is ruled out because the lowest asymptotic energy for a doubly-excited Δ_g state is 26.8 eV. This means that the final state leading to the fast atoms is a $^1\Pi_u$ state that dissociates to H(2*s*) +H(2*p*). It is noteworthy that this state (shown in Fig. 3) has not been previously reported in the literature.

The main disagreement between our conclusions and those given in the pioneering paper of Leventhal, Robiscoe, and Lea[1] is in the assignment of the excited state that is responsible for the fast H(2*s*) atoms. We differ from Czarnik and Fairchild in concluding that triplet states and pure dissociation, in addition to singlet states and predissociation, are important in the production of slow H(2*s*) atoms.

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Enhanced Transport in Toroidal Plasma Devices due to Magnetic Perturbations*

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It is shown that a magnetic perturbation may lead to an enhanced transport of heat and particles. The observation of anomalous electron heat conduction and particle diffusion in the experimental devices may be explained by the effect.

The presence of trapped particles enhances the collisional diffusion rate in an axisymmetric toroidal plasma (banana diffusion).[1] Some of the experimental results have shown that the diffusion rate, especially for electrons, may be larger than the theoretical predictions. In the following it will be shown that magnetic perturbations may lead to an additional transport of particles and heat. The magnetic perturbations could be produced either by the unavoidable imperfections of construction or by magnetohydrodynamic turbulence.

First we consider the static perturbation. If the flux surface is not closed, there is a trivial plasma loss through the flow along the flux lines. This type of loss has been discussed previously by several authors.[2] It is assumed here that the imperfection is small and the flux surfaces are deformed but still closed.

The magnetic disturbance will modify particle orbits. We use the magnetic moment μ and the longitudinal invariant J to describe the orbits of the guiding center:

$$\mu = \tfrac{1}{2}mv_\perp^2/B, \tag{1}$$

$$J = \oint (mv^2 - 2\mu B)^{1/2}\, dl, \tag{2}$$

where m is the mass of the particles, v and $v_\perp$ are the velocity and its perpendicular component, B is the magnetic field strength, and dl is the line element of a flux line.

The deviation of the guiding center due to the field errors is dependent on μ. The particles with large magnetic moments tend to follow curves of equal magnetic field strength and the particles with small magnetic moments tend to follow curves of equal flux-line length.

We rewrite Eq. (2) as

$$J=\oint(mv^2-2\mu B)^{1/2}(B_\chi/B)h\,d\chi, \qquad (3)$$

where (ψ, χ, φ) are taken as coordinates, ψ being the poloidal flux function, φ the toroidal azimuthal angle, and χ along the poloidal flux line; B_χ is the poloidal magnetic field, and h is the line element in the χ direction. With a magnetic perturbation, J is a function of v, μ, ψ, and φ. The displacement $\Delta\psi$ of the guiding center in the ψ direction is given by

$$\Delta\psi\approx\frac{\Delta\varphi\,\partial J/\partial\varphi}{\partial J/\partial\psi} \qquad (4)$$

when $\Delta\varphi$ is the angular wavelength in the azimuthal direction of the perturbation. By using Eq. (3) we have

$$\frac{\partial J}{\partial\psi}=\oint\frac{-\mu}{(mv^2-2\mu B)^{1/2}}\frac{\partial B}{\partial\psi}\frac{B_\chi}{B}h\,d\chi+\oint(mv^2-2\mu B)^{1/2}\frac{\partial}{\partial\psi}\left(\frac{B_\chi h}{B}\right)d\chi. \qquad (5)$$

For a large-μ particle the first term dominates, whereas for a small-μ particle the second term is important. In an average magnetic well there usually are particles with opposite polarity of $\partial J/\partial\psi$.

The diffusion coefficient D is given by

$$D=\nu\langle(\Delta\psi-\langle\Delta\psi\rangle)^2\rangle, \qquad (6)$$

where ν is the collision frequency and is assumed to be small compared to the reciprocal of the transit time of the particles across the field errors. Angular brackets denote the average over μ and v. If two terms in Eq. (5) have the same sign, the rms value $\langle(\Delta\psi-\langle\Delta\psi\rangle)^2\rangle$ is small because the guiding centers of the particles with various μ shift in the same direction. This is the case of a maximum J configuration for all particles, such as the region near an internal conductor of the multipole configuration. The region between the separatrix and the minimum of $\oint dl$ has similar properties for most particles. On the other hand in the region between the minima of $\oint dl$ and $\oint dl/B$, the two terms have opposite polarity and $\langle\Delta\psi^2\rangle$ is large. In Tokamak configurations the second term is small because the rotational transform angle decreases with the minor radius except near the magnetic axis. In Doublet, the second term is large outside of the separatrix because of the positive gradient of the transform angle. In general there is a value of μ for which $\partial J/\partial\psi$ vanishes unless the configuration is maximum J for all μ. These are the particles with vanishing average drift velocity across the magnetic field.

If the collision frequency is comparable to or larger than the transit time τ which is defined as the time for a drifting particle to travel across the error-field region, the diffusion coefficient is given by

$$D=\langle[\nu/(1+\nu^2\tau^2)](\Delta\psi-\langle\Delta\psi\rangle)^2\rangle.$$

This regime is not unlike the intermediate and the collisional regimes of trapped-particle diffusion. However the distribution of the wavelengths of the perturbation makes the distinction between the regimes less well defined here.

The magnetic field may be disturbed by magnetohydrodynamic turbulence. If the frequency of the turbulence is smaller than the bounce frequency, the trapped particles drift across the magnetic field with a velocity much larger than that of the untrapped particles. A simple estimate shows that the displacement between the trapped-particle and untrapped-particle orbits is given by

$$\Delta r^2\approx r^2(b_\theta/B_\theta)^2, \qquad (7)$$

where b_θ is the amplitude of the turbulence and B_θ is the poloidal magnetic field. For the deviation to be larger than the ion banana size, the amplitude of modulation is of the order of 0.1% of the poloidal magnetic field for typical machine parameters.

Because of the uncertainty of the type and size of the error field, it is difficult to calculate the diffusion coefficient for experiments. In Tokamak (T-3[3] and ST[4]) experiments, the ion heat conduction rate is consistent with the neoclassical formula. This indicates that $\langle\Delta\psi^2\rangle$ is not much larger than the ion banana size. However, the collision frequency for electrons is higher than that for ions and the electron heat conduction could be much larger than the neoclassical rate if $\langle\Delta\psi^2\rangle$ is between the electron and ion banana size. A rough estimate shows that the error fields of the order of less than 1% with short wavelengths are needed to produce such values for $\langle\Delta\psi^2\rangle$. It is likely that the observed electron heat conduction and transport are due to either the error field or the magnetohydrodynamic turbulence. In addition, the effect of a magnetic perturbation should be smaller near the magnetic axis, mainly because of a small population of trapped particles. This also fits the observation of the high-temperature region near the magnetic axis in ST.[4]

The experiment with the dc octupole[5] showed that the diffusion is collisional at high densities ($n > 10^9$ cm^{-3}). The measured diffusion coefficient is approximately the classical value inside the separatrix. The value is much larger outside of the separatrix where $\langle \Delta\psi^2 \rangle$ is expected to be large. More detailed measurements are underway to determine the scaling on the magnetic field.

In summary, a model is proposed to explain the experimental observations of the anomalous transport processes in Tokamaks and multipole devices. Since this type of transport is only weakly dependent on the magnetic field strength, a large fusion device must be carefully engineered to minimize the magnetic perturbations.

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Isotopic Impurity Tunneling in Solid ^{4}He†

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A study has been made of the motion of isotopic impurities in solid ^{4}He. The tunneling frequency of ^{3}He atoms with neighboring ^{4}He atoms in the ^{4}He lattice has been deduced from nuclear magnetic relaxation measurements. The volume variation of the ^{3}He-^{4}He tunneling rate is much greater than that of the ^{3}He-^{3}He tunneling rate (exchange).

Recent discussions by Andreev and Lifshitz,[1] Guyer and Zane,[2] and Balakrishnan and Lange[3] have suggested the existence of a set of many-body excitations, called mass fluctuation waves, associated with the motion of isotopic impurities in solid-helium crystals. Because of the large-amplitude zero-point motion in quantum crystals, there is an overlap of the atomic wave functions of atoms occupying adjacent lattice sites which permits a mutual tunneling of the atoms through the potential barrier of neighboring atoms. The pairs of atoms rotate about the hard-core sphere of repulsion. At sufficiently low temperatures and with sufficiently dilute isotopic impurities, the tunneling motion permits the isotopic impurity to be distributed over a large number of lattice sites, and, further, the impurity atom propagates through the lattice with a well-defined wave vector.[1] The striking decrease in the spin-lattice relaxation time T_1 which has been measured at low temperatures in ^{3}He crystals doped with ^{4}He impurities[4-6] has been analyzed in terms of the thermal reservoir associated with the mass-fluctuation waves of the ^{4}He atoms.[2,7,8] In the present work we have attempted to detect the characteristic tunneling motion of isotopic impurities by studying the nuclear magnetic relaxation of ^{3}He atoms diluted in ^{4}He crystals.

Let us construct a simple theory to account for the relaxation resulting from the tunneling motion. We begin by assuming that the ^{3}He atoms travel through the lattice by a random walk to nearest-neighbor positions with a mean time τ_{34} between steps. τ_{34}^{-1} is the tunneling frequency between ^{3}He atoms and ^{4}He atoms in the ^{4}He lattice. The correlation function for the fluctuations in the nuclear magnetic dipole field will thus be an exponential decay with a "correlation time" τ_{34}. The problem of spin-lattice relaxation by translational diffusion in a solid has been studied by Torrey.[9] A simple modification of his expression for T_1 yields

$$T_1^{-1} = (2M_2 x/\omega)\psi(k, y), \tag{1}$$

where M_2 is the second moment of the resonance line for a rigid lattice with $x = 1$,[10] x is the con-