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ABSOLUTE MOLECULAR BEAM INTENSITY DETECTOR: APPLICATION TO H_2 AND D_2 BEAMS

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A number of techniques for measuring the center-line intensity I_0 (particles $s^{-1}sr^{-1}$) of molecular beams have yet been developed. However, only few of them take advantage of the basic beam property, the directionality of momentum flux. Moreover, absolute intensity measurements, i.e. which need no calibration, are hardly at hand.

Here we report on the development of an absolute detector, which takes full advantage of the directed momentum flux, and its use with H_2 and D_2 nozzle beams. The intensity is obtained from the measurement of the momentum exchange between the beam molecules and a tangentially moving surface (Fig. 1). The method makes use of the low and constant bearing friction of magnetically suspended rotors /1/ and the almost perfect accommodation of the tangential momentum of molecules on technical surfaces /2/. The beam molecules, impinging on the cylindrical surface, cause a torque $\vec{T}$ opposing (respectively in) the direction of rotation, resulting in a deceleration (or acceleration) of the freely rotating body: the tangentially acting force $\vec{F}_t$ (i.e. the momentum flux) does work on the disk. Due to the complete momentum accommodation, the molecular beam momentum flux can be obtained from the amount of work done by the beam on the disk during a given time interval. This work is evaluated from the measured relative rotation frequency change $(-\dot{\omega}/\omega)$, using only the density and geometrical shape of the rotor and the average flow velocity $\tilde{v}$ of the beam molecules. The absolute intensity is given by:

$$I_0 = -\,\Theta(\dot{\omega}/\omega)\left[\frac{m\tilde{v}\,\sin\alpha\,R}{\omega}\right]^{-1} \qquad (1)$$

where Θ, m, R are the moment of inertia of the rotor, the molecular mass and the radius of the rotor, respectively. α is the angle of incidence of the molecular beam impinging on the rotor surface with respect to the surface normal. Since all quantities in eq.(1) are directly measurable, the detector is an absolute device. In addition, by measuring work and not force this is an integral method, i.e. the sensitivity increases with the measuring time.

All measurements have been performed with the pseudorandom TOF machine used in this laboratory /3,4/. The free jet source for H_2 and D_2 is a 10 µm nozzle. The stagnation conditions used here are T_0 = 78 K and 304 K and p_0 = 1-40 bar. The angular divergence of the collimated beam impinging on the detector surface (located 580 mm downstream the source) is 0.09°.

The cross sectional view of the detector is shown in fig. 2. The rotor constists of a 3.5 mm diameter soft iron cylinder (A) for magnetic suspension, a thin walled aluminium connector tube (B) and, supported by a small copper screw (C), a truncated copper cone (D) with a 2 mm cylindrical rim (E). The rim on which the beam is impinging has a diameter of 30 mm. In order to reduce the moment of inertia of the rotor the copper cone (and rim) wall is made as thin as possible (0.02 mm). All components of the magnetic suspension stator and of the rotor acceleration unit are combined in a stator package (F) outside the vacuum chamber. The magnetic suspension system is similar to that of the spinning rotor vacuum gauge; see for a detailed description ref. 5. The rotational frequency of the rotor is measured by means of a laser beam which is directed on the copper cone. The laser beam entering a phototransistor (P) after reflection on the cone is interrupted whenever it encounters a graphite mark (K). The frequency change $(-\dot{\omega}/\omega)$ is evaluated by means of a data processor. The detection limit for the present design is $I_0^{min} = 1.2\cdot 10^{15}/M\tilde{v}$ ($\tilde{v}$ in $m\cdot s^{-1}$).

In order to obtain intensity numbers from the momentum flux data the accurate knowledge of the average flow velocity $\tilde{v}$ of the molecular beam is necessary. According to continum theory $\tilde{v}$ is given by:

$$\tilde{v} = \left(\frac{2\gamma}{3\gamma-3}\right)^{1/2}\cdot\left(\frac{3k_BT_0}{m}\right)^{1/2} \qquad (2)$$

where γ is the heat-capacity ratio. Accordingly, $\tilde{v}$ is $u_1 = (5k_BT_0/m)^{1/2}$ for monatomic and $u_2 = (7/5)^{1/2}\cdot u_1$ for diatomic gases. The derivation of eq.(2) for diatomic gases implies a) that prior expansion the mean rotational energy is $k_B T$ and b) that during expansion this energy is fully transferred into the translational mode. Particularly in the case of hydrogen isotope expansions neither a) nor b) is fulfilled. Therefore, an exact evaluation of hydrogen nozzle beam intensities requires time-of-flight measurements for the determination of $\tilde{v}$. Figure 3 compares the measured reduced flow velocities $\tilde{v}/u_1$ for hydrogen and deuterium expansions as a function of the stagnation pressure. The quantity $(\tilde{v} / u_1) - 1$ is a direct measure of the transferred rotational energy.

Absolute intensity data obtained with the spinning rotor detector for hydrogen and deuterium are presented in fig. 4 as a function of the stagnation pressure. The data are taken at fixed angle of incidence $\sin\alpha = 0.57$ and two stagnation temperatures $T_0 = 78$ K and 304 K. They are calculated using the corresponding flow velocities in fig. 3. The relative error of these measurements evaluated from the errors of the various parameters in eq.(1) is less than ± 4.5 %.

The curves in fig. 4 have a similar behavior: with increasing pressure the intensity increases, reaches a maximum and then decreases. The maxima correspond to the following pressures measured in the nozzle chamber: $p_{304}^{H_2} = 2.2\cdot10^{-3}$ mbar, $p_{78}^{H_2} = 5.5\cdot10^{-4}$ mbar, $p_{304}^{D_2} = 1.1\cdot10^{-3}$ mbar and $p_{78}^{D_2} = 2.7\cdot10^{-4}$ mbar. These pressures appear to be related to the velocities of the molecules:

$$p_{304}^{H_2} : p_{304}^{D_2} : p_{78}^{H_2} : p_{78}^{D_2} = (\tilde{v}_{304}^{H_2})^2 : (\tilde{v}_{304}^{D_2})^2 : (\tilde{v}_{78}^{H_2})^2 : (\tilde{v}_{78}^{D_2})^2 \qquad (2)$$

The intensity decrease in fig. 4, which determines the location of the maxima is due to collision of the beam molecules with the residual gas. The $\tilde{v}^2$ dependency of the pressure measured in the nozzle chamber, when the intensity is maximum, is probably due to two contributions: 1) the almost linear $\tilde{v}^{-1}$ dependency of the total scattering cross section for hydrogen isotopes /6/ and 2) the similar $\tilde{v}^{-1}$ dependency of the ratio of the residual gas density in the nozzle-skimmer region to the measured pressure.

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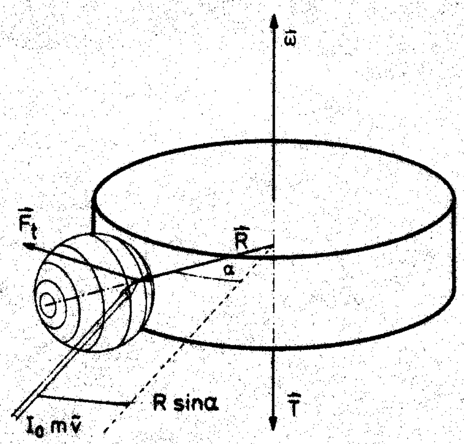

Fig. 1 Freely rotating disk as momentum flux detector α-angle of incidence, ω-angular velocity, R- disk radius, $\vec{F}_t$- the tangential force, $\vec{T}$-the resulting torque.

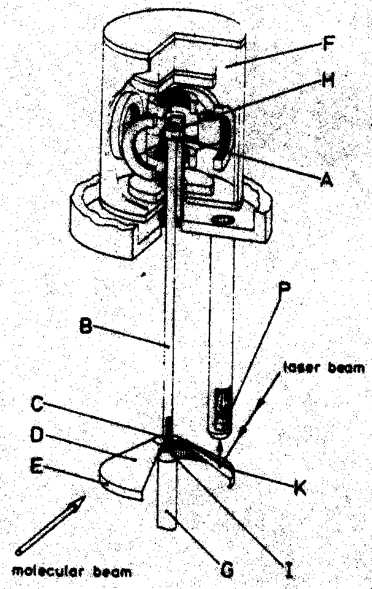

Fig. 2 Sectional view of the spinning rotor detector: A- soft iron cylinder, B- thin walled aluminium tube, C- copper screw, D- copper cone, E- cylindrical rim, F- stator package, G- supporting pivot, H- stainless steel tube, I- SmCo permanent magnet, K- graphite mark, P- phototransistor.

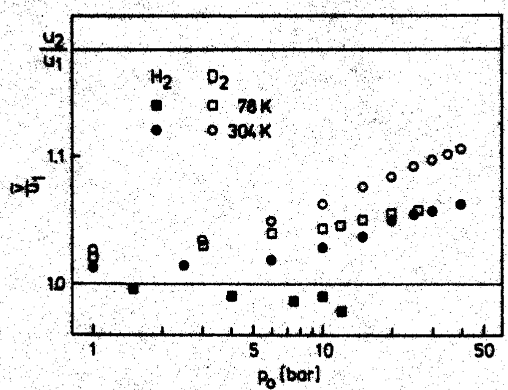

Fig. 3 Reduced flow velocity $\tilde{v}/u_1$ as a function of the stagnation pressure in H_2 and D_2 expansions.

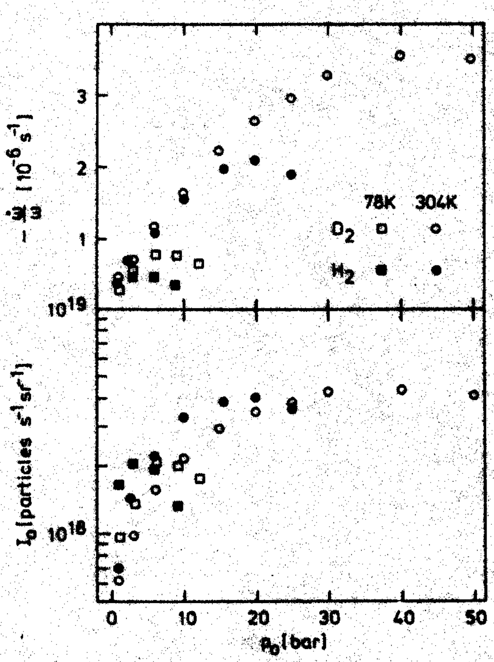

Fig. 4 The measured rotor decelerations $(-\dot{\omega}/\omega)$ due to the impinging beam particles and the resulting absolute intensity data as a function of the stagnation pressure at stagnation temperatures of 78 K and 304 K.