Experimental Study of Isotope Scaling of Ion Thermal Transport

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The wide divergence between most theoretical predictions of isotopic mass scaling of transport and tokamak experimental results motivated a basic physics experiment in the Columbia Linear Machine [R. Scarmozzino, A. K. Sen, and G. A. Navratil, Phys. Rev. Lett. **57**, 1729 (1986)]. The experiments on ion thermal conductivity due to ion temperature gradient-driven slab modes are performed using two different gases: hydrogen and deuterium. The results indicate inverse dependence of ion thermal conductivity on the isotope mass close to $K_\perp \sim A_i^{-0.5}$. This is similar to the tokamak results, but in stark contradiction to most present theoretical models.

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Isotope scaling of transport is an important issue for magnetic fusion. As there is strong divergence between most theoretical predictions and tokamak experimental results, this has become a critical open basic plasma physics issue. All Bohm-like scaling of transport parameters indicate $D_\perp$, $K_\perp \sim A_i^0$, while gyro-Bohm-like scaling implies $\sim A_i^{0.5}$, where A_i is the mass number of the isotope of hydrogen. These include most of the latest results of ion temperature gradient (ITG) turbulence, resistive ballooning mode theories, as well as 2D and 3D Gyrofluid and Gyrokinetic simulations [1]. However, the Bohm or gyro-Bohm-like scaling is in stark contrast with the vast majority of tokamak experiments, which show a scaling close to $A_i^{-0.5}$ [2]. This fundamental discrepancy motivated basic physics experiments in the Columbia Linear Machine (CLM) [3]. A preliminary experiment on isotopic scaling of particle transport due to the $\vec{E} \times \vec{B}$ rotational mode in CLM has been reported to yield $D_\perp \sim A_i^{-0.6\text{ to }-0.8}$ [4], which is similar to that of tokamaks. Now we report a thorough careful study of isotopic scaling of ion thermal transport due to ITG slab modes, which is a much more relevant and important issue. Unlike in tokamaks, we can maintain nearly identical plasma parameter profiles for two gases, hydrogen and deuterium, via adjustments of various knobs for rf heating voltage (T_i and ∇T_i), end plate bias (E_r and ∇E_r), discharge current/neutral pressure (n), and ring mesh bias (∇n) [5]. This will be in contrast to the somewhat uncertain results from a wide ranging tokamak database of disparate machines and operating parameters [2].

The experiment was performed in the CLM [3], which generates a steady-state collisionless cylindrical plasma column in a uniform axial magnetic field. The rf heating meshes, located in the transition region, effectively heated the core of the plasma in the parallel direction so that an ITG mode was excited [5]. The typical parameters are density $n \sim 2 \times 10^8$ to 1×10^9 cm^{-3}, electron temperature $T_e \sim 6$ to 8 eV, perpendicular ion temperature $T_{i\perp} \sim 5$ eV, parallel ion temperature $T_{i\parallel} \sim 5$ to 20 eV, $\eta_{i\parallel} \sim 0.5$ to 5, $\eta_{i\perp} < 1$ ($\eta_i = \partial \ln[T_i]/\partial \ln[n_i]$), magnetic field B (experimental cell) ≈ 1 kG, plasma cell length $L \sim 160$ cm, and plasma column radius $r_p \sim 3$ cm. The parallel and transverse ion temperatures were measured with gridded ion energy analyzers. The dc plasma potential was obtained from the floating potential of an emissive probe.

The ITG instability produced in the transition region, where a sharp temperature gradient is created via rf, travels down the machine with the plasma flow as shown in Fig. 1. Two ion energy analyzers, calibrated against each other, are located at $z = 67$ cm and $z = 145$ cm (see Fig. 1). The position of the heating mesh is taken as $z = 0$ cm. Therefore, the thermal transport can be measured by determining the ion temperature radial profile relaxation downstream [6]. In the steady state, the transport equation governing the ion temperature relaxation can be written as follows:

$$\frac{1}{2} n_i v_f \frac{\partial}{\partial z} T_{i\parallel} = \frac{1}{r} \frac{\partial}{\partial r} \left(r n_i K_\perp \frac{\partial}{\partial r} T_{i\parallel} \right), \tag{1}$$

where n, v_f, $T_{i\parallel}$, $K_\perp$, r, and z are density, flow velocity, parallel ion temperature, transverse ion thermal conductivity, and radial and axial coordinates of a cylindrical system, respectively. The flow velocity v_f of Eq. (1) has been estimated to be typically $v_f \sim (1/3$ to $1/4)v_s$, where $v_s =$ ion acoustic speed [7]. Then, Eq. (1) is numerically solved

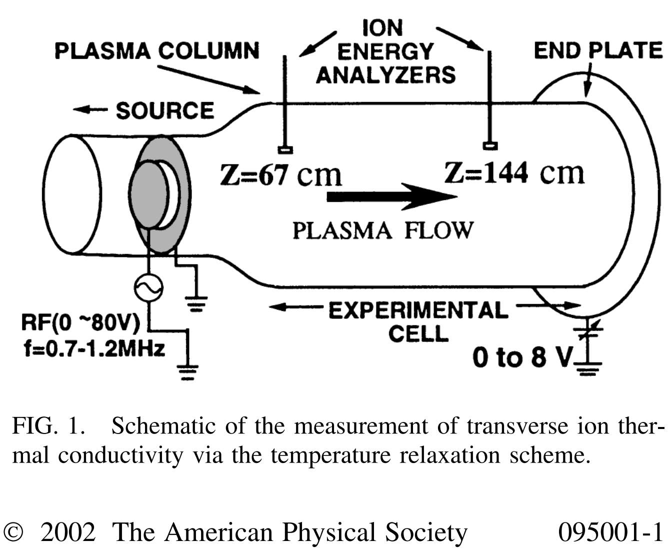

FIG. 1. Schematic of the measurement of transverse ion thermal conductivity via the temperature relaxation scheme.

by the explicit finite difference method with the upstream temperature profile data as a boundary condition. The thermal conductivity is modeled by a spline function with a number of adjustable parameters, such that the calculated downstream temperature profile is optimally fitted to the experimental data downstream. The result is a spatially variable ion thermal conductivity $K_\perp(r)$. For convenience, in the isotope scaling studies, we focus on the maximum value of $K_\perp(r)$ roughly at the radial location of maximum fluctuation level and maximum temperature gradient at $r = 1.6$ cm.

In our experiments, there is a possible extra channel for thermal transport via thermal convection due to particle transport caused by the $\vec{E} \times \vec{B}$ mode. However, as the density diffusion coefficient $D_\perp \ll K_\perp$ and $\nabla n/n \ll \nabla T_i/T_i$, the former may be neglected. More cogently, the ratio of thermal flux due to particle diffusion $D_\perp$ to that due to thermal conductivity $K_\perp$ is

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rT_{i\|}D_\perp\frac{\partial}{\partial r}n_i\right)\Bigg/\frac{1}{r}\frac{\partial}{\partial r}\left(rn_iK_\perp\frac{\partial}{\partial r}T_{i\|}\right)\sim\frac{D_\perp}{\eta_{i\|}K_\perp}\leq 0.06$$

for our experimental parameters.

Figure 2 shows the typical power spectra of density fluctuations. The mode with frequency $f \sim 75$ kHz has been identified as the $\vec{E} \times \vec{B}$ mode with $m = 1$, $k_\| = 0$; this mode is believed to be a Rayleigh-Taylor–type instability, driven by $\vec{E} \times \vec{B}$ rotation of the plasma column [8]. The mode with frequency $f \sim 135$ kHz satisfied the characteristics of the slab ITG mode with $m = 2$, $k_\| \sim 2\pi/300\ \text{cm}^{-1}$ [5]. For our plasma parameters, the number of e-foldings of the mode at the points of observation are > 2. In Fig. 3, the typical profile of upstream temperature has a significant gradient at $r = 1.6$ cm (average $\eta_{i\|} \sim 3$), and the profile of downstream temperature is flatter due to the radial thermal conductivity. The calculated downstream profile of $T_{i\|}$ with optimal fitting procedure described above is shown also and yields $K_\perp = 0.85\ \text{m}^2/\text{s}$ at $r = 1.6$ cm for hydrogen.

Ideally, for meaningful isotopic scaling experiments, one should maintain identical plasma parameter profiles in identical discharges for several gases. However, this has been nearly impossible for the large tokamak databases used for this purpose [2], but less so in specific campaigns in a specific tokamak [2,9,10]. In contrast, this is largely achievable in CLM via various experimental knobs as discussed above. But, even in CLM, it is difficult to obtain rigorously all identical parameter profiles, especially for our comprehensive study involving a wide range of instability drives and fluctuation levels designed to provide us with rich data sets. Therefore, besides obtaining as closely similar profiles as possible, we focus on maintaining the most important parameter(s) rigorously constant for both gases. In the case of ITG modes in CLM, it is $\eta_{i\|}$. Therefore, in the first set of experiments, we determine $K_\perp$ as a function of $\eta_{i\|}$ for both gases, where $\eta_{i\|}$ is varied over a wide range via adjustable rf heating. The results are shown in Fig. 4. We obtain the isotopic scaling by taking the ratio of the two values of $K_\perp$ for the two gases at the same $\eta_{i\|}$, resulting in $K_\perp \sim A_i^{-0.65\text{ to }-0.85}$. It is noted that this result is close to those of tokamak experiments [2,10].

We study another basis of comparison with the hope of clarifying some underlying basic physics. The isotopic role in the statistical mechanics of energy scattering by turbulence can be defined from the scaling of $K_\perp$ vs $(\tilde{n}/n_0)$. This is shown in Fig. 5, where we take the ratio of two $K_\perp$'s for the two gases at the same $(\tilde{n}/n_0)$. The result in our case is $K_\perp \sim (\tilde{n}/n_0)A_i^{-0.5}$. Next, we study the role of the isotopic effect in the nonlinear dynamics of the saturation of the instability by examining the scaling $(\tilde{n}/n_0)$ vs $\eta_{i\|}$. This is shown in Fig. 6, and the result in our case is $(\tilde{n}/n_0) \sim (\eta_{i\|} - \eta_{i\|})A_i^{-0.35\text{ to }-0.45}$, where we have included the role of $\eta_{i\|C}$, which is the critical value for the onset of the instability. If we now combine the above two results, we find $K_\perp \sim (\tilde{n}/n_0)A_i^{-0.5} \sim A_i^{-0.85\text{ to }-0.95}$. The experimental determination of $\eta_{i\|C}$ is difficult, because of a poor

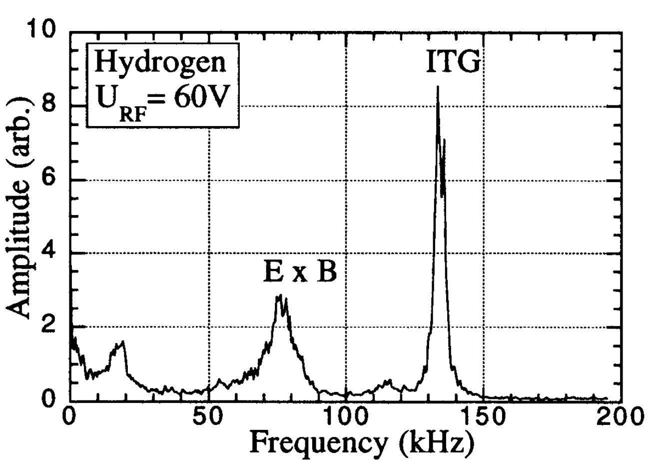

FIG. 2. Power spectra of density fluctuation.

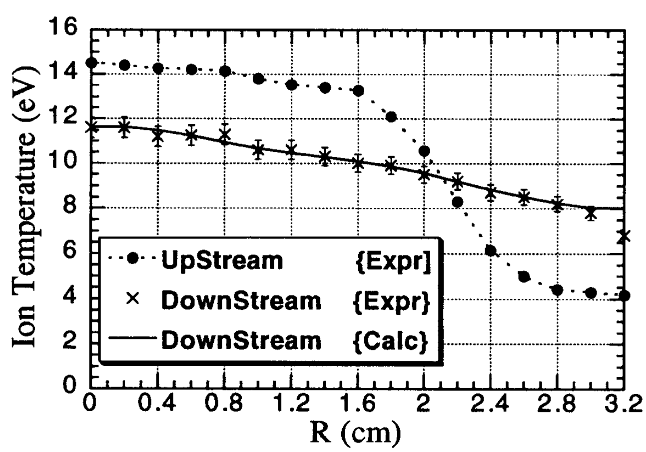

FIG. 3. Experimental ion temperature profiles and optimal fitting to a model.

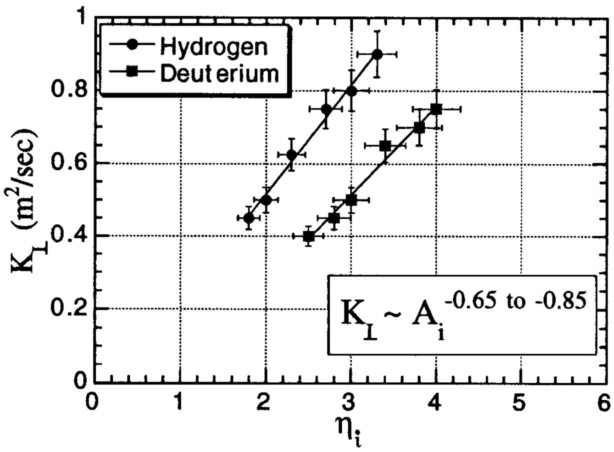

FIG. 4. Scaling of the ion thermal conductivity versus $\eta_{i\|}$ for hydrogen and deuterium.

signal/noise ratio in this regime leading to the reasonable assumption that $\eta_{i\|C}$ is approximately the same in both cases. The above result is not inconsistent with the result mentioned above for the more direct case of comparison at the same linear drive: $K_\perp \sim \eta_{i\|} \cdot A_i^{-0.65 \text{ to } -0.85}$. Therefore, it appears that, roughly speaking, the larger part of the isotopic effect may be in the physics of energy scattering of ions by turbulence and a smaller role is in the nonlinear saturation dynamics of the waves. The weaker isotopic dependence of the latter implies that the three-wave coupling model, which does not have any mass dependence, may not be an appropriate nonlinear model in this case.

Lastly, for a special case of indisputable fairness of comparison, we describe the results of an experiment with nearly identical profiles of all plasma parameters for both gases, as shown in Figs. 7(a) and 7(b). As the radial electric field shear is thought to influence transport scaling [11,12], we have made a special effort to maintain the radial electric field to be identical for both gases as shown in Fig. 8. We take the ratio of two values of $K_\perp$ for two gases displayed in Figs. 7(a) and 7(b), and find $K_\perp \sim A_i^{-0.48}$. This result is presumably most reliable and extraordinarily close to the tokamak results in Refs. [2,10].

Clearly, all Bohm and gyro-Bohm-like scaling theories are manifestly at odds with the experimental results presented. The exceptions are now discussed. A concept by Coppi [13] based on impurity species response to ITG modes predicts a scaling $A_i^{-2/5}$ which agrees with the tokamak experimental results. As the impurity levels in CLM plasma are truly negligible, this mechanism is not applicable. A theory by Scott [14] based on nonlinear excitation of dissipative drift waves at the edge of tokamaks also leads to a scaling similar to tokamak experiments. But this theory is not appropriate for the collisionless CLM plasma with collisionality $v_{e,i}^* \sim 10^{-2}$, where v^* is the collision frequency normalized to bounce or transit frequency. A mechanism based on radial electric field shear stabilization of ITG modes which leads to the breaking of gyro-Bohm scaling, according to Waltz [11] and Ernst [12], appears to be most interesting and plausible. However, our experiment motivated by this scenario, whose results are shown in Figs. 7 and 8, clearly indicates that even when the radial electric field profiles are identical for two gases, the same inverse scaling of transport with isotopic mass is obtained. Lastly, a multimode model applied to tokamak discharges has predicted a non-gyro-Bohm-type scaling [15]. However, its correlation with changes in neutral beam power deposition profiles makes it moot for comparison with our results. Therefore, we must conclude that no present theory appears to predict our basic physics experimental results. It should be noted that parallel flow shear can potentially introduce a mass dependent destabilization. However, this shear should be a function of the plasma potential profiles, which are shown to be identical.

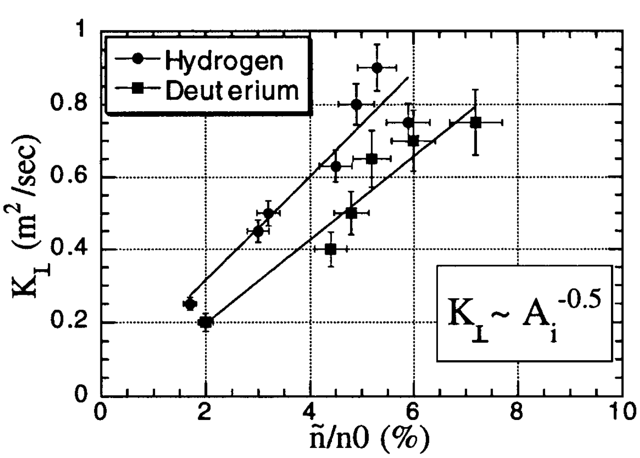

FIG. 5. Scaling of the ion thermal conductivity versus normalized fluctuation level for hydrogen and deuterium.

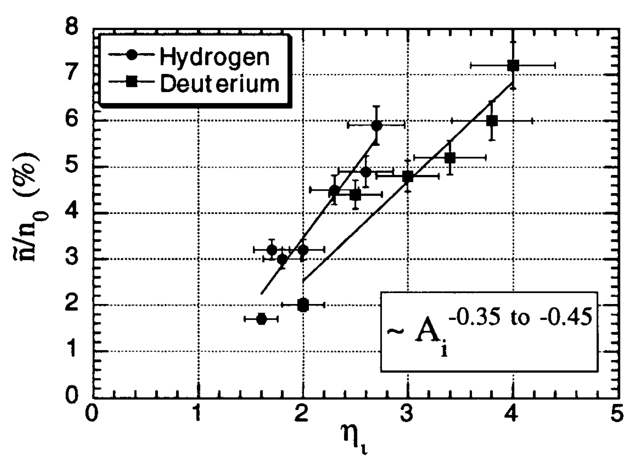

FIG. 6. Scaling of the normalized fluctuation level versus $\eta_{i\|}$ for hydrogen and deuterium.

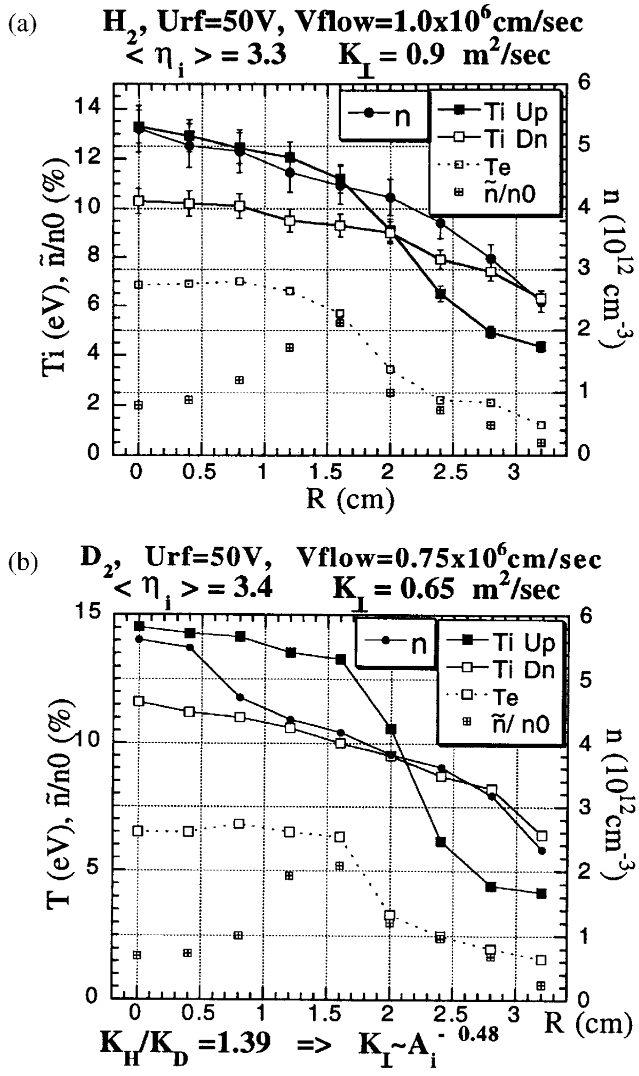

FIG. 7. (a) Profiles of plasma parameters in identical discharges (hydrogen). (b) Profiles of plasma parameters in identical discharges (deuterium).

The results of a basic physics experiment indicate an inverse dependence of ion thermal transport on the isotopic mass close to $K_\perp \sim A_i^{-0.5}$. This is very close to the tokamak experiments and in profound contradiction to all present theoretical models. Therefore, it raises serious questions about turbulent transport theories in general and poses a renewed critical challenge.

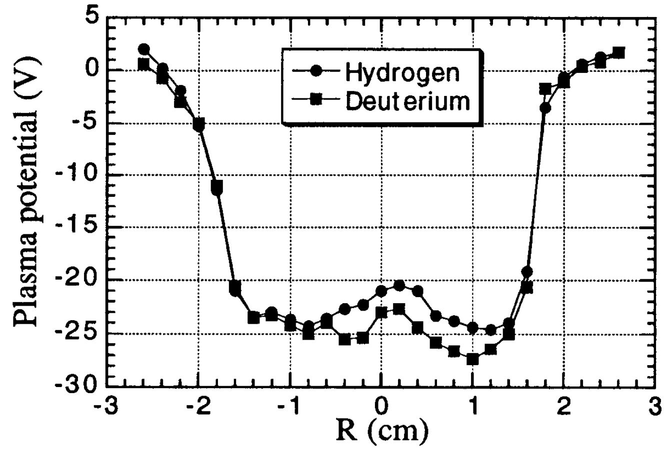

FIG. 8. Radial profiles of plasma potential for the identical discharges in Figs. 7(a) and 7(b).

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