Laser spectroscopy of Dy atoms in superfluid helium: Zero-phonon lines and phonon wings

P. Moroshkin[1], **K. Kono**[2]

RIKEN, Center for Emergent Matter Science, 351-0198 Wako, Japan

Synopsis By observing optical spectra of dysprosium atoms in bulk superfluid ^{4}He we investigate the scattering of phonons on atomic nano-bubbles in a quantum fluid.

When a metal atom is injected into superfluid helium, it resides in the center of a nanometer-sized cavity formed in the surrounding quantum fluid that is known as atomic bubble. Elementary excitations of superfluid He, such as phonons couple to various electronic properties of the impurity atom via the vibrations of the bubble surface. Of particular interest are optical transitions within the inner electronic shells of the embedded atom that are screened from the surrounding He by the valence electrons. In that case the kick on the bubble interface produced by the sudden change of the impurity electron configuration is rather small and the spectrum typically consists of two parts: a zero-phonon line (ZPL) and a phonon wing (PW). A number of experiments reported ZPL and PW spectra of various molecules attached to superfluid He nanodroplets. Among them, the spectrum of glyoxal had been interpreted in terms of elementary excitations (phonons) and provided the evidence for the superfluidity of the droplets [1]. The key feature is a $\approx$6 cm^{-1} gap between the ZPL and PW that arises due to a roton minimum - a peculiar structure in the spectrum of elementary excitations in superfluid He that is not present in normal liquids. However, no gap had been found between ZPL and PW in the spectra of atomic impurities in bulk liquid He, neither in superfluid, nor in normal fluid phase [2, 3]. Up to date, no satisfactory explanation was proposed for this discrepancy.

We present the results of a new experimental measurement of ZPL and PW spectra of Dy atoms in bulk superfluid ^{4}He (T = 1.4 – 2.1 K). The atoms are dispersed in liquid He by laser ablation using two pulsed Nd:YAG lasers and are excited by a cw frequency-doubled tunable Ti:Sapphire laser that is tuned to the wavelength of the inner-shell transition connecting the $4f^{10}6s^2\ ^5I_8$ ground state of Dy with the $4f^9 5d6s^2\ ^5K_7$ excited state (λ_{free} = 458.9 nm). We observe a spectrally-resolved laser-induced fluorescence originating from several lower-lying excited states of Dy, including both inner-shell and valence-electron transitions.

Both excitation and emission spectra of inner-shell transitions display ZPL and PW features. In the emission spectrum, ZPL has a resolution-limited linewidth (FWHM $\approx$4 cm^{-1}) and strongly overlaps with PW, with no gap between them. In the excitation spectrum, we obtain a significantly narrower ZPL (FWHM $\approx$ 0.1 cm^{-1}) and a well-resolved gap with a width $\Delta \approx$ 5.5 cm^{-1} between ZPL and PW (see Fig. 1). Due to its narrow linewidth and a large transition dipole, the laser-excited transition can be easily saturated, which leads to a distorted excitation lineshape with a strongly broadened and suppressed ZPL. This effect may explain the missing gap between ZPL and PW in earlier studies [2]. By applying a hydrodynamic bubble model we calculate the spectrum of the atomic bubble oscillations and the rate of phonon scattering by the bubble at rest. The former is related to the PW lineshape and the latter is responsible for the temperature-dependent broadening of ZPL. The results agree well with the measured width of ZPL in the excitation spectrum.

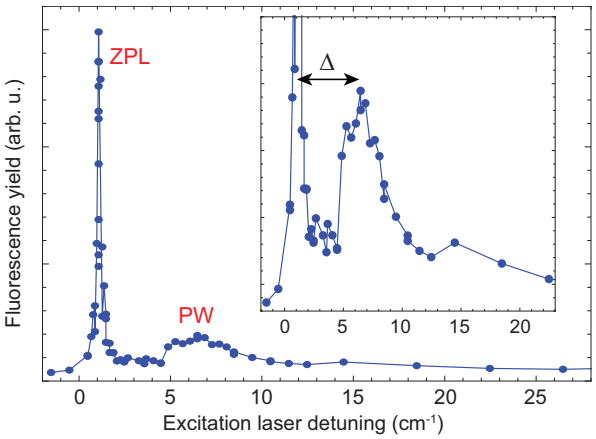

Figure 1. Excitation spectrum of a $4f^{10}6s^2$ - $4f^9 5d6s^2$ inner-shell transition of Dy in superfluid ^{4}He.

References

[1] M. Hartmann *et al.* 1996 *Phys. Rev. Lett.* **76** 4560

[2] Q. Hui, M. Takami 2000 *J. Low Temp. Phys.* **119** 393

[3] P. Moroshkin *et al.* 2011 *Phys. Rev. A* **84** 052519

[1]E-mail: petr.moroshkin@riken.jp
[2]E-mail: kkono@riken.jp