Theory Seminar

On the Isotope Effects in Tokamak Plasmas: Core and Edge

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Outline

1. Isotope effects in the core

2. Isotope effects at the edge

3. The related gyrokinetic force balance equation
   and gyrokinetic MHD

Abstract

Hydrogen isotopic scaling was first studied in D-T plasmas in TFTR [1]. Recently, isotope experiments have also been carried out on JT-60U [2], JET [3], and DIII-D [4]. In all of them, the favorable confinement effects for the isotopes have been observed. These observations violate the gyroBohm scaling of

$$\chi_i \sim \frac{\gamma_L}{k_\perp^2} \propto \sqrt{M},$$

which predicts that ion thermal diffusivity increases with mass, where γ_L is the linear growth rate of the most unstable mode with perpendicular wavenumber $k_\perp$. On the other hand, it has been shown by Lee and Santoro [5] in their study on the ITG modes that

$$\chi_i \sim \frac{\Delta\omega}{k_\perp^2} \propto \frac{1}{\sqrt{M}},$$

where $\Delta\omega$ is the frequency spread in the nonlinearly saturated state. The above scaling is based on the resonance broadening theory proposed by Dupree [6] and is in agreement with the experiments mentioned above [1–4]. Apparently, this paper [5] has attracted very little attention in the fusion community., e.g., Ref. [2–4]., but it does help in resolving this puzzle.

As for the H-mode plasma, it was shown by Lee and White [7], based on the gyrokinetic Poisson's equation and the force balance equation, that $\nabla_\perp p_i \approx 0$, in the plasma core and

$$p_i \propto exp(-\sqrt{2}r/\rho_i)$$

in the pedestal region, where p is the plasma pressure, r is the minor radius and

$$\rho_i \sim \sqrt{M}$$

is the ion gyroradius. Thus, heavier hydrogen isotopes will have a wider and less steep pedestal in agreement with the JT-60 experimental data [8]. Details will be presented.

* The present work is partially supported by the US DoE Grant to PPPL.

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[1] S. D. Scott, M. C. Zarnstorff, C. W. Barnes, R. Bell et al., Phys. Plasmas **2**, 2299 (1995)
[2] H. Urano and E. Narita , Plasma Phys. Control. Fusion **63**, 084003 (2021)
[3] L. Horvath, C. F. Maggi, A. Chankin et al., Nuclear Fusion **61**, 046015 (2021)
[4] L. Schmitz, Phil. Trans. R. Soc. **A381**: 20210237 (2022)
[5] W. W. Lee and R. A. Santoro, Phys. Plasmas **4**, 169 (1997)
[6] T. H. Dupree, Phys. Fluids **11**, 2680 (1968)
[7] W. W. Lee and R. B. White, Phys. Plasmas **26**, 040701 (2019)
[8] H. Urano, Takizuka, N. Aiba, M. Kikuchi et al., Nucl. Fusion **53**, 083003 (2013)

Isotope Scaling of Heating and Confinement in Multiple Regimes of TFTR

S. D. Scott, G. W. Hammett, C. K. Phillips, E. J. Synakowski, S. Batha, M. A. Beer, M. G. Bell, R. E. Bell, R. V. Budny, C. E. Bush, W. Dorland, P. C. Efthimion, D. R. Ernst, E. D. Fredrickson, S. von Goeler, J. C. Hosea, S. M. Kaye, M. Kotschenruether, F. M. Levinton1, Q. P. Liu3, R. P. Majeski, D. M. McCune, D. R. Mikkelsen, H. K. Park, A. T. Ramsey, J. H. Rogers, S. A. Sabbagh, G. Schilling, C. H. Skinner, G. Taylor, R. E. Waltz6, J. R. Wilson, and M. C. Zarnstorff

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Paper IAEA-F1-CN-64/A6-6

International Atomic Energy Agency SIXTEENTH IAEA FUSION ENERGY CONFERENCE Montreal, Canada, 7-11 October 1996

….. one is led to conclude that the isotope effect must be governed by a fairly powerful, non-gyroBohm mechanism that leads to reduced transport for heavier isotopes despite their larger gyroradius. The proposed theoretical model of shear-flow modifications to ion-temperature-gradient turbulence, as embodied in the I F S - P P P L transport code, embodies such an intrinsic isotope effect through the ratio of linear growth rate to E_r shearing rate.

$$\tau_E^{th} \propto \langle A \rangle^{0.5}$$

Number of citations: 7

Physics Plasmas **4** (1), January 1997, p.169-173

Gyrokinetic simulation of isotope effects in tokamak plasmas

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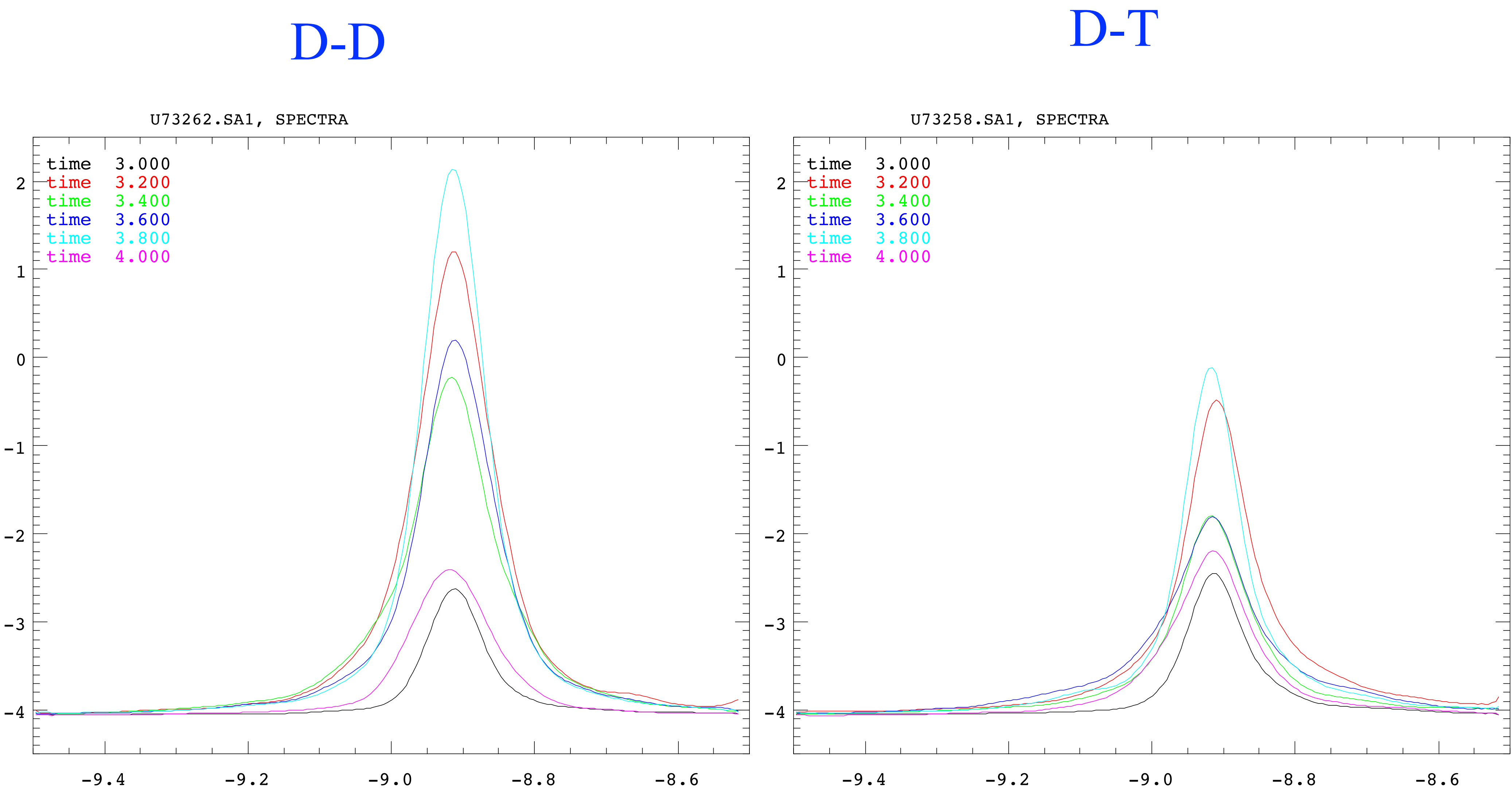
Received 29 November 1995; accepted 16 October 1996

A three-dimensional (3-D) global gyrokinetic particle code in toroidal geometry has been used for investigating the transport properties of ion temperature gradient (ITG) drift instabilities in tokamak plasmas. Using the isotopes of hydrogen (H^+), deuterium (D^+) and tritium (T^+), it is found that, under otherwise identical conditions, there exists a trend for favorable isotope scaling for the ion thermal diffusivity, i.e., χ_i decreases with mass. Such a trend, which exists both at the saturation of the instability and also at the fully nonlinear stage, can be understood from the resulting wave number and frequency spectra.

$$\chi_i \propto \frac{1}{\sqrt{M}}$$

Number of citations: 27



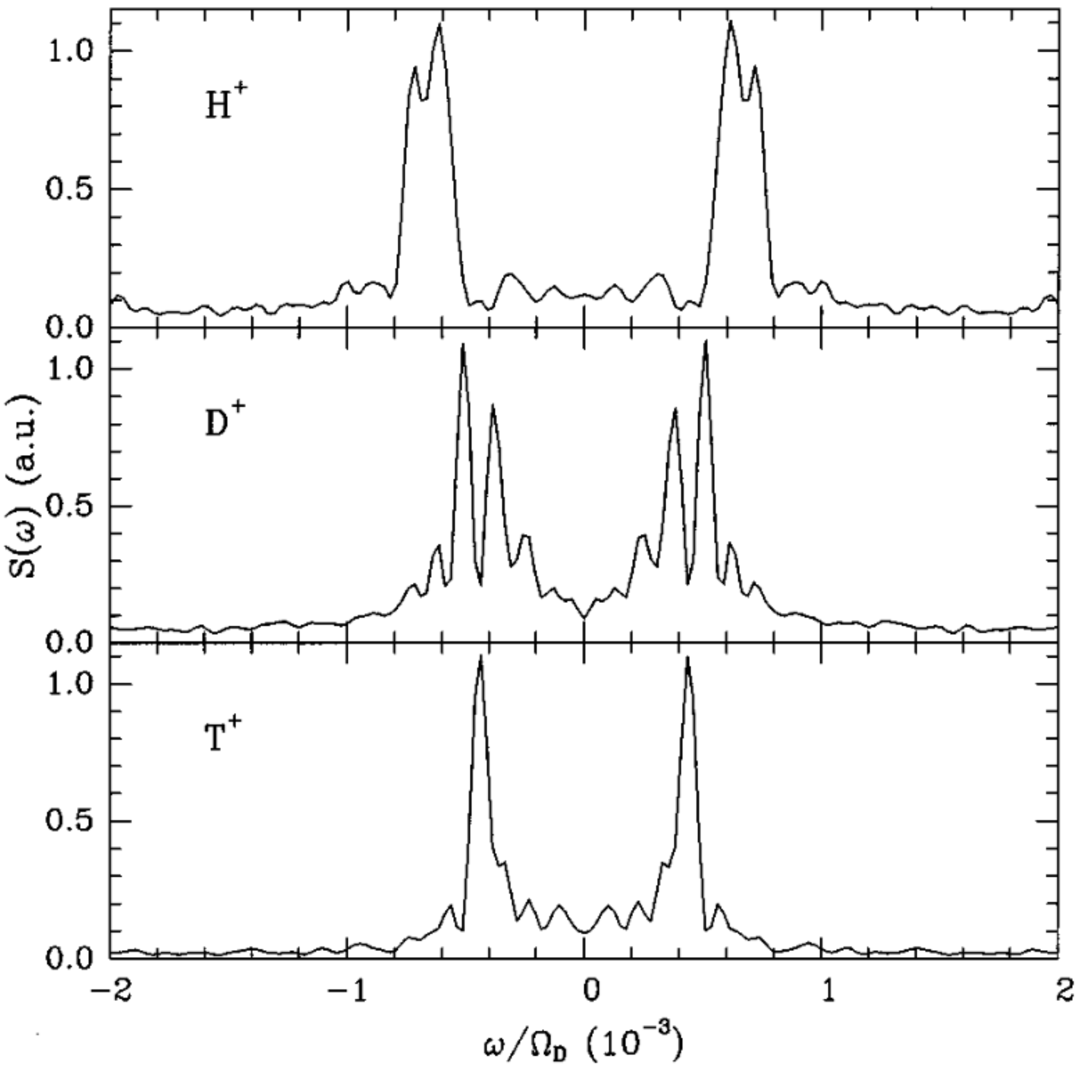
Microwave Scattering Data on Density Fluctuations in TFTR by N. Bretz et al. (unpublished, 1993)

Provided by Eric Frederickson

Phys. Plasmas 4 (1), January 1997, p.169-173

Gyrokinetic simulation of isotope effects in tokamak plasmas

W. W. Lee and R. A. Santoro



$$\Delta\omega \sim k_\perp^2 D.$$

FIG. 4. Spatially averaged frequency spectra along the weak magnetic field side of the midplane for the three hydrogenic isotopes, where subscript D denotes deuterium.

Plasma Phys. Control. Fusion 58 (2016) 115008

Isotope effect on gyro-fluid edge turbulence and zonal flows

O H H Meyer[1,2] and A Kendl[1]

Transport is found to be reduced with the effective plasma mass for protium, deuterium and tritium mixtures. This isotope effect is found for both cold and warm ion models, but significant influence of finite Larmor radius and polarisation effects are identified.

In any case the observed improvement in confinement is apparently inconsistent with primitive mixing length approximations of the turbulent gyro-Bohm cross-field diffusivities $\chi \sim \varrho_i \sim m_i$, where $\varrho_i \sim m_i$ is the ion gyro-radius.

Initial computations on the isotope effect on ion temperature gradient (ITG) core turbulence revealed a trend for favourable isotope scaling for the ion thermal diffusivity, which had partly been attributed to the ITG growth rate decreasing with isotope mass [DongHortonDorland, PoP97, LeeSantoro, PoP97].

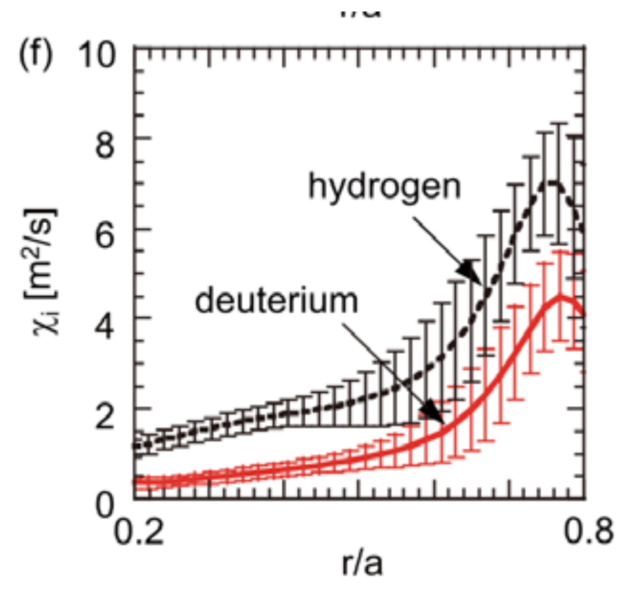
Increasing isotope mass has been found to lead to stronger zonal flows and GAMs, which in turn reduce the radial turbulent particle transport magnitude.

The simulations show reduced transport amplitudes in heavier plasmas in terms of the reduced radial particle flux.

IOP Publishing
Plasma Physics and Controlled Fusion
Plasma Phys. Control. Fusion **60** (2018) 014045 (14pp)
https://doi.org/10.1088/1361-6587/aa9901

Isotope effects on L-H threshold and confinement in tokamak plasmas

C F Maggi[1], H Weisen[2], J C Hillesheim[1], A Chankin[3], E Delabie[4], L Horvath[5], F Auriemma[6], I S Carvalho[7], G Corrigan[1], J Flanagan[1], L Garzotti[1] et al.



The favourable scaling of global energy confinement time with isotope mass, which has been observed in many tokamak experiments, remains largely unexplained theoretically.

Special Issue on Isotope Effects in Toroidal Devices

Plasma Phys. Control. Fusion **63** (2021) 084003 (10pp)

Review of hydrogen isotope effects H-mode confinement in JT-60U

H Urano* and E Narita

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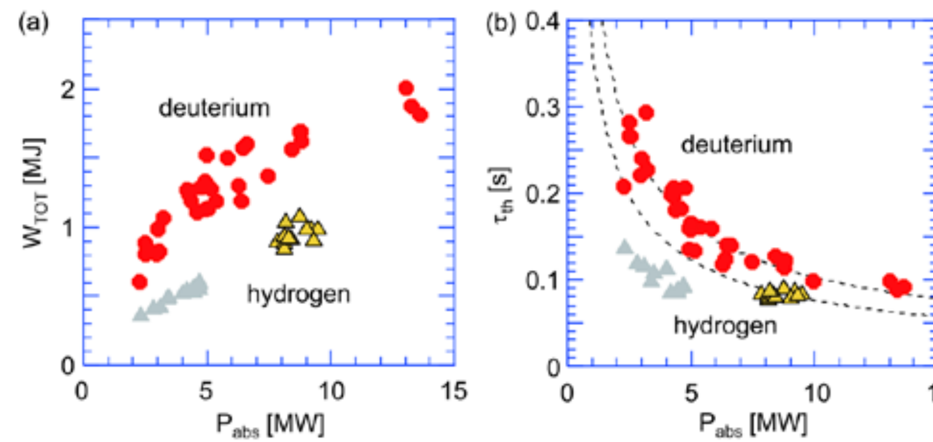

Hydrogen isotope effects on H-mode confinement in JT-60U are reviewed. The thermal energy confinement time becomes longer in deuterium by a factor of ~1.4 than in hydrogen at a given absorbed power.

J. Plasma Phys. (2020), vol. 86, 905860501

Isotope dependence of energy, momentum and particle confinement in tokamaks

H. Weisen[1,†], C. F. Maggi[2], M. Oberparleiter[3], F. J. Casson[2], Y. Camenen[4], S. Menmuir[2], L. Horvath[2,5], F. Auriemma[6], T. W. Bache[2], N. Bonanomi[7], A. Chankin[7], E. Delabie[8], L. Frassinetti[9], J. Garcia[10], C. Giroud[2], D. King[2], R. Lorenzini[6], M. Marin[11], P. A. Schneider[7], P. Siren[12,13], J. Varje[13], E. Viezzer[14] and JET contributors‡

[1]Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland

The isotope dependence of plasma transport will have a significant impact on the performance of future D-T experiments in JET and ITER and eventually on the fusion gain and economics of future reactors. In preparation for future D-T operation on JET, dedicated experiments and comprehensive transport analyses were performed in H, D and H-D mixed plasmas.

Remarkably, in H-mode all three transport channels, energy, momentum and particle transport, have similar isotope scalings, with mass exponents around 0.5.

Reference: S. Scott et al. '95

PHYSICAL REVIEW LETTERS **125,** 015001 (2020)

Reversal of Simple Hydrogenic Isotope Scaling Laws in Tokamak Edge Turbulence

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(Received 23 March 2020; accepted 9 June 2020; published 30 June 2020)

The role of nonadiabatic electrons in regulating the hydrogenic isotope-mass scaling of gyrokinetic turbulence in tokamak fusion plasmas is assessed in the transition from ion-dominated core transport regimes to electron-dominated edge transport regimes. We propose a new isotope-mass scaling law that describes the electron-to-ion mass-ratio dependence of turbulent ion and electron energy fluxes. The mass-ratio dependence arises from the nonadiabatic response associated with fast electron parallel motion and plays a key role in altering—and in the case of the DIII-D edge, favorably reversing—the naive gyro-Bohm scaling behavior. In the reversed regime hydrogen energy fluxes are larger than deuterium fluxes, which is the opposite of the naive prediction.

DOI: 10.1103/PhysRevLett.125.015001

Plasma Phys. Control. Fusion **63** (2021) 064006 (15pp) **Special Issue on Isotope Effects in Toroidal Devices**

Overview of the isotope effects in the ASDEX Upgrade tokamak

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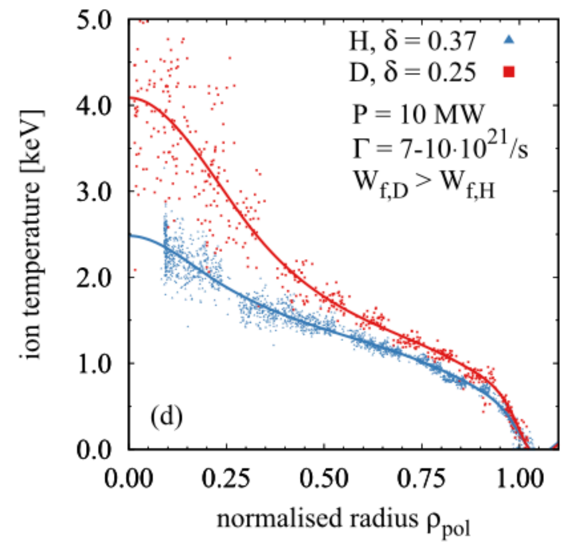

Assuming a state where turbulence is determined by the ion temperature gradient (ITG) with adiabatic electrons in the collisionless limit, gyrokinetic theory predicts a scaling of heat transport such that $\chi \propto \varrho_i \propto A^{0.5}$. However, this ideal state does not exist in reality. Such deviations from the gyroBohm scaling, associated with the main ion mass, are generally termed the 'isotope effect'. In most observations, the isotope effects manifest in a reversal of the ideal gyroBohm scaling, i.e. the confinement improves with mass. Therefore, whenever possible, we will discuss the influence of the isotope mass in experimental observations without a gyroBohm normalisation. In this case, we will refer to an 'isotope mass dependence'

At the plasma edge and when turbulence suppression via external E × B shear becomes important, the ion temperature and density gradients contribute to turbulence drive and suppression simultaneously.

Nucl. Fusion **61** (2021) 046015 (17pp) https://doi.org/10.1088/1741-4326/abdd77

Isotope dependence of the type I ELMy H-mode pedestal in JET-ILW hydrogen and deuterium plasmas

Nucl. Fusion **61, (2021) 046015**

L. Horvath[1,2,*], C.F. Maggi[1], A. Chankin[3], S. Saarelma[1], A.R. Field[1], et al.

The pedestal pressure is typically higher in D than in H at the same input power and gas rate, with the difference mainly due to lower density in H than in D [Maggi, Weisen, et al, 2018 Plasma Phys. Control. Fusion **60**, 014045].

Turbulence and $E \times B$ flow correlations across the L-H transition in DIII-D deuterium and hydrogen plasmas

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Phil. Trans. R. Soc. A 381: 20210237. https://doi.org/10.1098/rsta.2021.0237 (2022)

Experiments in many toroidal fusion devices have shown that radial thermal transport is enhanced in hydrogen plasmas compared to deuterium, in contrast with theoretical expectations based on the so-called Gyro-Bohm confinement scaling. …. The observed thermal confinement times in deuterium plasmas significantly exceed those in hydrogen plasmas, and the L-H power threshold is consistently observed to be 2–3x higher in hydrogen than in deuterium. The origin of this so-called gyro-Bohm transport scaling reversal, and of the difference in L-H transition threshold power has not been conclusively established.

Prompt core confinement improvement across the L–H transition in DIII-D: Profile stiffness, turbulence dynamics, and isotope effect

Cite as: Phys. Plasmas **30**, 032301 (2023); doi: 10.1063/5.0137669
Submitted: 5 December 2022 · Accepted: 14 February 2023 ·
Published Online: 3 March 2023

View Online Export Citation CrossMark

T. Kobayashi,[1,2,a] Z. Yan,[3] G. R. McKee,[3] M. E. Austin,[4] B. A. Grierson,[5] and P. Gohil[5]

We elaborate on the nature of the prompt core confinement improvement observed at the L–H transition in DIII-D, which is a longstanding issue unsolved for more than two decades and can impact future fusion reactor performance……. Properties of nonlocal confinement improvement across the L–H transition are experimentally assessed in hydrogen (H) and deuterium (D) plasmas. Prompt core confinement improvement is found to be more rapid in the lighter hydrogen isotope.

One of these conundrums is the prompt core confinement improvement across the low to high confinement mode transition (L–H). That is, although the radial electric field as the turbulence regulator is only excited in a limited peripheral region, the turbulent transport is nonlocally suppressed in a wide radial region including the core.

The effect of zonal flows is another candidate for the interpretation. As presented in theory and exhibited in numerical simulation and experiment, zonal flows are more activated in D plasmas than in H plasmas. With the reinforced zonal flow in D plasmas, the turbulence spreading is expected to be less pronounced. Direct detection of zonal flows affected by the isotope mass is a future task.

Isotope effects on energy transport in the core of ASDEX-Upgrade tokamak plasmas: Turbulence measurements and model validation

Cite as: Phys. Plasmas **30**, 082304 (2023); doi: 10.1063/5.0143416
Submitted: 23 January 2023 · Accepted: 21 July 2023 ·
Published Online: 16 August 2023

P. A. Molina Cabrera,[1,2,a)] P. Rodriguez-Fernandez,[1] T. Görler,[2] M. Bergmann,[2] K. Höfler,[2,3] S. S. Denk,[1] R. Bielajew,[1] G. D. Conway,[2] C. Yoo,[1] A. E. White,[1] and ASDEX Upgrade Team[b)]

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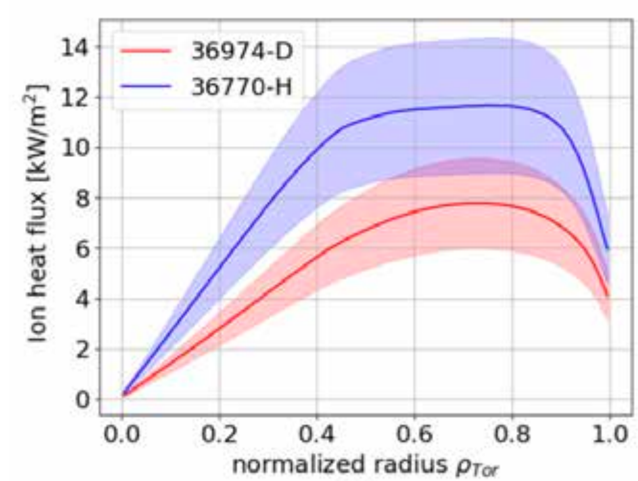
[2]Max Planck Institute for Plasma Physics, Boltzmannstr. 2, 85748 Garching, Germany
[3]Physics Department E28, Technical University of Munich, James-Franck-Str. 1, 85748 Garching, Germany

The improved energy confinement in deuterium can be hypothesized to be due to the fact that the external electron heating is most efficiently coupled to the ions in the hydrogen discharge and that the



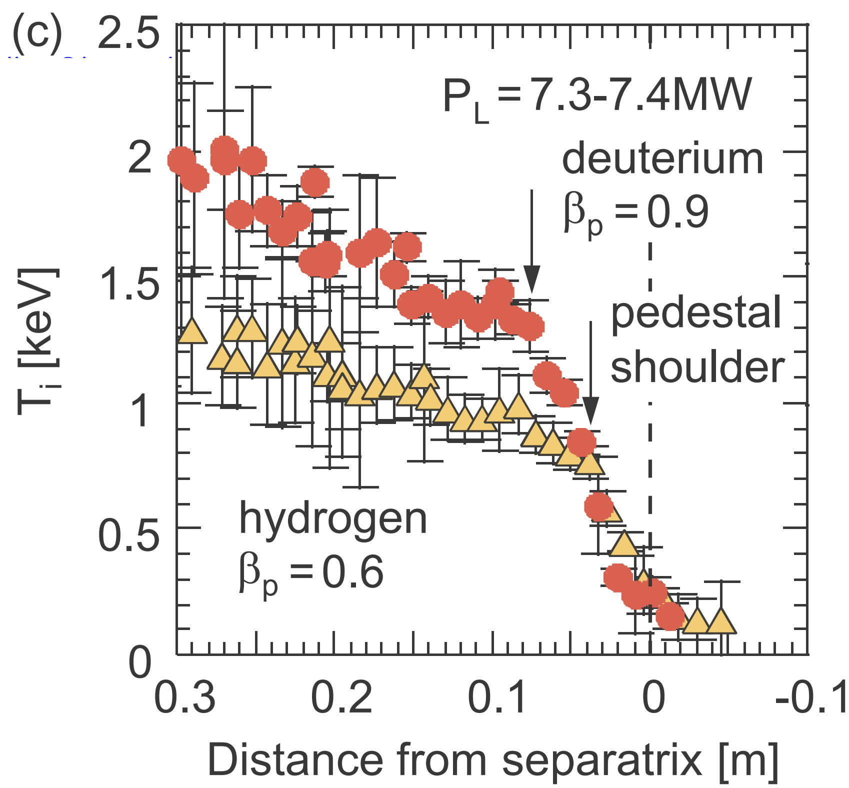
(b)

Nucl. Fusion 53 (2013) 083003 (8pp) doi:10.1088/0029-5515/53/8/083003

Hydrogen isotope effects on ITG scale length, pedestal and confinement in JT-60 H-mode plasmas

H. Urano[1], T. Takizuka[2], N. Aiba[1], M. Kikuchi[1], T. Nakano[1], T. Fujita[3], N. Oyama[1], Y. Kamada[1], N. Hayashi[1] and the JT-60 Team[1]

[1] Japan Atomic Energy Agency, Naka Fusion Institute, Naka, Ibaraki 311-0193, Japan
[2] Osaka University, Graduate School of Engineering, Suita, Osaka, 565-0871, Japan
[3] Nagoya University, Graduate School of Energy Engineering and Science, Chikusa, Nagoya, 464-8603 Japan



…. the Ti value at the pedestal shoulder for deuterium increases by a factor of approximately 1.5 compared with that for hydrogen.

Lee and White, "FLR effects at the H-mode pedestal and the related force-free steady state," Phys. Plasmas 26, 040701 (2019)

- FLR Modified Pressure balance:

$$\mathbf{J}_\perp \approx \frac{c}{B}\hat{\mathbf{b}} \times (\nabla p_i)\left[1 - \frac{1}{2}\rho_i^2 \frac{\nabla_\perp^2 p_i}{p_i}\right]$$ — related to gyroviscosity

- H-mode like pressure profile: $\nabla_\perp p_i \approx 0$ at the core; $p_i \propto exp(-\sqrt{2}r/\rho_i)$ at the edge

$$\mathbf{J}_\perp \rightarrow 0$$

— Isotope effects via ion gyroradius

- Force-free Steady State: $$\nabla \times \mathbf{B} = \frac{4\pi}{c}\mathbf{J}_\parallel$$ — spontaneous relaxation

- Woltjer/Taylor Equilibrium State: $\nabla \times \mathbf{B} = \mu \mathbf{B}$

Need simulation and experimental data on poloidal current near the pedestal region to compare with the theory

Gyrokinetic Quasineutrality at sharp density/pressure gradient

[Lee, PoP 26,556 (1983); Lee and Kolesnikov, PoP 16, 044506 (2009); Lee, PoP 23, 070705 (2016)]

FLR effects

$$\bar{n}(\mathbf{x}) = \int \left(1 + \frac{1}{4}\frac{v_\perp^2}{\Omega^2}\nabla_\perp^2\right) F_{gc}(\mathbf{R})dv_\parallel d\mu \longrightarrow \frac{n_i|_{particle}}{n_i|_{gc}} = 1 + \frac{1}{2}\rho_i^2\frac{1}{p_i}\nabla_\perp^2 p_i$$

FLR effects

— related to gyroviscosity in 2 fluid mom eqts [Scott, 2007]

From gyrokinetic Poisson's Eqtn →

$$\mathbf{v}_{E\times B} \approx -\frac{1}{2}\hat{\mathbf{b}} \times \frac{\nabla_\perp p_i}{p_i}\frac{cT_i}{eB}$$

-- Zonal Flow

$$\mathbf{J}_\perp^{E\times B}(\mathbf{x}) = \sum_\alpha q_\alpha \langle \int \mathbf{v}_{E\times B}(\mathbf{R})F_\alpha(\mathbf{R})\delta(\mathbf{R} - \mathbf{x} + \rho)d\mathbf{R}d\mu dv_\parallel\rangle_\varphi$$

$$\mathbf{J}_\perp = \frac{c}{B}\hat{\mathbf{b}} \times \nabla p + en_i\frac{\rho_i^2}{2}\left[\nabla_\perp^2\mathbf{v}_{E\times B} + \frac{\mathbf{v}_{E\times B}}{p_i}\nabla_\perp^2 p_i\right]$$

Difference in gyroradius effects between ions and electrons

$$\mathbf{J}_\perp \approx \frac{c}{B}\hat{\mathbf{b}} \times (\nabla p)\left[1 - \frac{1}{2}\rho_i^2\frac{\nabla_\perp^2 p}{p}\right]$$

-- FLR modification of pressure balance

gyroviscosity

Conclusions:

- We believe that we understand the origin of the favorable isotope scaling

- Hydrogen isotopes will have higher higher core pressure and milder edge pressure gradient and thicker pedestal

- Is it too far fetched to think about aneutronic reactions of D-3He with an ignition temperature about 4 times as high as that of the D-T reaction

- Differences between gyrokinetic MHD vs. conventional MHD should be further pursuit