CONDENSED-MATTER NUCLEAR PHYSICS WITH RADIOACTIVE BEAMS SNOWBALLS IN SUPERFLUID HELIUM *

N. TAKAHASHI

Osaka University, Graduate School of Science, Department of Physics
Toyonaka, Osaka, 560 Japan

(Received December 10, 1996)

Novel methods were applied successfully to trap radioactive ions and atoms and to freeze out their nuclear spin polarization inside aggregates of helium atoms, "snowballs" in superfluid helium. Polarized beta-ray emitting ^{12}B ions ($T_{1/2}$ = 20.4 ms) were introduced into superfluid helium and snowballs were created around the impurity ions. Beta rays were detected to locate snowballs and the beta-ray asymmetry was measured to obtain the nuclear polarization of decaying ^{12}B. The comparison with the initial value of ^{12}B polarization establishes that no relaxation in polarization was observed throughout lifetime of ^{12}B. Most of the impinged high-energy ions are neutralized. While they may constitute background in the above measurements, the neutrals are themselves interesting in their behaviour. It has been found that there are two components that stay in a position after stopping and that move quite swiftly in superfluid helium. The strange behaviour of neutrals is discussed.

PACS numbers: 24.70. +s

1. Introduction

Impurity atoms and ions in superfluid helium constitute a large field of interests in low-temperature physics. Energetic radioactive ion beams, produced from heavy-ion reactions, are extremely fine sources to create impurities in superfluid helium, since their range in matter is reasonable and it is not difficult to introduce them into liquid helium through a thin window. Most of the impinged ions lose quickly their charge before they end up neutralized. There is a certain probability that considerable fraction remains

* Presented at the XXXI Zakopane School of Physics, Zakopane, Poland, September 3–11, 1996.

singly charged, when they come to stop. Snowball is a microcluster of helium atoms created around an impurity ion through electrostriction [1], as found for the first time in the measurements of ion mobility in liquid helium [2]. Such a cluster is presumed to sustain a highly symmetric structure and may constitute an ideal environment to maintain nuclear orientations for study of electromagnetic moments of nuclei. Inversely, relaxation phenomena for nuclear polarization of core ions encapsulated in snowballs are also a good probe to seek into the inherent structures of the aggregates. The novel methods used in studies of heavy-ion polarization [3] and exotic nuclear beams [4] enabled us to conceive renewed interests in impurity atoms and ions in liquid helium [5]. A decisive result has been obtained that the nuclear spin polarization of impurity ions is maintained throughout their lifetime in "snowballs" [6]. Here the effectiveness of beta-ray detection in locating snowballs is demonstrated and the behaviour of spin polarization is observed. While they may constitute background in the measurements as introduced above, the neutrals are themselves interesting in their own behaviour. It has been found that there are two components; one that stays in a position after stopping and another that moves quite swiftly in superfluid helium. The strange behaviour of neutrals is discussed.

2. Experiments

Polarized radioactive nuclei ^{12}B were produced in the reaction of the pulsed beam of ^{14}N with the target ^{9}Be at an incident energy of 38.5 MeV/u and at 5 degrees with respect to the direction of incidence. The ^{12}B ions sustaining an average initial polarization of -30 % were separated isotopically through the secondary beam line at the Research Centre for Nuclear Physics (RCNP), Osaka University. The polarized radioactive beam was pulsed and was injected into superfluid helium at a temperature of 1.4 K. The in-beam period was in the range of 5–30 ms. Some of the ions survived neutralization and came to rest as singly-charged ions, thus core ions of snowballs. A static electric field was supplied to collect positive-charge carriers at the point of detection sensitive region, thus the configuration was accelerating between the impingement and detection and decelerating beyond the detection region. After transportation in an electric field, the snowballs were detected through beta rays from the core ions ^{12}B and the nuclear polarization of the decaying ^{12}B in the snowballs was determined through the beta-ray asymmetry measurements under application of NMR. The rf-field was impressed for 3 ms to invert adiabatically the ^{12}B polarization during every other out-beam period. A waiting time of 5 ms was necessary from the end of the in-beam period to allow the snowballs produced close to the end of the in-beam period to attain the detection region, so that they were subject to NMR. The measurements of drift velocity of the singly charged ions, thus snowballs, were carried out in the essentially same configuration of the experimental setup but with a more strict geometrical limitation in the detection sensitive positions. A narrow slit system was supplied to locate the snowballs. The drift velocity observed was consistent with the values known at the corresponding electric field. Time spectra were observed with the pulsed ^{12}B beams of less than 5 ms width.

3. Results

The observed beta-ray asymmetry is plotted in Fig. 1 against the time sequence of the measurements. Note that there is essentially no asymmetry observed before the application of NMR. As soon as the NMR has been applied, huge asymmetry appears and remains unchanged. The measured asymmetry is shown here as ^{12}B polarization.

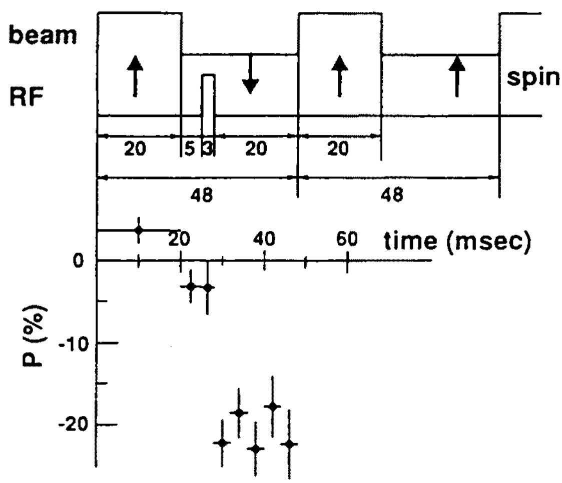

Fig. 1. Beta-ray asymmetry plotted in the time chart of the measurement.

The polarization is maintained during out-beam period and essentially no relaxation is observed. This result shows decisively that the nuclear spin polarization of core ions is maintained in the snowballs. The average polarization is $-20.7 \pm 1.5\%$; the value is smaller than the estimated initial polarization in the implanted ^{12}B ion beams. Figure 2 shows the time spectrum to determine the drift speed of radioactivity in superfluid helium, corrected for the decay of the ^{12}B. The arrival of the charged ^{12}B is expected after 15 ms.

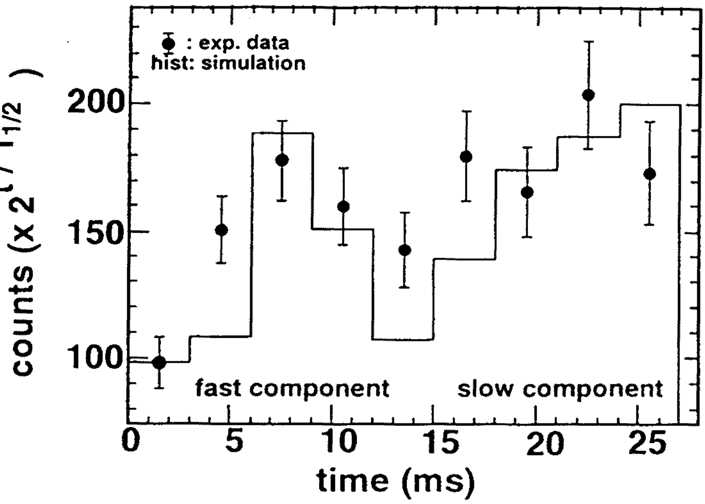

Fig. 2. Time spectrum of beta-rays plotted against time of arrival. The count rate is corrected for the decay of ^{12}B.

There is a component that arrives earlier than that of snowballs and this component disappears in 10 ms. Note that the charge carriers are transported to the detection sensitive region and are kept in this region. The decrease, *i.e.*, the passing of radioactivity means that this is due essentially to neutrals. The amount of neutrals behaving in that way has been measured about 20% of the whole neutrals created after impingement. A statement is made that there are two components in neutrals; (1) that stays as the high-energy ions have been decelerated upon entering superfluid helium and (2) that moves swiftly almost at the critical velocity in superfluid helium.

4. Discussions

There existed a small amount of beta-ray background, when the electric field to drag the snowballs to the detection region was zero. The asymmetry was essentially zero for this component. With inclusion of this correction, the average polarization of ^{12}B observed became thus $-23.9 \pm 1.6\%$. A correction was further needed for the effects due to a long transit time for ions produced close to the end of the in-beam periods, thus evading the application of NMR. The correction for this effect increased the polarization to the value corresponding the incident ^{12}B ions, thus to the original ^{12}B polarization. The behaviour of neutrals are somewhat not decisive. There are two components and the one that stays as the ions have been neutralised is naturally understandable. The component may diffuse with interactions of various excitations in the liquid. The other component that moves swiftly in superfluid helium proposes issues of whether the difference arises from the stopping process or in the interactions of the impurity with superfluid helium. The tentative interpretation is that the swiftly moving component is carried through the movement in superfluid helium. The interaction between the impurity atom and the fluid, macroscopic or microscopic must have to be studied. It is proper here to mention that an extremely high efficiency has been attained in detecting snowballs through this beta-ray method and the measurements on freezing-out of polarization and behaviour of impurity atoms have been successfully carried out, which otherwise is not easy with the conventional electric current methods in detecting snowballs.

5. Conclusion

Our conclusion, therefore, is that the efficiency in locating snowballs through our beta-ray detection is high and the nuclear polarization is maintained in the ions encapsulated in snowballs. The application may be found in the determination of moments in nucleus far from the stability, as the polarization is kept preserved in snowballs. The neutrals are also interesting in seeking the collective flows in superfluid helium or the different behaviour for possibly different electronic structure in the neutrals. This opens a new way to use impurities, positively charged (snowballs) or neutral as versatile tools in physics of nuclear structure and of condensed-matter.

It is a pleasure to thank many of my collaborators, especially Prof. T. Shimoda, Dr. H. Miyatake for their persistent effort to bring the whole idea in reality. I thank Profs. Morinobu and Asahi, Drs. S. Mitsuoka, H. Ueno and H. Izumi and also Y. Mizoi, H. Kobayashi, M. Sasaki and T. Shirakura for their help during the measurements. It is a great pleasure for the authors to acknowledge the kind understanding and help of all the staff at RCNP with our experiments. Financial supports were kindly supplied as the Grant in Aid of Scientific Research from the Ministry of Education and Culture, Tokyo, and as the Toray Science and Technology Grants and the Grants from the Mitsubishi Foundation.

REFERENCES

[1] K. R. Atkins, *Phys. Rev.* **116**, 1339 (1959).

[2] L. Meyer, F. Reif, *Phys. Rev.* **110** 279L (1959).

[3] K. Sugimoto, M. Ishihara, N. Takahashi, in *Treatise on Heavy-Ion Science*, edited by D. A. Bromley, Vol. 3, Plenum Press, New York 1985, p. 395 and N. Takahashi, *Hyperfine Interact.* **21**, 173 (1985).

[4] I. Tanihata, H. Hamagaki, O. Hashimoto, S. Nagamiya, Y. Shida, N. Yoshikawa, O. Yamakawa, K. Sugimoto, T. Kobayashi, D. E. Greiner, N. Takahashi, Y. Nojiri, *Phys. Lett.* **160B**, 380 (1985). I. Tanihata, H. Hamagaki, O. Hashimoto, Y. Shida, N. Yoshikawa, K. Sugimoto, O. Yamakawa, T. Kobayashi, N. Takahashi, *Phys. Rev. Lett.* **55**, 2676 (1985) and T. Shimoda, H. Miyatake, S. Morinobu, *Nucl. Instrum. Methods* **B70**, 320 (1992).

[5] N. Takahashi, T. Shimoda, Y. Fujita, T. Itahashi, H. Miyatake, *Z. Phys.* **B98**, 347 (1995).

[6] N. Takahashi, T. Shimoda, H. Miyatake, Y. Mizoi, H. Kobayashi, M. Sasaki, T. Shirakura, S. Mitsuoka, S. Morinobu, K. Asahi, H. Ueno, *Hyperfine Interact.* **97/98**, 469 (1996).