Rayleigh scattering from argon clusters in a planar expansion

F. M DeArmond, R. Dill, J. Suelzer, and M.F. Masters
Department of Physics, Indiana University Purdue University Fort Wayne, Fort Wayne IN 46805

Abstract

Rayleigh scattering is presented as the evidence for the presence of large argon clusters formed in a planar expansion. Based on the observed scattering signal, the dependence of mean cluster size on stagnation pressure is $\langle N\rangle \propto P_0^{3.38}$. This is in contrast to the dependence of the mean cluster size on stagnation pressure for a symmetric expansion of $\langle N\rangle \propto P_0^{2.29}$. Using interferometry in conjunction with the Rayleigh scattering signal we are able to estimate the mean cluster size for clusters formed in the planar expansion.

Principle of Corresponding Jets

The principle of corresponding jets is used to predict mean cluster size given a variety of parameters:

$$\Gamma^* = \frac{kd^{*q}}{T_0^{2.5-sq}} P_0$$

Γ^* is a dimensionless parameter related to the cluster size

k is a characteristic constant that depends upon the gas the geometry of the expansion.

d^* is the effective aperture opening

q varies from 0 to 1 and is determined experimentally by varying d and examining cluster size. It is 0.85 for axisymmetric expansions.

s depends upon geometry and is 0.25 for axisymmetric expansions and 1 for a planar expansion.

The mean cluster size is determined by $\langle N\rangle = C\Gamma^{*\beta}$

Measuring the mean cluster size by Rayleigh scattering

Differential Rayleigh scattering cross section:

$$\left.\frac{d\sigma}{d\Omega}\right|_{total} = \frac{9\pi^2 \; M_a{}^2}{\rho^2\lambda^4}\left(\frac{n^2-1}{n^2+2}\right)^2 \left[N_c\langle N^2\rangle\right]\sin^2\phi$$

$$Vol^2 = \frac{M_a{}^2}{\rho^2} = \frac{16\pi^2}{9}R^6$$, M_a is the atomic mass, ρ is the density of the cluster, R is the radius of a cluster.

n is the index of refraction of the cluster. (~1.3 for argon clusters)

N_c is the number density of clusters

$\langle N^2\rangle$ is the square of the mean cluster size.

ϕ is the angle between the incident radiation's polarization and the polarizability of the cluster.

The number density of clusters is unknown but can be related to the atomic number density by: $N_c = \left(\frac{\alpha N_a}{\langle N\rangle}\right)$

N_a is the atomic number density in the expansion and is proportional to the stagnation pressure P_o.

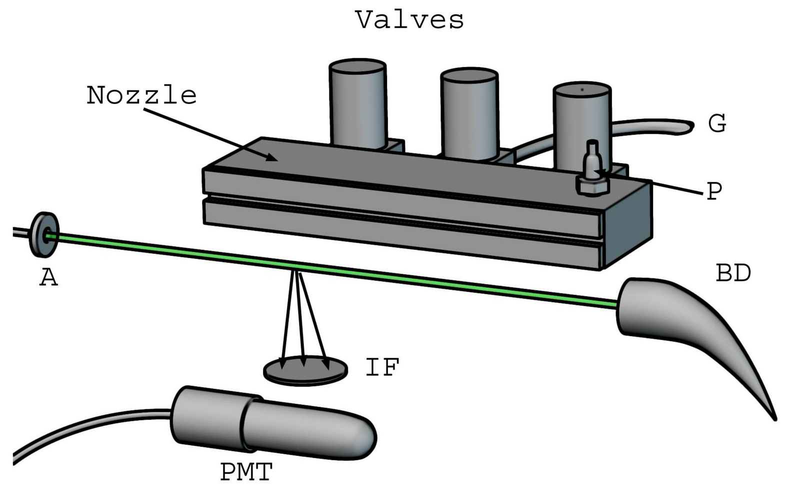
α is the fraction of atoms in clusters.

$\langle N\rangle$ is the mean cluster size $\frac{\langle N^2\rangle}{\langle N\rangle} \sim \langle N\rangle$ and $\langle N\rangle = C\;\Gamma^{*\;\beta} \propto P_0^\beta$

$$\sigma|_{total} \propto P_0\langle N\rangle \propto P_0^{\beta+1}$$

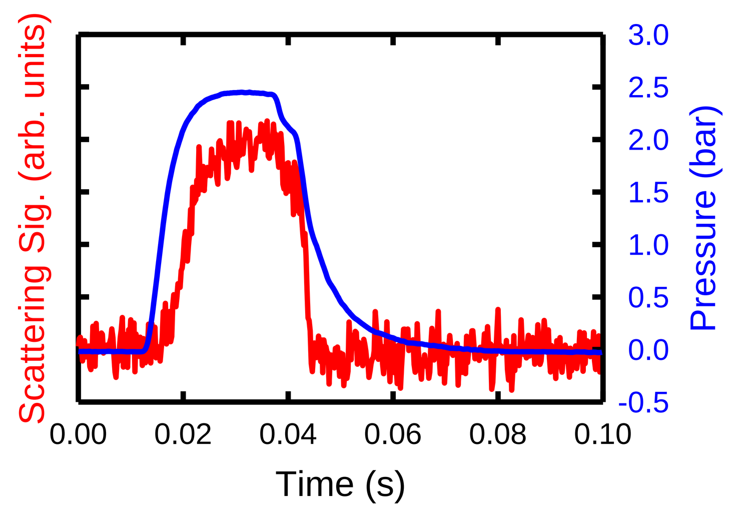
By determining the dependence of Rayleigh scattering signal on stagnation pressure we can find the dependence of the mean cluster size on stagnation pressure determining β.

Scattering Experimental Configuration

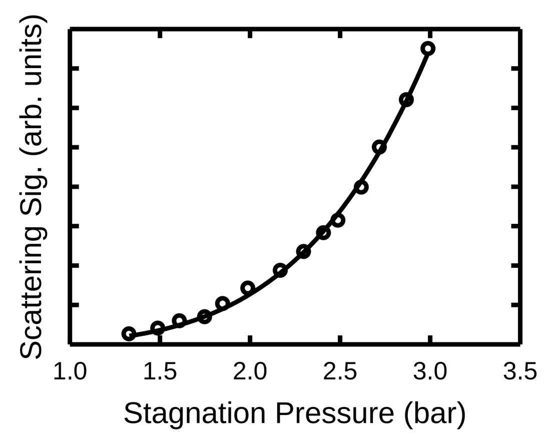


G is the gas line, A is an aperture, IF is an interference filter/aperture before the detector, PMT is the photomultiplier tube, BD is a beam dump, and P is the pressure sensor inside the plenum.

Rayleigh scattering signal from planar expansion.

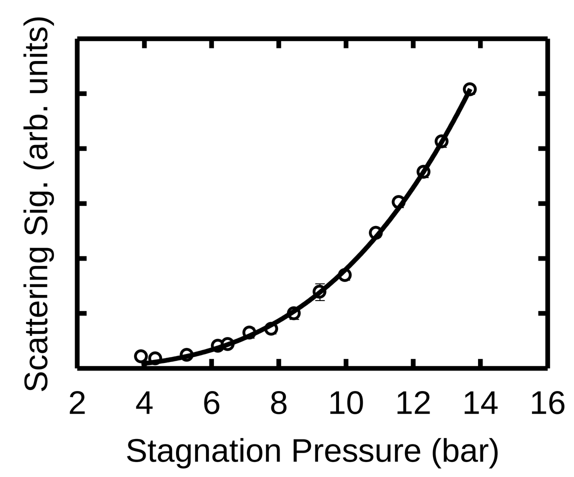


Pressure dependence of Rayleigh scattering for a planar expansion



The peak value of the scattered signal for the planar expansion is plotted as a function of measured stagnation pressure. The uncertainty in the values is no larger than the size of the markers. The fit curve correspondZing to $S_R = Dp_0^{4.38\pm0.09}$ ($\beta = 3.38\pm0.09$) is shown.

Pressure dependence of Rayleigh scattering for an axisymmetric expansion



The peak value of the scattered signal for the axisymmetric expansion is plotted as a function of measured stagnation pressure. The uncertainty in the values is no larger than the size of the markers. The fit curve corresponding to $S_R = Dp_0^{3.29\pm0.06}$ ($\beta = 2.29\pm0.06$) is shown. Reported values range from β=1.5 to 2.5

Interferometry

The polarization of dielectric sphere in an external field is given by:

$$\vec{P}_i = \left(\frac{\varepsilon-1}{\varepsilon+2}\right)R_i^3\vec{E}$$

Relating this to the cluster size we get $\vec{P} = \left[\sum_{\substack{i\\ molec}}\left(\frac{\varepsilon-1}{\varepsilon+2}\right)\left(\frac{3}{4\pi}\frac{M_a}{\rho}N_i\right)\right]\vec{E}$

Given a size distribution of clusters $N_c(N_i)$, we can change the summation to be over cluster size rather than molecule so that

$$\vec{P} = \left[\sum_{\substack{cluster\\ size}}\left(\frac{\varepsilon-1}{\varepsilon+2}\right)\left(\frac{3}{4\pi}\frac{M_a}{\rho}\;N_c\;N_i\;N_i\right)\right]\vec{E}$$

Completing the summation results in $\vec{P} = \left[\left(\frac{\varepsilon-1}{\varepsilon+2}\right)\frac{3}{4\pi}\left\{\frac{M_a}{\rho}\langle N\rangle N_c\right\}\right]\vec{E}$

Since $\vec{D} = \vec{E} + 4\pi\vec{P} = \varepsilon\vec{E}$, the relative dielectric constant

$\varepsilon = n^2 = \left(1+4\pi\left[\left(\frac{\varepsilon-1}{\varepsilon+2}\right)\frac{3}{4\pi}\left\{\frac{M_a}{\rho}\langle N\rangle N_c\right\}\right]\right)$ yielding an index of refraction of the granular gas:

$$\boxed{n-1 = \frac{3}{2}\left[\left(\frac{n_b-1}{n_b+2}\right)\left\{\frac{M_a}{\rho}\langle N\rangle N_c\right\}\right]}$$

Note that the change in index of refraction is proportional to the product of $\langle N\rangle N_c$ the product of the mean cluster size and the number of clusters.

In the Rayleigh scattering cross section, we did not know the number of clusters. Comparing this to the total detected Rayleigh scattered light:

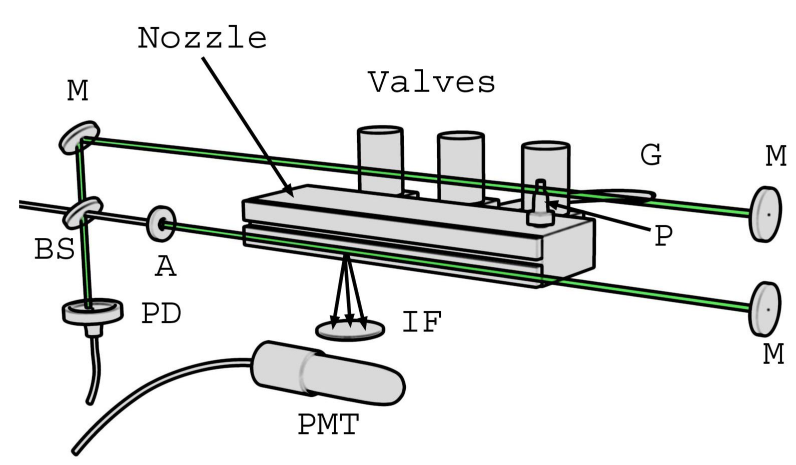
$$P_R = \frac{\sigma_R P_0}{A} = \left(\int\frac{9\pi^2\;M_a{}^2}{\rho^2\lambda^4}\left(\frac{n_b{}^2-1}{n_b{}^2+2}\right)^2\left[N_c\langle N^2\rangle\right]\sin^2\phi\;d\Omega\right)\frac{P_0}{A}$$

So if we look at the ratio scattering signal to the index of refraction of the gas we find:

Issues

To determine the cluster size in this way you must:
- Have an absolute calibration of detection system.
- Accurately measure the phase shift due to the gas.

Interferometry Experimental Configuration



BS is the beam splitter, M are mirrors, PD is a photodiode to detect fringes, G is the gas line, A is an aperture, IF is an interference filter/aperture before the detector, PMT is the photomultiplier tube, BD is a beam dump, and P is the pressure sensor inside the plenum.