Zeeman resonance spectroscopy of $^{84-87}$Rb in superfluid helium

X.F. Yang,[*1,*2] T. Furukawa,[*1,*3] T. Wakui,[*1,*4] K. Imamura,[*1,*5] T. Fujita,[*1,*6] Y. Mitsuya,[*1,*5] M. Hayasaka,[*1,*7] Y. Ichikawa,[*1] Y. Ishibashi,[*1,*9] H. Shirai,[*1,*8] T. Suzuki,[*1,*8] Y. Ebara,[*3] A. Hatakeyama,[*10] M. Wada,[*1] T. Sonoda,[*1] Y. Ito,[*1] T. Kobayashi,[*11] S. Nishimura,[*1] M. Kurata-Nishimura,[*1] Y. Kondo,[*1,*8] K. Yoneda,[*1] H. Ueno,[*1] T.Shinozuka,[*4] T. Shimoda,[*6] K. Asahi,[*1,*8] and Y. Matsuo[*1,*12]

OROCHI is a newly developed laser spectroscopy method for optical determination of nuclear spins and moments of exotic radioisotopes (RIs)[1)]. It aims to overcome several experimental limitations due to the low yield of RIs and large contaminations in the production of RIs by taking advantages of the characteristic properties of atoms in superfluid helium (He I-I). Firstly, it utilizes condensed He II as the trapping medium for the RI beam and the matrix of in situ laser spectroscopy of trapped atoms. Subsequently, by measuring the hyperfine and Zeeman splitting energies of atoms using optical pumping and laser microwave (MW)/radiofrequency (RF) double resonance method, nuclear moments and spins of RIs can be determined. Initial studies with the OROCHI method were concentrated in field of the technological research and development with a considerable number of off-line experiments, which confirmed the feasibility of the OROCHI method[1)]. Recently, after extensive tests and calculations, the first on-line experiments with the $^{84-87}$Rb beam have been successfully performed. In this experiment, the primary ^{85,87}Rb and secondary ^{84,86}Rb beams produced from RIPS were precisely trapped in He II. Optical pumping and Zeeman resonance (ZR) for $^{84-87}$Rb and the isomer state ^{84m}Rb have been successfully observed.

Figure 1 shows the measured spectra for $^{84m,84-87}$ Rb isotopes, which are recorded by scanning the applied magnetic field (B_0) with a fixed-frequency RF field. The corresponding beam for each spectrum and isotopes for each observed ZR are marked in Fig. 1. Note that in the case of ^{86}Rb, to reduce the deformation of the observed spectra owing to beam instability, the recording time for one cycle is changed to 1 s (10 s for ^{84,85,87}Rb). The detailed measurement method is explained in an early report[2)]. Conventionally, nuclear spin can be directly deduced from the resonance peaks with the relation (for the ground state of an alkali atom) $I = \frac{\mu_B B}{\nu} - \frac{1}{2}$, where ν is the RF frequency and B is the magnetic field. In practice, the accuracy of the deduced nuclear spin is degraded by the residual magnetic field (B_L). The detailed information about how B_L affects the results can be found in a recent article[3)]. In this work, to eliminate the effects of B_L, we used a combination relation of the Bell-Bloom equation[4)], which describes optical pumping in longitudinal ($B_\parallel$: $B_0 + B_{L\parallel}$ (parallel component of B_L)) and transverse magnetic fields ($B_\perp$: perpendicular component of B_L) (for details, see Yang et al.[3)]) and $I_{LIF} \propto N_{atom}(1 - P_z)$ to fit the peaks at $B_0 = 0$, while the ZR peaks are fitted with the Lorentz function (red curve in Fig. 1).

From the ZR, after eliminating the effect of B_L, nuclear spins were deduced as 1.9(1) for the ^{84}Rb, 6.2(1) for ^{84m}Rb, 2.5(1) for ^{85}Rb, 1.9(2) for ^{86}Rb, and 1.53(6) for ^{87}Rb. The inaccuracy of the B_0 and the estimated $B_L$is supposed to be the main experimental error. In addition, 3.3% of error arises from the field inhomogeneity within the observation region and uncertainty of the observation region (1 mm). Taking all the factors into account, the nuclear spins of $^{84m,84-87}$Rb were correctly deduced within the experimental error, which are consistent with the literature values.

Consequently, we have successfully observed the ZR spectra for $^{84-87}$Rb isotopes and their nuclear spin can be determined with a good accuracy, which directly confirms the feasibility of the OROCHI method. It is worth emphasizing here that the measured spectra were recorded in 30 minutes or less with a beam intensity of $\sim 10^4$ pps. All the results suggest that, after further being developed and improved, the OROCHI method can be established as a promising method to precisely measure nuclear spins and moments of various nuclear species near the drip line with a low yield.

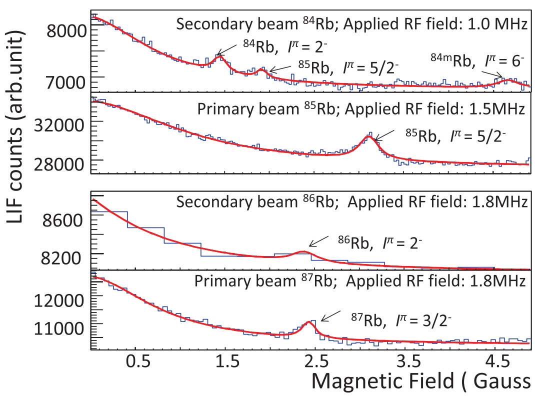

Fig. 1.: Zeeman resonance spectra for $^{84m,84-87}$Rb.

*1 RIKEN Nishina Center
*2 School of Physics, Peking University
*3 Department of Physics, Tokyo Metropolitan University
*4 Cyclotron Radioisotope Center, Tohoku University
*5 Department of Physics, Meiji University
*6 Department of Physics, Osaka University
*7 Department of Physics, Tokyo Gakugei University
*8 Department of Physics, Tokyo Institute of Technology
*9 Department of Physics, University of Tsukuba
*10 Department of Applied Physics, Tokyo University of Agriculture and Technology
*11 Laser Technology Laboratory, RIKEN
*12 Department of Advanced Science, Hosei University

References

1) T. Furukawa et al.: Hyp. Int. **196**, 191 (2010).
2) T. Furukawa et al.: RIKEN. APR. **46**, xi(2013).
3) X.F. Yang et al.: Hyp. Int. **227**, 147 (2014)
4) M. Arndt et al.: Phys. Rev. Lett **74**, 1359(1995)