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Feasibility study on the Nuclear Spin Imaging (NSI)

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We started developing the Nuclear Spin Imaging (NSI). The NSI is the MRI (Magnetic Resonance Imaging) with hyperpolarized nuclei artificially created. Among a number of candidate nuclei to be hyperpolarized, we chose ^{3}He in view of particular importance in the medical application. The method to produce the hyperpolarized ^{3}He in a gas phase is based on the production of the highly polarized solid ^{3}He by means of the brute force method, and a subsequent rapid melting of the solid to gas through the liquid phase of ^{3}He in a time short enough to avoid the serious relaxation of polarization. For this purpose, we employed a ^{3}He/^{4}He cryogenic refrigerator and a high magnetic field generated by a superconducting solenoidal coil.

In this report, some of the progress in producing the hyperpolarized ^{3}He and the future plan of the NSI project are presented.

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1. Introduction

One of the central topics of this conference is the imaging, where the spatial structure of the heavy ion collisions is extensively discussed down to the femtometer scale by means of the particle correlations. Our approach of the imaging based on the NSI (Nuclear Spin Imaging) is, however, considerably different from the above aspect. In fact, the imaging scale is macroscopic as exemplified by mm. In addition, we aim not at fundamental nuclear physics, but at the medical application for the human health care. Moreover, the principle of imaging is based not on the interference term of the quantum mechanics, but on the Nuclear Magnetic Resonance (NMR), in which the polarized nuclei created by an extremely low temperature and strong magnetic field are rigorously employed. Nevertheless, we hope that our development will hopefully be beneficial to an object of this conference.

Japan is one of the worst countries that the radiation-based diagnostic equipments such as the X-ray CT and PET (Positron Emission Tomography) are most frequently used [1, 2]. Furthermore, the fallout due to the nuclear reactor accident in Fukushima gives rise to the serious influence on the ecology in Japan. Therefore, it is of particular importance for us to make an effort to reduce the radiation exposure. One of the promising solutions is to use the radiation-free diagnostic equipments such as the MRI instead of the radiation-based equipments. However, the usefulness of the MRI so far is rather limited. Therefore, there is an urgent need to extend the versatility of the MRI to meet the above requirement.

Our group at the RCNP, Osaka has been working, for a long time, on the spin physics. A few of the achievements are the polarized ^{3}He ion sources [3] using the laser optical pumping and the polarized HD (Hydrogen Deuteride) target [4, 5] by means of the brute force method. Guided by aforementioned rich experiences, we decided a few years ago to develop the spin physics technologies for the medical application. This decision is also encouraged by the recent success in the lung and brain MRI (Magnetic Resonance Imaging) using hyperpolarized rare gases, e.g., ^{3}He and ^{129}Xe in Europe and USA[6]. Though their projects are remarkably progressive, the practical use for the medical diagnosis is still restricted to the test experiments because of the difficulty in producing a large amount of highly polarized gases within a short time.

Frossati[7] examined the possibility to produce nuclearly polarized ^{3}He gas with a large volume even up to 1000 ℓ/day by the cryogenic method, where the brute force method and the Pomeranchuk cooling[8] play a substantial role. His idea is based on that of Castaing et al. [9, 10, 11]. The RCNP group started a project to produce a plenty amount of the highly polarized ^{3}He gas in a short time. A somewhat detailed description on our project is given in Sec. 2.

In addition, we paid attention on the success of the ^{13}C, and ^{15}N MRI, in which the nuclei were hyperpolarized by means of either the DNP (Dynamic Nuclear Polarization) [12] or the PHIP (Parahydrogen Induced Polarization) [13, 14]. Then, we can conceptually extend the present project to a more general idea, i.e., the NSI (Nuclear Spin Imaging) since the brute force method can be used to polarize any nuclei irrespectively of nuclear species. This is a striking contrast with the other methods such as the laser optical pumpings, DNP, or PHIP because they are effective only for specific nuclei. Now, the NSI project in Osaka has been revised so that it may include the MRI not only with the hyperpolarized ^{3}He, but also ^{13}C, ^{15}N, ^{19}F, and ^{31}P, which are nuclei important for the study particularly of the biomedical research.

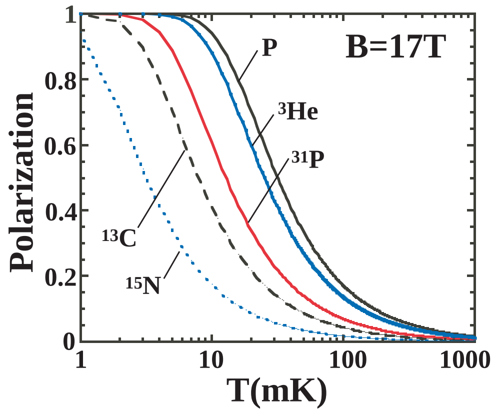

Figure 1: Polarizations attainable by means of the brute force method for some nuclei important in biomedical research .

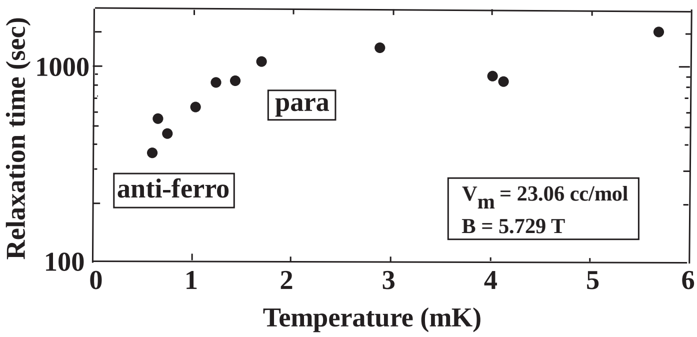

Figure 2: T_1 Observed spin relaxation times plotted as a function of temperature for the solid ^{3}He (see ref. [15]).

2. Brute force method and its application to ^{3}He

The brute force method employed in the NSI project is a general and attractive method to polarize nuclei, though the method itself requires a sophisticated technology in attaining an extremely low temperature and a high magnetic field. In Fig. 1, the calculated polarizations for nuclei with a spin 1/2 attainable by the brute force method are plotted as a function of temperature in case of B = 17 T. Note that a sizable amount of the polarization is obtained, though the maximum polarizations at a certain temperature differ from each other, depending on the magnitude of the nuclear magnetic moment. For ^{3}He , we plan to lower the temperature down to around 1 mK by using the Pomeranchuk cooling specific to the Fermi liquid like ^{3}He, from which we expect a ^{3}He polarization exceeding 0.95.

However, when the brute force method is applied to ^{3}He, a special attention should be paid. It is well known that ^{3}He in a liquid phase is not highly polarized because the Fermi temperature is high, $T_F \sim 180$ mK. This suggests that even if the liquid ^{3}He is cooled down to 1 mK, the effective temperature never goes down lower than T_F. To overcome this difficulty, ^{3}He in a solid phase is used since the solid ^{3}He undergoes para magnetism except at an extremely low temperature lower

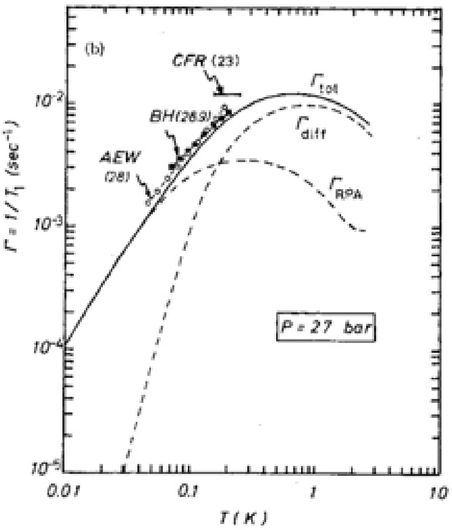

Figure 3: Inverse T_1 spin relaxation times plotted as a function of temperature for the liquid ^{3}He (see Ref. [19], and see also Ref. [7]).

than 1.5 mK. Then, the solid ^{3}He polarization recovers its full values, since the temperature is given not by the T_F but by the real temperature. The ^{3}He solidification is simply done by compressing the liquid ^{3}He up to over 34 bar. This compression process also facilitates the lowering of the ^{3}He sample temperature by the principle of the Pomeranchuk cooling. Fortunately, the T_1 spin relaxation time of the solid ^{3}He is is 1000∼2000 seconds as seen in Fig. 2. Therefore, the time needed for the polarization is conveniently short, which is an advantage of the brute force method applied to ^{3}He. When the solid ^{3}He is created, it is rapidly gasified through a liquid phase because the T_1 spin relaxation time in a liquid phase is estimated to be shorter than 100 seconds. at 1 K as shown in Fig. 3.

For the rapid melting of the solid ^{3}He, we attached a special device to the Pomeranchuk cell as conceptually shown in Fig. 4.

3. Experiment

As the first step of the NSI project, a test experiment will be done with the ^{3}He/^{4}He dilution refrigerator, DRS2500, which has a cooling power of 2500 μW at 120 mK. A superconducting solenoidal coil can generate 17 T at the central region of the Pomeranchuk cooling cell. Since basics of the project was presented elsewhere [16, 1], only the latest progress is presented in this report. Before the above test experiment with the high power cryogenic system, DRS2500 and the 17-T superconducting solenoid, we must prepare an equipment allowing a pre-test experiment of the Pomeranchuk cooling system in order to more conveniently obtain an optimized condition of the system. For this purpose, we constructed, and tuned a cryo-free ^{3}He/^{4}He dilution refrigerator, $KOBE10\mu$ expected to have a refrigeration power of 10μW at T=150 mK, and a superconducting Helmholtz coil producing 1 T [1]. Recently, we succeeded in measuring the NMR signals for liquid ^{3}He by a new NMR circuit [17, 18]. In Fig. 5, the first observation of the NMR spectra is plotted

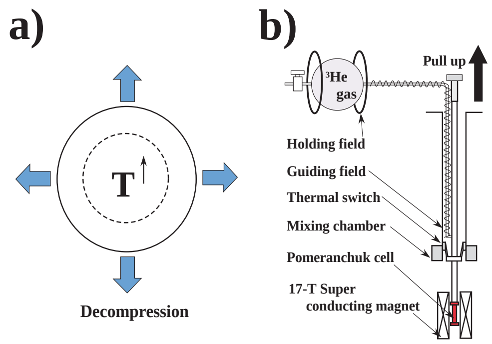

Figure 4: Conceptual view of the rapid melting: a) Temperature increase by decompression of the solid ^{3}He since the decompression process, i.e., the reverse process of the Pomeranchuk cooling produces a thermal energy. b) Schematic picture of an equipment for the rapid melting method. Small helical coils are wound around an extraction tube of the polarized ^{3}He gas to keep the ^{3}He polarization large against the perturbing fields.

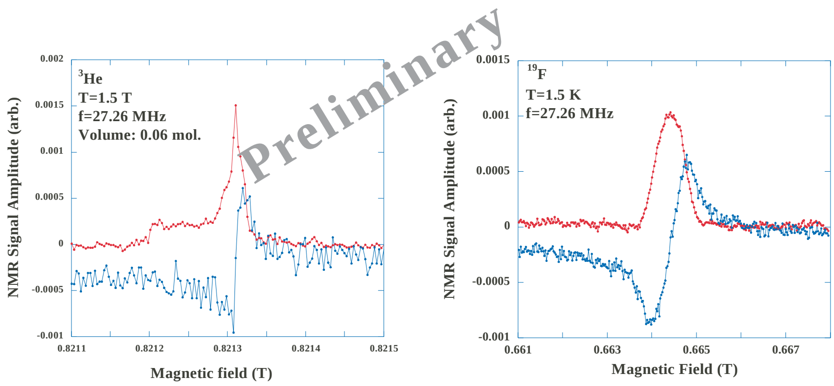

Figure 5: NMR spectra observed for ^{3}He (liquid) and ^{19}F (solid), where the red (upper) and blue (lower) curves correspond to the imaginary and real parts of the magnetic susceptibility, respectively.

as a function of the external magnetic field (B∼0.8 T) at the temperature of 1.5 K for the liquid ^{3}He (left) and for ^{19}F (right) in a solid Kel-F (left) for comparison. The ^{3}He nuclear polarization estimated assuming the thermal equilibration (TE) is 0.04 %.

4. Future Prospect

After success in producing a hyperpolarized ^{3}He gas, we will have a test experiment of the lung imaging with animals, and, then, human beings. Production of heavier nuclei, such as ^{13}C will also be tried. In particular, the hyperpolarized ^{19}F -MRI may give a striking impact on the diagnosis of the circulatory diseases.

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