ATOMIC INTERACTION WITH QUANTUM FLUID CLUSTERS : 3He-CLUSTER BEAM GENERATION AND Cs-SCATTERING BY4He-CLUSTERS

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ATOMIC INTERACTION WITH QUANTUM FLUID CLUSTERS : ^{3}He-CLUSTER BEAM GENERATION AND Cs-SCATTERING BY ^{4}He-CLUSTERS

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Résumé. — La production d'agrégats d'hélium 3 utilisant une source à tuyère, avec recyclage interne du gaz, est décrite.

Les tailles mesurées des agrégats sont comparables à celles des agrégats d'hélium 4 obtenus avec la même tuyère : quelques millions d'atomes par agrégat.

On étudie la diffusion d'un faisceau atomique de Cs par un faisceau d'agrégats d'hélium 4 comme moyen d'investigation de l'interaction d'atomes avec les agrégats d'hélium qui sont uniques en leur genre car certainement liquides à cause des propriétés de fluide quantique de l'hélium.

Abstract. — The recently accomplished generation of ^{3}He-clusters using nozzle sources with internal recycling of the nozzle feed gas is described. Measured cluster sizes are in the same range of some millions of atoms per cluster as in the case of ^{4}He-clusters generated with the same nozzle. Cesium atomic beam scattering by ^{4}He-cluster beams is studied as a means of investigating the atomic interaction with helium clusters which are unique in being certainly liquid due to the quantum fluid properties of helium.

1. **Introduction.** — The possibility of generating ^{4}He-cluster beams by nozzle expansion of precooled gas has been shown already some time ago [1, 2]. With ^{3}He, no experiments have been done, mainly due to its costs, though it is interesting in itself if ^{3}He-cluster beams can be produced as ^{3}He is the most reluctant of all substances to condense.

Liquid helium does not freeze down to the absolute zero of temperature if not put under the substantial pressure of at least 25 bar in the case of the isotope ^{4}He and of about 32 bar at 0 K in the case of ^{3}He. Therefore, clusters of helium are distinguished from all other kinds of clusters originating from partially condensing nozzle flows by being certainly liquid droplets. This argument is not changed when also the internal pressure due to the surface tension is considered. Because of the very low values of the surface tension σ of 0.38 dyn./cm for liquid ^{4}He and 0.16 dyn./cm for liquid ^{3}He, the internal pressure of a spherical helium droplet of radius R calculated as $2\,\sigma/R$ is lower than the freezing pressure for all cluster sizes, down to a sphere containing only two bulk atomic volumes of ^{4}He or 1/15 bulk atomic volume for ^{3}He. For droplets of 10^6 atoms one calculates an internal pressure of about 250 torr for ^{4}He and of about 100 torr for ^{3}He. These values are below those calculated for, e.g., metal clusters by roughly the ratio of the values of the surface tensions, that is about three orders of magnitude.

Furthermore, helium clusters can be superfluid if sufficiently low internal cluster temperatures are reached. While this is rather likely the case with ^{4}He-clusters, the temperature range below 1 mK necessary for unpressurized ^{3}He to become superfluid is very probably inaccessible with free clusters. Therefore, a different behaviour of the liquid clusters of the two helium isotopes should be expected. Since superfluidity is a macroscopic quantum phenomenon we are not working with microclusters of a few atoms but with clusters in the size range of some millions of atoms per cluster.

Finally, it should be mentioned that cluster beams are considered as a means of fueling or heating of nuclear fusion plasmas [3, 4]. Of the important reactions involving deuterium, the D-^{3}He reaction has the largest energy release and the second largest cross-section. In addition, it has the special advantage of providing only charged reaction products, namely ^{4}He and H, allowing thus direct energy conversion. The neutron induced radioactivity and the tritium handling problems which do arise only from the accompanying D-D reactions are substantially lessened if compared with a D-T fusion plasma. Very probably, usage of the D-^{3}He reaction will require the injection of accelerated ^{3}He [5].

In the following, the recently accomplished generation of ^{3}He-cluster beams and results of cesium atomic beam scattering by ^{4}He-cluster beams are reported.

2. **^{3}He-cluster beam generation.** — The high costs of ^{3}He require very careful recovery of the nozzle feed gas. After some rather unsuccessful attempts to produce ^{3}He clusters at least for some minutes of time by a single passage of the available amount of gas through the nozzle and subsequent reprocessing of the gas by the commercial supplier, we have installed an internal ^{3}He cycle which proved to work very satisfactorily.

Figure 1 shows schematically the experimental set-up used to generate helium cluster beams which intersect an atomic beam of cesium. Precooled helium gas expands through a converging-diverging nozzle of 0.11 mm throat diameter thereby partially condensing. More than 95 % of the nozzle throughput is compressed mechanically from pressures of about 0.1 torr in the expansion chamber to about 1 000 torr by two Roots pumps and a rotary pump in series. The compressed gas passes through an oil filter and a liquid nitrogen trap into a 10 l-storage vessel which again feeds the nozzle inlet *via* a throttling valve. The nozzle feed gas is precooled by a copper tubing heat exchanger immersed in the liquid ^{4}He-bath which cools the nozzle, the skimming orifices, and an impurity trap of sintered metal mounted just in front of the nozzle inlet. The nozzle feed gas cycle is filled from a supply cylinder which also serves to replenish the cycle according to the amount of gas which passes through the skimmer into the following pressure stages. The second pressure stage (10^{-4} torr) and the main vacuum chamber (10^{-6} torr) are pumped by oil diffusion pumps and a common forepump stage compressing the gas flow into a 50 l-cylinder. Its contents are purified after termination of the experiment by several passages through flexible stainless steel tubing immersed in liquid helium.

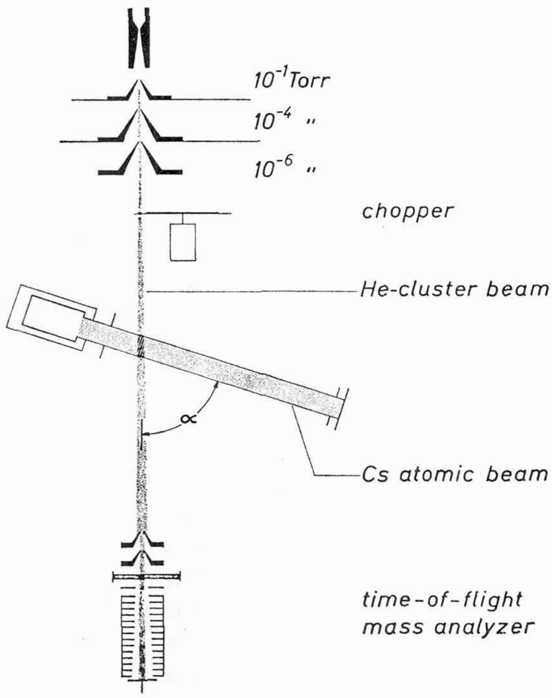

FIG. 1. — Schematic view of the experimental set-up.

The intensity of the helium cluster beam in the main vacuum chamber is obtained from stagnation pressure measurements with an ion gauge probe. The detector depicted in figure 1 serves to measure the cluster sizes by a special version of time-of-flight mass spectrometry [6], using now pulsed ionization by electron impact of the continuously running cluster beam.

Figure 2 shows experimental results of intensities and cluster sizes of the ^{3}He-cluster beam as function of the nozzle inlet pressure. The nozzle temperature of 3.2 K is obtained by lowering the pressure above the cooling liquid ^{4}He-bath to 240 torr. The rather distinct peak structure of the ^{3}He-cluster beam intensity has been observed with ^{4}He too and is believed to be due to condensation shocks occuring in the 15 mm long diverging part of the nozzle with 10° initial angle of divergence.

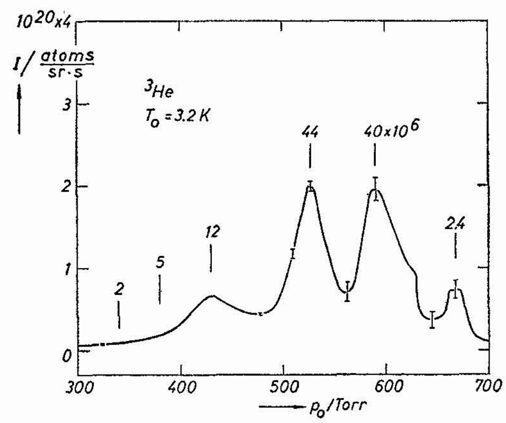

FIG. 2. — Intensity of ^{3}He-cluster beam as function of the nozzle inlet pressure p_0 at a nozzle temperature T_0 of 3.2 K. Vertical bars indicate the range of rapid intensity fluctuations, numbers denote the measured average cluster size given in ^{3}He atoms per cluster.

3. **Cesium scattering by ^{4}He-clusters.** — The extinction of an atomic beam of cesium by a crossed ^{4}He-cluster beam is measured as a function of the relative velocity between the colliding particles. This dependence is supposed to be important in view of the critical velocities not to be exceeded with superfluid flow of bulk liquid ^{4}He. In order to obtain low relative velocities, the angle of intersection of the beams can be decreased to a minimum of 15°. In addition, time-of-flight techniques are used to resolve the distribution of relative velocities for each angle of beam intersection [7]. As indicated in figure 1, a rotating chopper interrupts the helium cluster beam for very short intervals. These gaps in the cluster beam intensity travel with the very uniform speed of the cluster beam to the intersection zone, leading there to pulsed increases of the transmitted cesium inten-

sity. The pulses spread on the way to the cesium atomic beam detector according to the cesium velocity distribution. Comparison of these time-of-flight signals with those obtained when the cesium beam is interrupted by a rotating slotted disc chopper provides a measure of the effective scattering cross section.

It has been reported earlier [8] that the measured signal amplitudes fall short of those calculated the more the lower the relative velocities are if the signals are fitted at the highest relative velocity. As will be shown in greater detail elsewhere, this could be accounted for by assuming an amount of less than 1 atom % of uncondensed ^{4}He hard-sphere atoms. At low relative velocities free ^{4}He-atoms do not scatter enough in the center-of-mass frame to lead to detectable scattering in the laboratory frame while at higher relative velocities they may contribute substantially to the observed scattering. Assuming these uncondensed atoms to have exactly the cluster velocity, the measured maximum signal amplitudes at different angles of beam intersection can be explained rather well. An unresolved discrepancy remains, however, when the complete time-of-flight signals are considered. As indicated by figure 3, at the lowest relative velocities, below about 100 m/s, a larger than calculated scattering seems to be observed, contrary to an originally supposed deficiency of scattering due to eventual superfluidity effects.

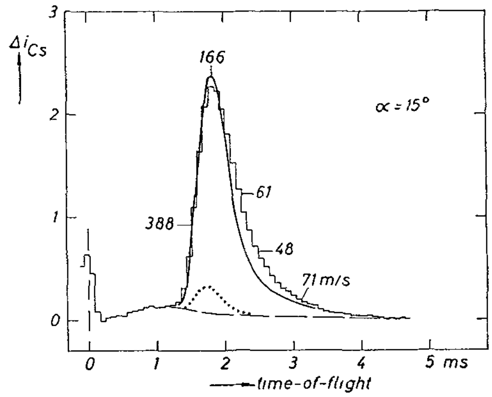

FIG. 3. — Time-of-flight distribution of scattered Cs atoms in arbitrary units obtained at 15° angle of intersection of the Cs atomic beam and the ^{4}He-cluster beam. Measured values: stepwise display ; calculated total signal : smooth curve ; calculated signal due to uncondensed ^{4}He atoms in the beam : dotted curve ; background signal due to faster atoms effusing from the second pressure stage : dashed curve. Numbers denote the respective relative velocities of the colliding particles.

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