Properties of DT ice in Cryotargets

Spherical target used to contain DT fuel

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The summary/overview

• The total error in measuring the composition of the hydrogen gas in cryotargets with a 77 K iron-doped alumina column is 2%. The random error in the measurement is 1.2%.

• The distribution of the H/D/T species making up the six isotopologues approaches equilibrium by the time H/D/T liquid is formed.

• The triple point, vapor pressure and ice density of DT ice can be extrapolated from the molecular composition of the D/T gas.
Step 1: Transfer DT from the uranium storage bed to the condensation tube and remove residual helium-3
Step 2: Transfer DT from the condensation tube (CT) to the Assay volume, assay the gas, take a sample and return to the CT.
Step 3: Drive DT through the Pd diffuser to the DTHPS Condensation Tube
Step 4: Drive DT through the Pd diffuser to the DTHPS Condensation Tube

![Diagram showing the flow of DT through various gloveboxes and containment systems.]
Step 5: Expand DT into the Syringe pump volume
Step 6: Compress the DT into the Permeation Cell in the Cryostat
Step 7: Cool the Permeation Cell to 50 K
Step 8: Return residual DT to the uranium storage bed
The hydrogen isotopologue fractions are measured by gas chromatography; H/D/T ratios are calculated from the area ratios.

The spectrum is used to calculate the H/D/T fractions.

The spectrum:
- 5.45% H
- 60.62% D
- 33.93% T

The peaks are labeled as follows:
- H₂
- HD
- D₂
- DT
- T₂

Diagram:
- Neon
- Vacuum
- Sample
- T₂ monitor
- TCD
- To effluent treatment
- Fe-doped alumina column at 77 K

TCD – Thermal conductivity detector

Error:
- Systematic† < 6%
- Relative (peak to peak) < 1.2%

† Based on cross comparison with measurements Lawrence Livermore National Lab.
The target-filling process enhances the lighter isotopic species

Composition in %: H/D/T

Estimated composition in italic
The cumulative error in calculating the tritium-to-deuterium ratio in the permeation cell is 1.2%.

The protium content increased at 1.9% per month since the fuel was isotopically purified.
The equilibrium $D_2$, $DT$, and $T_2$ distribution is fixed by the equilibrium constant ($K_{DT}$), and the T/D fuel ratio.

Initial Mixture

$[T_2] = x$
$[D_2] = 1 - x$

Final Mixture

$[T_2] = x - a$
$[D_2] = 1 - x - a$
$[DT] = 2a$

$[D_2] + [T_2] = \frac{K_{DT}}{2[DT]}$

$[DT] = [K_{DT}[T_2][D_2]]^{0.5}$

Theory overestimates or measurements underestimate the isotopic composition by $\sim 2\%$.
The protium (H) contribution to the isotopologue distribution is derived by including $K_{HD}$, $K_{HT}$, and the initial T/H ratio in the fuel.

\[ [H_2] + [D_2] \overset{K_{HD}}{=} 2[HD] \]

\[ [H_2] + [T_2] \overset{K_{HT}}{=} 2[HT] \]

\[ [D_2] + [T_2] \overset{K_{DT}}{=} 2[DT] \]

\[ [H_2] + [DT] \overset{K_4}{=} [HD] + [HT] \]

\[ [D_2] + [HT] \overset{K_5}{=} [HD] + [DT] \]

\[ [T_2] + [HD] \overset{K_6}{=} [DT] + [HT] \]

Theory underestimates or measurements overestimate the isotopic composition by $\sim 2\%$. 
Raoult’s law connects the molar isotopic compositions in the vapor to the liquid and solid molar compositions.

\[
\begin{align*}
    x_{D_2} &= \left( y_{D_2} \frac{P_{D_2}}{P^o_{D_2}} \right) \\
    x_{T_2} &= \left( y_{T_2} \frac{P_{T_2}}{P^o_{T_2}} \right) \\
    x_{DT} &= \left( y_{DT} \frac{P_{DT}}{P^o_{DT}} \right)
\end{align*}
\]

- \(x\) = mole fraction in liquid
- \(y\) = mole fraction in vapor
- \(P^o\) = saturated vapor pressure
- \(P\) = partial pressure
Several ice properties can be predicted from the hydrogen isotopologue composition of the ice.

- **Triple point**
  - Includes $D_2$, $DT$, $T_2$ in the ice only

- **Vapor pressure over the ice/liquid**
  - $T/D \sim 1.0$

- **Density of the D/T ice mixture**
  - $T/D = 1.044$
  - $J = 0$ spin

- **Temperature (K)**
  - 16, 17, 18, 19, 20

- **Vapor Pressure (Torr)**
  - 10, 100, 1000, 10000

- **Tritium/Deuterium ratio**
  - 0.5, 1.0, 1.5

- **Triple Point (K)**
  - 19.4, 19.6, 19.8, 20
The triple point is a sensitive measure of the isotopic composition of the D/T ice.

- Need the temperature offsets for each cart
- Relative measurements for the same cart sidesteps offsets and provides a better comparison with theory.
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