution follows (1+3 $\cos^2\theta$) relation as is shown in eq.(10). Then the neutron emission along $\vec{B}$ is four times as likely as that across $\vec{B}$. As a result of these concentration of the neutron emission, the collimation of useful neutron beams becomes much easier and amount of shielding material for unwanted neutron becomes smaller. Though the reaction cross section remains same as that for unpolarized deuteron injection, effective neutron yield will be increased for the same injected deuteron beam intensity.

4. Conclusion

As new application of the polarized ions we have discussed at first about the polarized fuel fusion and reduced convenient formulation to ion source people and secondly 14 MeV neutron generator for cancer therapy. There exist, of course, many problems both theortical and experimental to be solved before these applicalion become feasible. As an anothor application of the polarized ions, More et al.[8] have shown the possibility of using spin-polarized D-T fuel for inertial-confinement fusion. This application seems to us more practical than heavy ion or laser inertial fusion. We believe that if we could succeed in producing very high intense polarized ions, new area of application of them will be opened.

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