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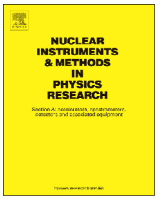

Temperature dependence of the leak rate and permeability of helium gas through Kapton foils

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ABSTRACT

The leak rate of helium gas through thin Kapton HN foils was measured for various temperatures between 310 and 150 K and gas pressures ranging from 10 to 300 mbar. From these measurements the permeability constant $P(T)$ and its temperature dependence were determined. At room temperature the permeability constant for Kapton HN is $P(T=296\text{ K}) = (2.56 \pm 0.31)$ barrer. The temperature dependence of $P(T)$ was verified to drop exponentially with decreasing temperature, causing a change in the permeability by more than two orders of magnitude in the range between 310 and 150 K.

1. Introduction

Many nuclear and particle physics experiments require a target filled with gas in order to manipulate or stop particles within [1–4]. To minimize the energy loss of charged particles entering the target and various backgrounds, its walls should be as thin as possible. This fact, and a possible requirement to apply electric fields in the gas, makes it often desirable to use other materials than metal. A straightforward choice are thin foils, because they are usually cheap, easily available and can be processed without the need for special equipment.

Concerning the recently proposed novel muon beamline [5,6], a vertical temperature gradient in a helium gas target has to be established at cryogenic temperatures, requiring minimal thermal conductivity across the target walls. Thus, thin Kapton foils[1] might be suited to enclose the gas target in the cryostat. Kapton is a well-known material in space research, electrical and cryogenic applications, as well as in nuclear and particle physics. Some of its most advantageous features are excellent chemical and radiation resistivity, high mechanical stability at both warm and cold temperatures, low thermal conductivity, and outstanding electrical insulation [7–9]. Additionally, Kapton is widely used as support material for flexible circuit boards and many companies can provide custom-designed electrodes on Kapton foils. Unfortunately, Kapton has a rather high permeability P for helium gas at room temperature of about $63\text{ l mil}/(\text{m}^2\text{day MPa}) = 2.4$ barrer for a 25 μm thin foil, according to the manufacturer [9]. This might be a problem for high vacuum, as in the case of an isolation vacuum of a cryostat. The cryostat used in our experiment for building the novel muon beamline requires a vacuum well below 10^{-7} mbar and a leak rate smaller than 10^{-8} mbarl/s, taking into account the impedance of our pumping system. This translates to a permeability of the Kapton foils of approximately 0.1 barrer at 10 K for our current target design with a surface of about 8000 mm^2. However, to our knowledge, no conclusive values for P and its temperature dependence at cold temperatures can be found in literature although Kapton has been used for many applications. Here, we provide values for the permeability constant of helium gas permeating Kapton HN foils at room temperature as well as its dependence on the temperature of the foils.

2. Theoretical background

In the simplest case permeation through a thin foil with thickness d and area A can be described as one-dimensional diffusion problem. A mathematical formalism to describe diffusion was originally developed by Fick [10]. The flux F is defined as the amount of a substance (in mol) per unit time $\dot{n}$ passing through an area:

$$F = \dot{n}/A. \tag{1}$$

The driving force for the flux is a pressure difference $\Delta p \equiv p_1 - p_2$ between the two sides of the foil [11]:

$$F = P\frac{\Delta p}{d}. \tag{2}$$

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[1] Kapton HN is a registered trademark of DuPont$^{\text{TM}}$. It is a Polyimide with chemical composition $C_{22}H_{10}N_2O_5$.

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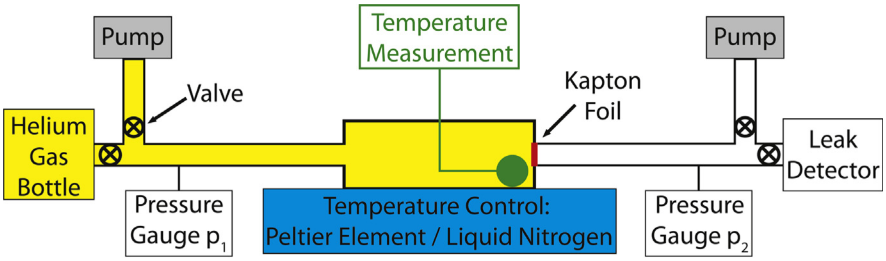

Fig. 1. Schematic overview of the setup. The Kapton foil is glued onto a KF 25 flange whose temperature is controlled by either a Peltier element or liquid nitrogen. The temperature of the foil is determined by a temperature sensor placed close to the foil in the helium gas.

Here, P is the permeability constant which should depend on the temperature T according to Arrhenius' law [12]:

$$P = P_0 e^{-E_P/RT} \tag{3}$$

where E_P is the so-called permeation activation energy, $R = 8314\ \mathrm{l\ Pa}\ K^{-1}\mathrm{mol}^{-1}$ the universal gas constant and $P_0 = P(T \to \infty)$. The recommended unit [13] for the permeability constant is *barrer*:

$$1\ \mathrm{barrer} = 10^{10}\ \frac{\mathrm{cm}^3(STP)\ \mathrm{cm}}{\mathrm{cm}^2\ \mathrm{s\ cmHg}} \tag{4}$$

where STP means standard temperature and pressure. In the experiment presented here the measured quantity is the so-called throughput Q defined as $Q = \frac{d}{dt}(pV)$, which is more commonly known as leak rate. The ideal gas equation $pV = nRT$ and Eq. (1) and (2) yield the relation between flux and leak rate:

$$Q = F \cdot A \cdot RT = P\frac{\Delta p \cdot A \cdot RT}{d}. \tag{5}$$

3. Experimental setup and measurements

The leak rate Q of helium gas through thin Kapton foils (with different thicknesses d = 25, 50 and 125 μm) is measured. The foils are glued with Stycast 1266 two-component epoxy[2] onto standard KF 25 vacuum flanges. The area A of the foil exposed to the helium gas is therefore about 491 mm^2. We use metal seals to eliminate diffusion through rubber O-rings. To ensure that no contribution to the measured leak rate comes from leakage through the glue, background measurements were performed by replacing the foil with a 1 mm thick metal plate, showing no measurable leak rate when pressurising the system with up to 1 bar of helium gas. In our experiment the leak rate is directly measured by means of a leak detector *SmartTest HT 550* from Pfeiffer Vacuum, which relies on mass spectrometry of ^{4}He. The setup used here is sketched schematically in Fig. 1.

In the measurements, both sides of the foil are evacuated to a pressure $p_{1,2} \leq 10^{-3}$ mbar (see also Fig. 1) . Then, helium gas is filled into one side up to a pressure $p_1 \gg p_2 \approx 0$. For leak rate measurements between 2 and 40 °C a Peltier element is used to stabilize the temperature. The leak rate is measured for about 10 min in steady state conditions before changing p_1 or T. For these measurements p_1 is varied between 10 and 300 mbar for each temperature.

Temperatures below 0 °C are achieved by suspending the relevant parts above a liquid nitrogen bath. When measuring the leak rate while cooling down no stable temperature is established. The pressure p_1 changes according to the ideal gas equation since no gas is refilled during the cool down. The temperature sensor is placed close to the foil in the helium gas. By cooling down very slowly (less than 1°/min) the measured gas temperature will be always very close to the temperature of the metal parts and the foil, as the foil is directly cooled by the gas and does not see thermal radiation other than from the cooled metal. Nevertheless, values from measurements obtained while cooling down have larger systematic uncertainties and are used primarily to verify the exponential behaviour of $P(T)$.

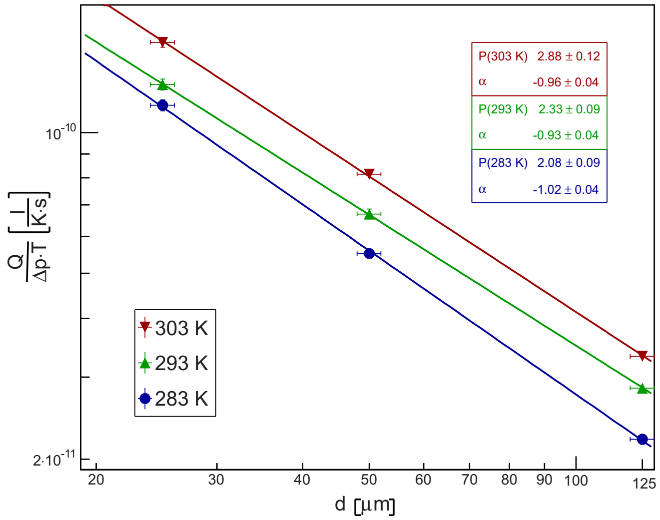

Fig. 2. Fitting $Q/(\Delta p \cdot T)$ as function of $P_T \cdot A \cdot R \cdot d^{\alpha}$ shows that the leak rate scales as $Q \propto 1/d$ with the foil thickness because $\alpha = -0.97 \pm 0.02$. Furthermore, the values for P agree with the overall result presented later (see Eq. (7)) for the corresponding temperatures. The data points are displayed together with their common systematic uncertainties.

4. Results

4.1. Proportionality of Q to foil thickness

By measuring Q for different foil thicknesses d = 25, 50 and 125 μm it is possible to fit $Q/(\Delta p \cdot T)$ as a function of $P_T \cdot A \cdot R \cdot d^{\alpha}$, with P_T and α being the fit parameters (P_T corresponds to P at temperature T). This is shown in Fig. 2, where the resulting values for α are also listed. The weighted average for $\alpha = -0.97 \pm 0.02$ shows that the leak rate is inversely proportional to d and thus P does not depend on the foil thickness, as expected from Eq. (5).

4.2. Determining P at room temperature

In order to determine the permeability constant at room temperature, a linear function $Q = Q_0 + P \cdot x$, where $x \equiv \Delta p \cdot A \cdot RT/d$, is fitted for each temperature to all data obtained in thermal equilibrium. An example of such a fit for the 25 μm thin foil is shown in Fig. 3. The largest contribution to the error comes from the pressure gauge with a systematic uncertainty of up to $\Delta p_1/p_1 = 15\%$ at these pressures [14] and an uncertainty in the linearity of the leak detector of approximately $\Delta Q/Q = 1\%$. The thickness of our foil samples was measured with a micrometer screw gauge to have a deviation of less

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[2] Stycast®is a product of Emerson & Cuming™.