First Measurement of the Velocity Slip Coefficient (VSC) and the Tangential Momentum Accommodation Coefficient (TMAC) of Pure Tritium

Johanna Wydra, Robin Größle, Alexander Marsteller, Simon Niemes, Tim Poppe, Florian Priester, Vincent Skrobocz, and Michael Sturm

***Abstract*—The tangential momentum accommodation coefficient (TMAC) describes to what degree the interaction of a molecule with a surface is specular or diffuse and is therefore an important quantity for gas dynamics simulations and tritium processing in future fusion power plants. To the best of our knowledge, up to now, no TMAC values for tritium can be found in literature: neither ab initio calculated nor experimentally obtained. At the Tritium Laboratory Karlsruhe (TLK), with a license to handle up to 40 g of tritium, we have set up a cryogenic viscosity measurement apparatus (Cryo-ViMA) experiment aimed at measuring the viscosity of tritium. The Cryo-ViMA setup is based on a spinning rotor gauge, with a stainless steel rotor. The measurement principle and accuracy have been verified using helium, hydrogen, and deuterium. In this measurement, the normalized deceleration rate (DCR) of the spinning rotor is measured as a function of the pressure of the surrounding dilute gas. In addition to the viscosity, the analysis of the data acquired in this manner allows access to the velocity slip coefficient (VSC), from which the TMAC can be extracted as described in (Tekasakul et al., 1996). Therefore, the measurement data from (Wydra, 2025) will be used in this article to calculate the VSC and the TMAC. The Cryo-ViMA setup allows for cooling over a wide temperature range using evaporated liquid nitrogen. With slow thermal cycling, this system enables a high-resolution measurement of the temperature dependence of the TMAC between 110 and 300 K. The results of these measurements show that for the VSC, the values for H_2 and D_2 range from 1.25 to 1.4, depending on the temperature, whereas for T_2, the VSC is approximately 1.15. This leads to values for the TMAC for H_2 and D_2 between 0.80 and 0.87, whereas the TMAC of T_2 is much closer to one with 0.93. Moreover, the results show that a simple extrapolation of the value for tritium from the other hydrogen isotopologues is insufficient.**

***Index Terms*—Cryogenic temperatures, spinning rotor gauge, tangential momentum accommodation coefficient (TMAC), tritium, velocity slip coefficient (VSC).**

NOMENCLATURE

C_0	Parameter describing the flow of a sphere rotating inside a cylinder with rotation axis perpendicular to the cylinder axis.
I	Moment of inertia of the SRG rotor.
K_n	Knudsen-number.
T	Temperature.
α	Tangential momentum accommodation coefficient.
μ	Viscosity.
$\frac{d\Omega}{dt}/\Omega$	Normalized deceleration rate of the SRG rotor.
a_1	Radius of the SRG rotor.
a_2	Radius of the cylinder surrounding the SRG rotor.
c_m	Velocity slip coefficient.
k_B	Boltzmann's constant.
p	Pressure.
Cryo-ViMA	Cryogenic Viscosity Measurement Apparatus.
DCR	Normalized deceleration rate.
SRG	Spinning rotor gauge.
TLK	Tritium Laboratory Karlsruhe.
TMAC	Tangential momentum accommodation coefficient.
VSC	Velocity slip coefficient.

I. INTRODUCTION

THE VSC and the tangential momentum accommodation coefficient (TMAC) are quantities relevant in fusion science, concerning the interaction between tritium molecules and the walls of the fuel cycle, which are mainly made of stainless steel. These quantities are very sensitive to the surface structure and, therefore, also on impurities on the surface. The flow and behavior of tritium inside components, such as vessels, pumps, distillation columns, the plasma chamber, and the divertor, have to be simulated for optimization and development of the systems [3], [4]. For these simulations, the viscosity, the VSC, and the TMAC are needed. For many

Received 31 July 2025; revised 18 September 2025, 7 October 2025, and 8 October 2025; accepted 8 October 2025. This work was supported in part by the Helmholtz Association (HGF), Germany; in part by German Ministry for Research, Technology and Space (BMFTR) under Grant 05A20VK3; and in part by the Deutsche Forschungsgemeinschaft (DFG) Graduate School Karlsruher Schule für Elementarteilchen- und Astroteilchenphysik (KSETA), Germany, under Grant GSC 1085. The review of this article was arranged by Senior Editor M. Kovari. *(Corresponding author: Johanna Wydra.)*

The authors are with the Institute for Astroparticle Physics, Tritium Laboratory Karlsruhe (IAP-TLK), Karlsruhe Institute of Technology (KIT), Eggenstein-Leopoldshafen, 76344 Baden-Württemberg, Germany (e-mail: johanna.wydra@kit.edu).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TPS.2025.3620100.

Digital Object Identifier 10.1109/TPS.2025.3620100

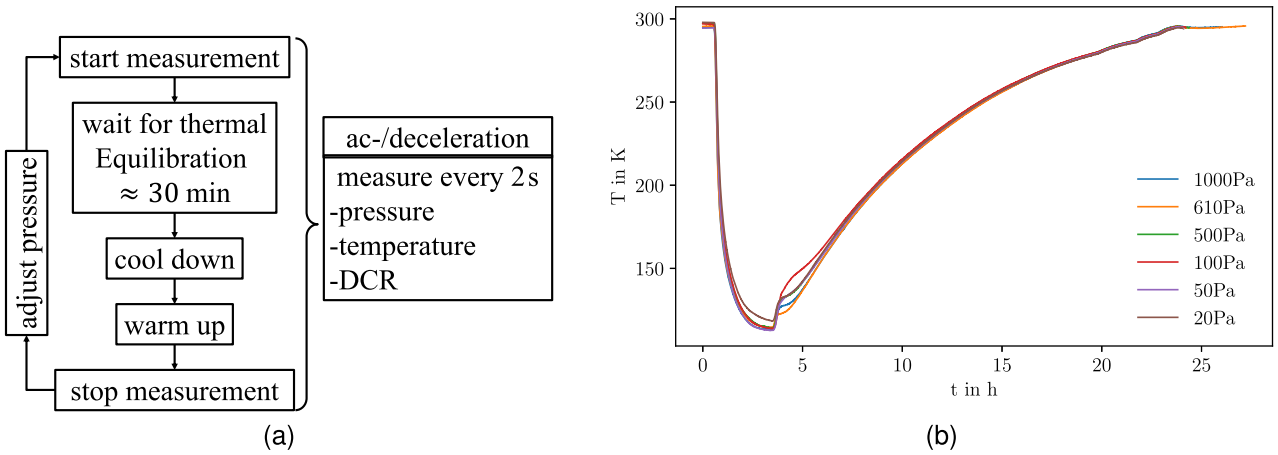

Fig. 1. (a) Shows the measurement procedure for temperature cycling with Cryo-ViMA, while in (b), thermal cycles of the setup are shown, from which only the warm-up curves of the measurements are used for the analysis of the T_2 measurement. The deviation at temperatures below 150 K arises from adjustments as explained in [2].

properties, such as viscosity, values are often generated by extrapolation from hydrogen and deuterium using mass ratios or similar approaches, neglecting the individual quantum-mechanical effects of the hydrogen isotopologues and the radioactivity of tritium [5], [6]. Such extrapolations are not a reliable way to estimate properties in general, and their applicability needs to be verified. New results for the viscosity of tritium (see [2]) indicate, that at least for the viscosity, these extrapolations deviate by up to 12 % from the measured values. A question arising from this discrepancy is, if there is a similar effect for other properties like the VSC and the TMAC. The Cryo-ViMA experiment at the TLK has been designed to measure the viscosity of tritium in a temperature range from 110 K to 300 K. However, with the same measurement data, also the VSC and the TMAC can be calculated as described in [1]. The Cryo-ViMA setup is described in detail in a prior publication [7]. It is based on a spinning rotor gauge (SRG), with only stainless steel as a wetted material. The SRG is mounted inside a cryostat, which is cooled with a cold gas system utilizing nitrogen as a coolant. Caused by the choice of the SRG, the values for the VSC and TMAC give information on the interaction between tritium and stainless steel surfaces with a technical/industrial grade surface finish, which are representative for most components of the tritium fuel cycle.

II. Measurement Procedure

The measurements conducted with Cryo-ViMA are usually performed in an isochoric fashion by cycling the temperature, as shown in Fig. 1(a), but it is also possible to measure in an isothermal fashion by pressure cycling, as described in [2]. For thermal cycling, the pressure inside the SRG is adjusted to one setpoint. Then, the measurement is started where values for the pressure, the temperature, and the normalized DCR are logged every 2 s. When the system is in thermal equilibrium, which takes approximately 30 m, the thermal cycle with the coldgas system is started, cooling the SRG down to 110 K before the cooling is stopped and the system is slowly warmed up through the ambient temperature inside the glovebox. After this thermal cycle, the measurements are stopped and the pressure inside the SRG is changed. This is repeated several times to gather enough measurement points. The analysis is described in the following section. For the analysis, only the data taken during warm-up are used, as the thermal gradient inside the system is too high during the cool-down period.

III. TMAC Analysis With a Spinning Rotor Gauge

The analysis is done in two steps. The first step is the linear fitting of (1) (as derived in [8]) to the inverse normalized DCRNormalized deceleration rate of the SRG rotor ($\frac{\mathrm{d}\Omega}{\mathrm{d}t}/\Omega$) of the SRG rotor as a function of the inverse pressure Pressure (p) for every temperature Temperature (T) separately. The temperature is sliced into intervals of 0.1 K and averaged. This means, that for every 0.1 K interval, one measurement point for the fit consists of approximately ten averaged deceleration/pressure pairs at five to seven pressure setpoints

$$\frac{1}{\frac{\mathrm{d}\Omega}{\mathrm{d}t}/\Omega} = \frac{I(I)}{8\pi a_1^3 C_0 \mu} + \frac{I}{p}\cdot\sqrt{\frac{2k_\mathrm{B}T}{m}}\left(\frac{c_\mathrm{m}}{8\pi a_1^3 C_0}\left(\frac{3}{a_1}+\frac{1}{a_2}\right)\right) \tag{1}$$

where I is the moment of inertia of the SRG rotor, Radius of the SRG rotor (a_1) and Radius of the cylinder surrounding the SRG rotor (a_2) are the radii of the rotor and the cylinder of the SRG, respectively, C_0 is a calibration constant, which depends on the ratio between a_1 and a_2, and k_B is the Boltzmann constant. In this equation, c_m is the VSC and defined as

$$c_\mathrm{m} = \frac{2-\alpha}{\alpha}\left[(1-\alpha)\frac{\sqrt{\pi}}{2}+0.9875\alpha\right] \tag{2}$$

where Tangential momentum accommodation coefficient (α) is the TMAC [1].

In a second step, the viscosity Viscosity (μ) can be calculated from the y-axis intercept, whereas the VSC is calculated from the slope.

IV. Data Selection

As described in [8], (1) only holds true within the slip regime, corresponding to Knudsen numbers Knudsen-number (K_n) of $0.01 < K_\mathrm{n} < 0.1$ [9]. A key challenge for this work is that for the calculation of K_n, the mean free path is needed [10], as well as the characteristic length of the system. The mean free path can either be calculated with the viscosity or on a classical approach through the kinetic gas theory. Even

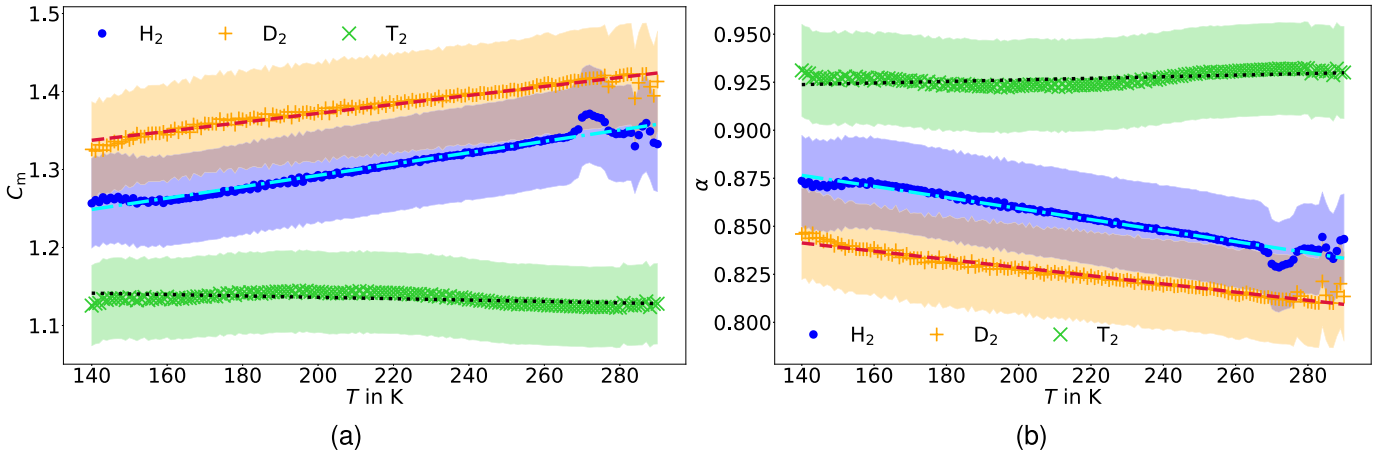

Fig. 2. (a) VSC and (b) TMAC of hydrogen (blue small dots), deuterium (orange plus signs), and tritium (green crosses) with stainless steel in dependence on the temperature. The light bands show the uncertainty of the measurements, which are mainly caused by systematic uncertainties like the radius of the rotor.

if the mean free path would be known with high precision, the characteristic length of the system will lead to another problem. For the SRG, the characteristic length is not trivial to define, as the diameter of the cylinder is 7 mm, but there is the rotating sphere inside with a diameter of 4.5 mm, leaving a minimum slit between the cylinder wall and the rotor of 1.25 mm. This is nearly one order of magnitude in difference, leaving a wide pressure range that could or could not be within the slip regime. To solve this issue, in a first step, the measurement cycles are selected according to the strict slip regime, calculated with the inner diameter of the cylinder. In a second step, all measurement cycles, which are partly or fully within this regime, are used for the final analysis of the VSC and the TMAC. The measurements at higher or lower pressure setpoints are neglected. This maximizes the number of data points used for the fit while preventing any edge effects. Additionally, this selection of data prevents excessive cutting of data and does not significantly affect the results by including values outside the allowed region. An example of such a data selection can be seen in [2, Fig. 4.2].

V. VSC and TMAC of Tritium and Stainless Steel

The results for the viscosity of tritium are published elsewhere (see [2]). The results for the VSC and TMAC are shown in Fig. 2(a) and (b), respectively. For temperatures close to 300 K, the VSC and TMAC of H_2 and D_2 show some irregularities. These arise from a different thermal cycle than the one used for T_2. For the first two isotopologues, the coldgas system was also used to heat up the system from 270 K upward, but this caused the system to leave thermal equilibrium. For the T_2 measurement, this additional heating was not used, resulting in a smoother dataset. The VSC for H_2 and D_2 shows a slight temperature dependence, whereas the VSC for T_2 shows no such behavior. It should be noted that the absolute values for H_2 and D_2 are about 30 % higher than those for T_2 and, in addition, the ordering is not consistent with the mass ordering. D_2 has the highest values for the VSC, followed by slightly lower values for H_2. If the VSC from these two isotopologues is used to extrapolate based on the masses, one would expect the values for T_2 slightly above the ones for D_2. However, Fig. 2(a) shows that the VSC for tritium is by far the lowest value. This shows that scaling the VSC for T_2 from other hydrogen isotopologues, as it is often done for other properties such as the viscosity, where the results indicate better agreement with the extrapolated values but still with high deviations as shown in [2], is not a suitable approach.

As the TMAC is calculated from the VSC with (2), the results show a similar pattern but with inverted ordering. The TMAC of H_2 is reported by [11] to be around 0.85 at 300 K with an uncertainty band ranging from 0.75 to 0.99, which is four times higher than the uncertainty of our current measurements. Still, our results are in good agreement within the uncertainty of the reported values of [11]. As reported by [12], the values for the TMAC of D_2 are slightly lower than the ones for H_2, which also fits to the results of the current measurement. This shows that the measurement principle is valid, so the results for the measurement with T_2 are not systematically biased, but rather based on the nature of tritium and is discussed in the following section.

VI. Discussion

The TMAC is a measure of the proportion of the tangential momentum transfer during the interaction between the gas particles and the surface. For $\alpha = 1$, all information about the tangential momentum is lost through the interaction, and the gas particle is adsorbed and desorbed, leading to diffuse reflection. For $\alpha = 0$, the reflection is specular, as seen in the reflection of light. The VSC is a measure for the velocity slip, meaning the difference between the velocity of the particles in the boundary layer of the fluid and the velocity of the surface. The higher the VSC, the higher the velocity slip.

There are four main contributions to the behavior of the VSC and TMAC.

1) The mass of the molecules.
2) The quantum mechanics (ortho-para equilibrium) of the molecules.
3) The surface roughness.
4) The surface composition.

For the viscosity, the mass of the molecules poses the highest impact on the results, regarding the homonuclear isotopologues, which is also shown through the mass ordering of the absolute viscosity values for all hydrogen isotopologues (see, for example, [2]). In case of the VSC and TMAC, our results show that this does not apply as the ordering of the isotopologues is not consistent with the mass ordering: The

VSC of D_2 is the highest one, while T_2 shows the lowest values here. If this result was primarily a result of differences in quantum mechanic behavior, caused by, for example, the ortho-para equilibrium between the different isotopologues [13], [14], [15], it would lead to T_2 and H_2 being closer together. However, the results show the values of H_2 to be closer to the ones of D_2 than T_2. The surface roughness does not change dramatically on macroscopic scale, as the setup is the same for all three measurements. But as tritium induces radiochemical reactions, this can lead to a chemical modification of the interaction partners on the surface of the SRG and the inner cylinder wall, which will affect the interaction of the isotopologues with the surface and therefore the VSC and TMAC. One common radiochemical effect of tritium in pristine stainless steel systems is the generation of tritiated methane [16], [17], often called a burn-in phase. This process exhausts deposits of carbon on the stainless steel surface, such as monolayers of hydrocarbons, which can remain from manufacturing, cleaning procedures, or exposure to ambient atmosphere. Similarly, it can also remove surface bound water. Such a modification of the stainless steel surface means that any measurements performed with only H_2 and D_2 on technical grade stainless steel will fundamentally be different from those of T_2 on stainless steel that has been through a burn-in phase. To cross-check this effect, the measurements with H_2 and D_2 will be repeated. If T_2 changed the surface and the effect of this has a major impact on the measurement results, this would lead to a visible shift of the VSC and TMAC values in the second measurement of H_2 and D_2.

If none of the above effects are singularly responsible for the observed behavior, the reason for the strange ordering can be some combination of all the previously named effects. To explain this, a hypothetical base value for the TMAC, which would be the same for all hydrogen isotopologues, is assumed. The mass difference would shift this base value to higher numbers according to the mass scaling of the molecules. The influence of the ortho-para composition of the isotopologues could then alter these different values, where the isotopologues of fermionic nuclei (H_2 and T_2 in this case) would be changed in the same fashion, while the isotopologue of bosonic nuclei (D_2) changes in another way or not all. In comparison to the shown data for H_2, D_2, and T_2, only results where the isotopologues with fermionic nuclei are increase or the isotopologues with bosonic nuclei are decreased could explain the data. This means, that in the case of VSC and TMAC, under the assumption that the surface did not change significantly between the measurements, the values are dependent on the masses of the molecules and their quantum mechanical state. In this case, QM effects either increase the values of the fermionic isotopologues or decrease the values of the bosonic isotopologues.

VII. Conclusion

In this contribution, we have presented the first measurement of the VSC and TMAC of tritium (T_2) on a technical grade stainless steel surface. These measurements are presented alongside new measurements for hydrogen (H_2) and deuterium (D_2) using the same apparatus. The good agreement of the measured H_2 values with literature values has verified the applicability of our approach.

We have found that a simple extrapolation of the VSC and TMAC from H_2 and D_2 using masses is not an appropriate approach. We have discussed possible reasons for the deviation from this mass scaling behavior and will follow up on the hypothesis of significant surface modification due to radiochemical reactions induced by tritium with further measurements.

References

[1] P. Tekasakul, J. A. Bentz, R. V. Tompson, and S. K. Loyalka, "The spinning rotor gauge: Measurements of viscosity, velocity slip coefficients, and tangential momentum accommodation coefficients," *J. Vac. Sci. Technol. A: Vac., Surf., Films*, vol. 14, no. 5, pp. 2946–2952, Sep. 1996. [Online]. Available: https://pubs.aip.org/jva/article/14/5/2946/243003/The-spinning-rotor-gauge-Measurements-of-viscosity

[2] J. M. Wydra, "First measurement of the tritium viscosity in a temperature range from 100 K to 300 K," Ph.D. dissertation, Inst. Astroparticle Phys.,Tritium Lab. Karlsruhe (IAP-TLK), Karlsruhe Inst. Technol. (KIT), Baden-Württemberg, Germany2025. [Online]. Available: https://publikationen.bibliothek.kit.edu/1000178925

[3] M. Abdou et al., "Physics and technology considerations for the deuterium–tritium fuel cycle and conditions for tritium fuel self sufficiency," *Nucl. Fusion*, vol. 61, no. 1, Nov. 2020, Art. no. 013001, doi: 10.1088/1741-4326/abbf35.

[4] D. Matveev et al., "An integral approach to plasma-wall interaction modelling for EU-DEMO," *Nucl. Fusion*, vol. 64, no. 10, Sep. 2024, Art. no. 106043, doi: 10.1088/1741-4326/ad73e7.

[5] J.-U. Lee et al., "Thermodynamic property calculation for pure component hydrogen isotopologues considering tritium processing technologies in fusion fuel cycle," *Fusion Eng. Des.*, vol. 197, Dec. 2023, Art. no. 114059. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0920379623006397

[6] J. D. Kress, J. S. Cohen, D. A. Horner, F. Lambert, and L. A. Collins, "Viscosity and mutual diffusion of deuterium-tritium mixtures in the warm-dense-matter regime," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 82, no. 3, Sep. 2010, Art. no. 036404.

[7] J. Wydra, A. Marsteller, R. Grle, F. Priester, *ViMA—The Spinning Rotor Gauge To Measure the Viscosity of Tritium Between 77 and 300 K*. [Online]. Available: https://www.tandfonline.com/doi/epdf/10.1080/15361055.2023.2238170?needAccess=true

[8] S. K. Loyalka, "Theory of the spinning rotor gauge in the slip regime," *J. Vac. Sci. Technol. A: Vac., Surf., Films*, vol. 14, no. 5, pp. 2940–2945, Sep. 1996. [Online]. Available: https://pubs.aip.org/jva/article/14/5/2940/242969/Theory-of-the-spinning-rotor-gauge-in-the-slip

[9] N. Dongari, A. Sharma, and F. Durst, "Pressure-driven diffusive gas flows in micro-channels: From the Knudsen to the continuum regimes," *Microfluidics Nanofluidics*, vol. 6, no. 5, pp. 679–692, May 2009.

[10] F. Sharipov, *Rarefied Gas Dynamics: Fundamentals for Research and Practice*. Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA, 2016.

[11] J. F. M. Velthuis and L. van Bokhoven, "Measurement of the tangential momentum accommodation coefficient of H2 on stainless steel, extreme ultraviolet-resist, and polyimide," *J. Vac. Sci. Technol. A, Vac., Surf., Films*, vol. 31, no. 6, Nov. 2013, Art. no. 061605. [Online]. Available: https://pubs.aip.org/jva/article/31/6/061605/388341/Measurement-of-the-tangential-momentum

[12] A. Agrawal and S. V. Prabhu, "Survey on measurement of tangential momentum accommodation coefficient," *J. Vac. Sci. Technol. A, Vac., Surf., Films*, vol. 26, no. 4, pp. 634–645, Jul. 2008. [Online]. Available: https://pubs.aip.org/jva/article/26/4/634/97820/Survey-on-measurement-of-tangential-momentum

[13] M. Aker et al., "Quantitative long-term monitoring of the circulating gases in the KATRIN experiment using Raman spectroscopy," *Sensors*, vol. 20, no. 17, p. 4827, Jan. 2020. [Online]. Available: https://www.mdpi.com/1424-8220/20/17/4827

[14] B. Krasch, S. Mirz, A. Smolinski, O. Süß, and R. Größle, "Raman spectroscopy for ortho-para hydrogen catalyst studies," *Int. J. Hydrogen Energy*, vol. 48, no. 77, pp. 29952–29961, Sep. 2023. [Online]. Available: https://publikationen.bibliothek.kit.edu/1000159256

[15] B. Krasch, "Spectroscopic investigations of intermolecular effects in the KATRIN tritium source loop," Ph.D. dissertation, Inst. Astroparticle Phys., Tritium Lab. Karlsruhe(IAP-TLK), Karlsruhe Inst. Technol. (KIT), Baden-Württemberg, Germany, 2023. [Online]. Available: https://publikationen.bibliothek.kit.edu/1000158844

[16] M. Sturm et al., "Kilogram scale throughput performance of the KATRIN tritium handling system," *Fusion Eng. Des.*, vol. 170, Sep. 2021, Art. no. 112507. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0920379621002830

[17] R. D. Penzhorn et al., "Radiochemistry of an equimolar deuterium–tritium mixture or of T_2 with CO," *Fusion Eng. Des.*, vols. 49–50, pp. 927–937, Nov. 2000. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0920379600003434