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Transition between isotope-mixing and non-mixing states in hydrogen-deuterium mixture plasmas in the Large Helical Device

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Transition between isotope-mixing and non-mixing states in hydrogen-deuterium mixture plasmas is observed for the first time in the world in the isotope (hydrogen and deuterium) mixture plasma in Large Helical Device. In the non-mixing state, the isotope density ratio profile is un-uniform when the beam fueling isotope species differs from the recycling isotope species and the profile varies significantly depending on the ratio of the recycling isotope species, although the electron density profile shape is unchanged. The fast transition from non-mixing state to isotope-mixing state (nearly uniform profile of isotope ion density ratio) is observed associated with the change of electron density profile from peaked to hollow profile by the pellet injection near the plasma periphery. The transition from non-mixing to isotope-mixing state strongly correlates with the increase of turbulence measurements and the transition of turbulence state from TEM to ITG is predicted by gyrokinetic simulation.

Bulk charge exchange spectroscopy[A] has been applied to measure the radial profiles of hydrogen (H) and deuterium (D) density in the plasma from H_α and D_α lines emitted by the charge exchange reaction between the bulk ions and the neutral beam injected in Large Helical Device (LHD). Figure 1 shows radial profiles of electron density normalized by the line-averaged electron density and H and D density in the plasma with H beam fueling but without gas puff. Electron density and the ratio of H recycling increase shot by shot due to the H beam fueling in the previous shot. The electron density profile shapes are almost identical for these three discharges with different line-averaged density and different wall recycling isotope ratio. However, radial profile shapes of H and D density are quite different depending on the ratio of H recycling. The amount of H density increases as the H recycling is increased, although the amount of D density is similar for these three discharges. When the isotope recycling ratio is close to unity (Γ_H/Γ_D = 0.8), there is almost no difference in profiles between H and D density as seen in Fig.1(b). In contrast, a significant difference in the profile shape (peaked or hollow) between H density and D density is observed in the lower density plasma where the H recycling is low enough (Γ_H/Γ_D = 0.3), as seen in Fig.1(d).

The transition from non-mixing state to isotope-mixing state is observed after H and D pellet injections[B]. Because of the relatively shallow pellet deposition, pellet injections make the electron density profile more hollow. Before the pellet injection the H density profile is much more peaked than the D density profile due to the H beam fueling and D dominant recycling. After the pellet injection, the H density profile becomes similar in shape to D density profile regardless of the species of pellet as seen in Fig.2. Therefore, the flattening of H fraction profile both for the H and the D pellet is a clear evidence for isotope-mixing. If plasma is non-mixing state, the H fraction profile should be more peaked after the D pellet injection because of the edge pellet deposition. The transition from non-mixing state to isotope-mixing state occurs in a time scale shorter than the global particle confinement time (less than $\sim$15 ms), which implies the large ion diffusion coefficient in the isotope-mixing state.

Figure 3(a)(b) shows the electron density profile and, the density fluctuation spectrum integrated from edge to core along the laser beam line of the central chord of phase contrast imaging (PCI) for non-mixing and isotope-mixing states. As seen in Fig.3(b), the turbulence level increases by an order of magnitude in the isotope-mixing state. Electron temperature and its normalized gradient decreases significantly but ion temperature decreases slightly. The ratio of electron temperature to ion temperature (T_e/T_i ratio) also decreases. Figure 3(c) shows the linear growth rates calculated with gyrokinetic simulation code GKV[C] for TEM and ITG turbulence, based on the radial profile of the density and the temperature measured. The non-mixing state is observed in the low-density plasmas with electron cyclotron heating (ECH) and neutral beam injection (NBI), where the beam fueling isotope species differ from the isotope species due to recycling. After the pellet injection, the isotope-mixing state is observed in higher density plasmas.

When the sign of density gradient changes from negative (peaked) to positive (hollow), the growth rates of both TEM and ITG decrease. The gyrokinetic simulation predicts that TEM propagating in the electron diamagnetic direction is unstable for the non-mixing state. However, the TEM is stabilized and ITG mode propagating in the ion-diamagnetic direction becomes unstable for the isotope-mixing state. In this experiment, the ratio of ion diffusion to electron diffusion coefficient, D_i/D_e, defined as $-[\Gamma_H/(\partial n_H/\partial r) + \Gamma_D/(\partial n_D/\partial r)]/[2\Gamma_e/(\partial n_e/\partial r)]$ is evaluated from the quasilinear approximation in the gyrokinetic calculations, where the ambipolar condition of $\Gamma_H + \Gamma_D + Z_C\Gamma_C - \Gamma_e = 0$ holds in the simulation. The D_i/D_e

is 0.4 for the case of the TEM dominant state before the pellet injection, while D_i/D_e is 2.5 for the case of the ITG-dominant state after the pellet injection. These simulation results are consistent with the non-linear GKW simulation results[D] where the isotope mixing is predicted to occur when ITG is dominant ($D_i > D_e$) and not to occur when TEM is dominant ($D_i < D_e$).

The fast transition between mixing and non-mixing state of isotope observed in this experiment stimulates the future development of non-linear global gyrokinetic simulation for multiple ion species, which is numerically challenging work. This results demonstrate that non-mixing and the isotope-mixing states depends on the turbulence state and give the important knowledge for predicting the isotope density profiles in the D-T mixture plasma in JET and ITER.

[A] K.Ida, et.al., Rev. Sci. Instrum. **90**, (2019) 093503.

[B] K.Ida, et.al., Phys. Rev. Lett. **124**, (2020) 025002.

[C] M.Nakata, et.al., Phys. Rev. Lett. **118**, (2017) 0165002.

[D] C.Bourdelle, et. al., Nucl. Fusion **58**, (2018) 076028

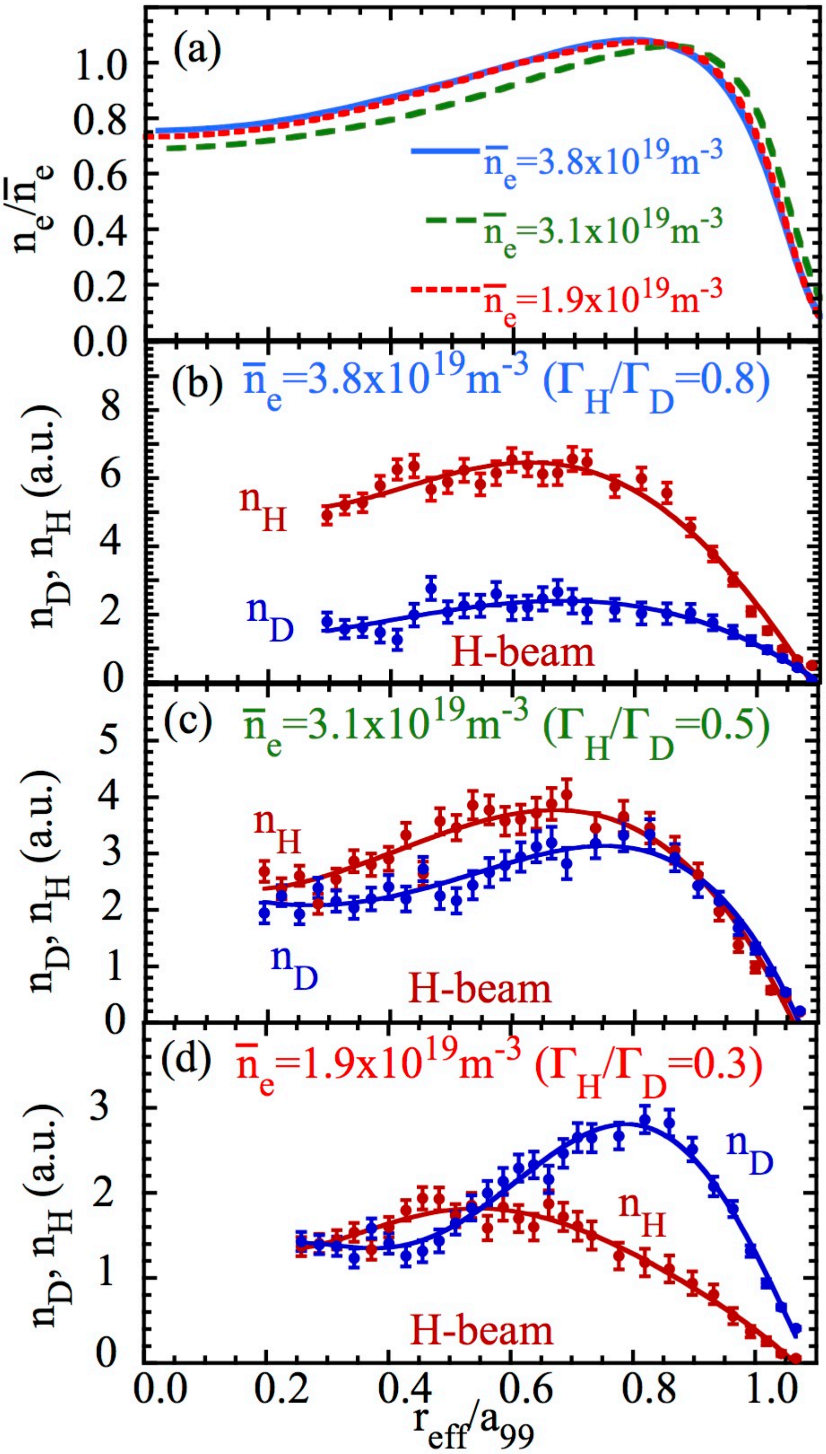

Figure 1: (a) Radial profiles of electron density and (b)(c)(d) radial profiles of H and D density in the plasma with H-beam fueling for the different line-averaged density and wall recycling isotope ratio of (b) 3.8×10 ^{19}m^{-3} (Γ_H/Γ_D = 0.8), (c), 3.1×10^{19}m^{-3} (Γ_H/Γ_D = 0.5), and (d) 1.9×10^{19}m^{-3} (Γ_H/Γ_D = 0.3).

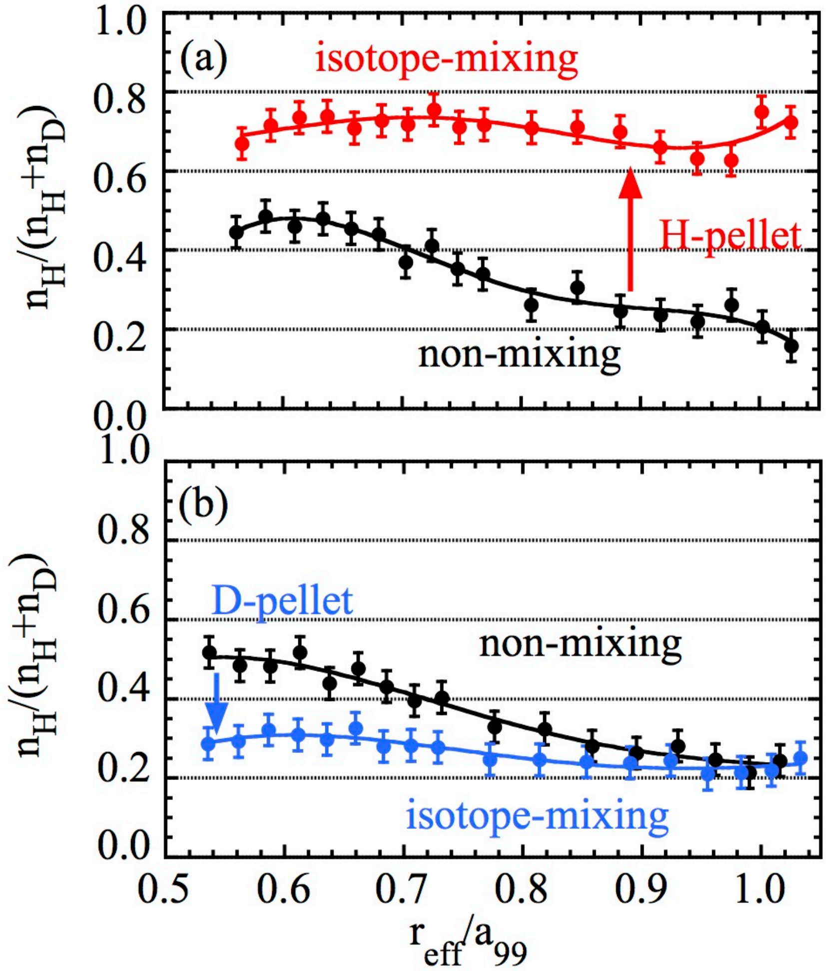

Figure 2: Radial profiles of hydrogen isotope fraction, $n_H/(n_H + n_D)$ before and after the (a) H-pellet and (b) D-pellet.

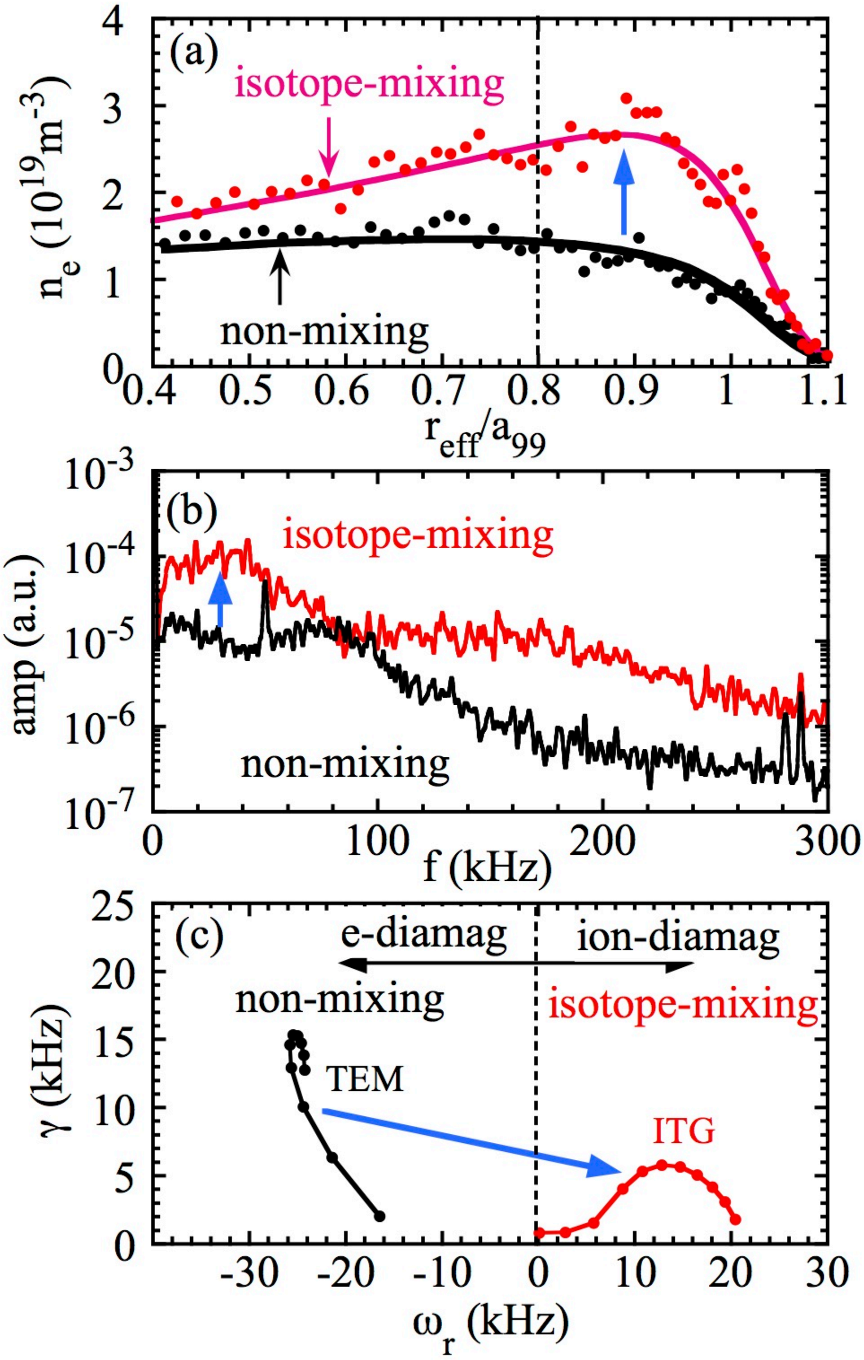

Figure 3: Radial profiles of (a) electron density and (b) density fluctuation spectrum before pellet injection (non-mixing state) and after pellet injection (isotope mixing state) and (c) the linear growth rate at $r_{\rm eff}/a_{99}$ = 0.8 for the non-mixing and isotope-mixing sates calculated with GKV.

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