Mobility of ^{9}Li^{+} and ^{12}B^{+} Snowballs in Superfluid Helium

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The superfluidity of helium has been investigated in a wide variety of experimental methods. One of the microscopic approaches was the studies of interaction of the impurity ions with helium atoms through their mobilities. The He^{+} impurities were produced by immersing a radioactive α-source and the mobilities were measured through the electric current. The observed very small mobilities led the idea of the "snowball", a helium microcluster surrounding the ion, colliding with rotons in superfluid helium [1].

The mobility of the snowball of effective mass M at the helium temperature T is expressed [2] as

$$\mu = \frac{3(2\pi)^{3/2}(2\pi\hbar)^3}{4p_0^2 kT\sigma_{ir}}\left(\frac{e}{M}\right)\left(1+\frac{3\mu_0}{M}\right)^{1/2}\exp\left(\frac{\Delta}{kT}\right), \tag{1}$$

where k and σ_{ir} are the Boltzmann constant and the interaction cross section between the ion and the rotons with mass μ_0 ($\mu_0 = 0.15m_{\mathrm{He}}$), respectively, and p_0 and Δ the parameters in the Landau's dispersion relation,

$$\epsilon(p) = \Delta + \frac{(p-p_0)^2}{2\mu_0}. \tag{2}$$

In the simple model by Atkins assuming a point charge and the continuum helium media, the effective mass was estimated as $M \sim 40m_{\mathrm{He}}$ [1]. By ignoring the μ_0/M term, the observed linear dependence of $\log\mu$ on the inverse temperature $1/T$ was well explained. Then, the He^{+} snowball mobilities were measured in detail in a wide temperature range [3].

The mobilities of some of alkali and alkaline earth ions were measured also through the electric current, introducing the ions by the arc-discharge [4] or by the laser sputtering [5]. Contrary to the Atkins model, the mobilities clearly showed dependence on ion species: Generally speaking, the alkali ions and alkaline earth ions showed smaller and larger moblities, respectively than that of He^{+}. Be^{+} was exceptional. The mobility of the light ions is of interest. Recent quantum mechanical treatment by the variational Monte Carlo simulations [6] predicted extraordinarily small effective mass, hence large mobility, of Li^{+} snowball. Note that Eq.(1) was deduced based on a microscopic picture that the snowballs collide with the rotons in helium and is still useful to discuss the structure part ($\sigma_{ir}M$) from the experimental mobility.

We have measured the mobilities of the Li^{+} and B^{+} snowballs, for the first time, in a temperature rage of 1.33 - 1.88 K, based on the new method using radioactive nucleus ions [7, 8]. The ^{9}Li($T_{1/2}$ = 178.3 ms) and ^{12}B(20.2 ms) nuclei were produced in the reactions of the 59.9 MeV/u ^{18}O beam from the ring cyclotron on a ^{9}Be target (292 and 487 mg/cm^{2} for ^{9}Li and ^{12}B, respectively), and were isotope-separated and formed into secondary beams through the EN-course. The beam was then implanted into superfluid helium through a 0.5 mm thick Al window. The helium temperature was controlled within 0.002 K. The primary beam was turned on and off for the time periods of T_1 and T_2, respectively. The optimum combination of T_1 and T_2 was determined for each temperature so as to minimize the errors in the velocity measurements. The T_1 (T_2) ranged from 1.5 ms (15 ms) for ^{12}B at 1.35 K to 20 ms (150 ms) for ^{9}Li at 1.88 K.

The mobilities of both the ^{9}Li and ^{12}B snowballs were considerably smaller than those of He. The experimental mobility of ^{9}Li snowball is in conflict with the quantum mechanical prediction [6]. The small mobility suggests large effective mass M and/or large cross section σ_{ir} in Eq.(1). Figure 1 shows the inverse of the "reduced mobility", $\mu T\exp(-\Delta/kT)$, for ^{9}Li, ^{12}B and ^{4}He [3] as a function of the helium temperature. Note that $(\mu T\exp(-\Delta/kT))^{-1}$ is proportional to $(\sigma_{ir}M)$. It is to be noted that the quantity $(\sigma_{ir}M)$ shows clear dependence on the ion species and linear dependence on T for all the ion species.

The structure change according to T was discussed by Nakayama *et al.* [9] based on the path integral Monte Carlo calculations. Their theory predicts a triple-layer structure of helium around the impurity ion and the superfluidity change as the temperature in the second shell. The observed temperature dependence on $(\sigma_{ir}M)$ may be related with the structure change predicted by Nakayama *et al.* If we express the observed temperature dependence as

$$\sigma_{ir}M \propto (\sigma_{ir}M)_0 + \alpha T, \tag{3}$$

the first term, $(\sigma_{ir}M)_0$, denotes the structure at $T = 0$ and α is the degree of the structure change. The parameters $(\sigma_{ir}M)_0$ and α were determined by fitting the data in Fig. 1 with Eq.(3). The results are plotted in Fig. 2, together with those for the previous data for other ion species [3, 4, 5]. It is very interesting to note the systematics that (i) all the data are on a straight line, (ii) the alkaline-earth ions show small $(\sigma_{ir}M)_0$ and α, whereas the alkali ions show large $(\sigma_{ir}M)_0$ and α and (iii) the light ions of Li, Be and B are exceptional in the sense that they show by far larger $(\sigma_{ir}M)_0$ and α than the ions in the same group.

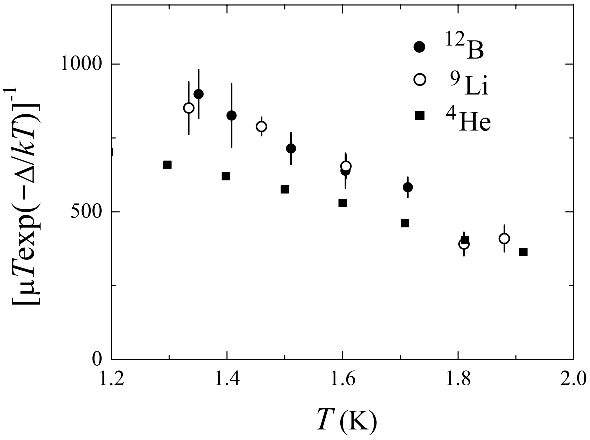

Figure 1: Inverse of the reduced mobility as a function of helium temperature (preliminary).

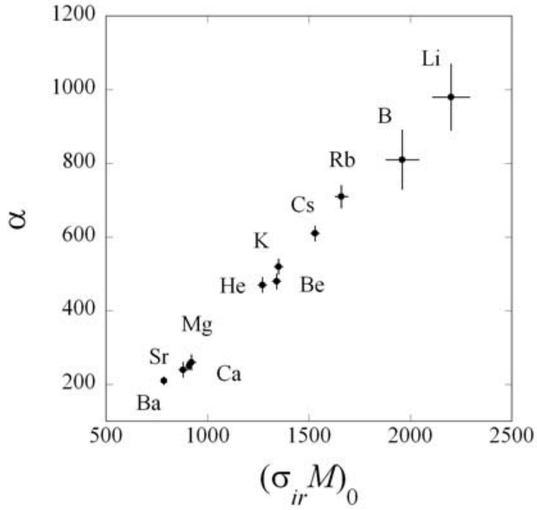

Figure 2: Parameters describing the temperature dependence of $\sigma_{ir}M$ for various ion species. The data for Li and B are obtained in the present work, and others are from the previous works [3, 4, 5].

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