# BRUTE-FORCE POLARIZED SOLID $^3$HE AND POSSIBLE APPLICATION TO THE PRODUCTION OF POLARIZED GAS FOR MEDICAL IMAGING

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We started the development of a polarized $^3$He solid target for medical use, e.g., the hyperpolarized $^3$He-MRI (Magnetic Resonance Imaging). $^3$He nuclear polarizaton in a solid phase is created by the brute force method which employs a high magnetic field and low temperature. To achieve a high magnetic field, a 17-T superconducting solenoidal coil is used, and to realize an extremely low temperature (~ 10 mK), a $^3$He/$^4$He dilution cryogenic system is used. The Pomeranchuk cooling specific to the behavior of $^3$He is used to further lower the temperature (~ 1 mK). An obtainable $^3$He polarization, $P_{3He}$ in a liquid phase is much less than that expected by the brute force method. $P_{3He}$ would recover the predicted value in a solid phase. Therefore, we are aiming at the polarized solid $^3$He. The created highly polarized solid $^3$He is then gasified through a liquid phase of $^3$He. Since the spin relaxation time at a liquid phase is very short, the gasification should be done as quickly as possible. For this purpose, we suggest a rapid melting method based on a quick cut-off of a thermal flow and decompression of the solid $^3$He.

## 1. Introduction

It is a great tragedy that the eastern part of Japan was attacked by a huge earthquake and subsequent tsunami this March. A lot of people were killed, and many fission products fell out on a broad area as a result of the melt-down of the nuclear reactors caused by the tsunami. We are suffering from the radiation exposure now and possibly even in the future too. As a result, we cannot help being insensitive to the health problem induced by the radiation exposure. Moreover, as discussed in the previous report [1, 2], 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. Under these circumstances, it is of particular importance for us 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. This is one of the motivations of the present project.

Our group in the RCNP, Osaka has been working for long time with the spin physics. A few of the achievements in the instrumental developments are the polarized $^3$He ion sources [3] and the polarized HD (Hydrogen Deuteride) target [4, 5] by means of the brute force method. On the above rich experiences, we decided a few years ago to start developing a program of spin physics applied to the medical use. This decision is also due to the encouragement 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



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remarkably progressive, their practical use for the medical diagnosis is still restricted to the test experiments certainly because of difficulty in producing a large amount of highly polarized gases within a short time. This may be partly due to the fact that the method they use, i.e., the laser optical pumping is insufficient in producing rare gases with a large volume in a short time.

Frossati [7] examined possibility to produce nuclearly polarized $^3$He gas with a large volume even up to a 1000 *l*/day by combination of the brute force method and the Pomeranchuk cooling [8]. His idea owes significantly to the success in producing a highly polarized liquid $^3$He by Castaing *et al.* [9-11]. Encouraged by this achievement, the RCNP group started producing a highly polarized $^3$He gas in order to overcome difficulties associated with the above laser optical pumpings. A somewhat detailed description on our project is given in Sec. 2 of this report.

Ignited further by 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 (Para-hydrogen Induced Polarization) [13, 14], we conceptually extended our project to a more general idea, i.e., the NSI (Nuclear Spin Imaging) since the brute force method which we employ can basically polarize any nuclei irrespectively of nuclear species. This is a striking contrast with the other methods such as the laser optical pumpings, DNP, and PHIP because these methods are effective only for specific nuclei. Now, our project has been revised so that it may include the MRI not only with the hyperpolarized $^3$He, but also $^{13}$C, $^{15}$N, $^{29}$Si, and $^{31}$P, which are important nuclei for study of the biomedical research.

## 2. Brute force method and its application to $^3$He

The brute force method employed in our NSI project is one of the general and attractive methods to polarize nuclei, though the method itself requires a sophisticated technology in attaining an extremely low temperature and high magnetic field. In Figure 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 could be obtained, though the maximum polarizations at a certain temperature differ from each other, depending on the magnitude of the nuclear magnetic moment.

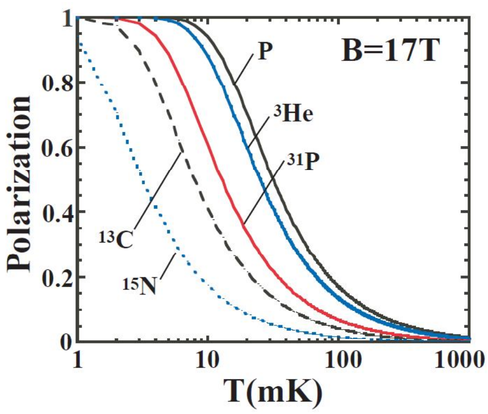


Figure 1. Polarizations attainable by means of the brute force method for some nuclei important in biomedical research.

For $^3$He, we plan to lower the temperature down to 1 mK by using the Pomeranchuk cooling specific to the Fermi liquid like $^3$He, from which we expect a $^3$He polarization exceeding in principle 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 cannot be 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 than 1.5 mK. The solid $^3$He polarization obeys the principle of the brute force method, which results in a large nuclear polarization. The $^3$He solidification is simply done by compressing the liquid $^3$He up to around 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 not so long (1000 ~ 2000 sec.) as shown in Figure 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 should quickly be gasified through a liquid phase because the $T_1$ spin relaxation time in a liquid phase is very short (~ 100 sec. at 1 K) as shown in Figure 3.



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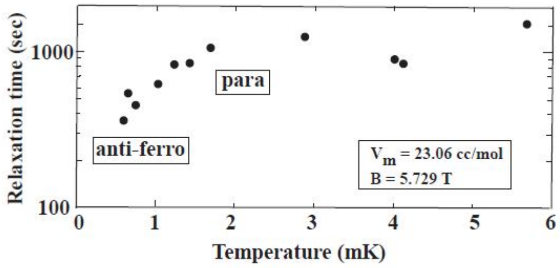


Figure 2. $T_1$ Spin relaxation times plotted as a function of temperature for solid $^3$He (see ref. [15]).

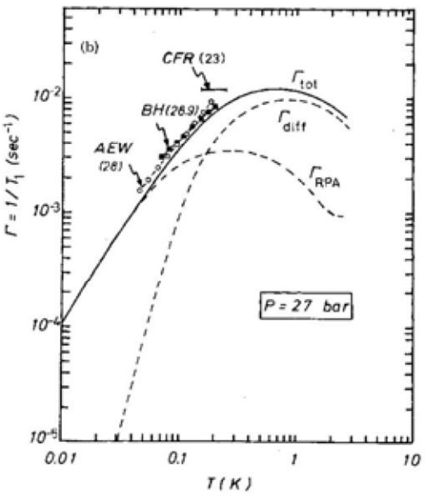


Figure 3. Inverse spin relaxation times plotted as a function of temperature for liquid $^3$He (see ref. [19]. See also ref. [7]).

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

## 3. Experiment

As the first step of our 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 our project was presented elsewhere [1, 16], only the latest progress will be given.

Before the above test experiment with the high power cryogenic system, DRS2500 and the 17$^{th}$ 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 cryofree $^3$He/$^4$He dilution refrigerator, *KOBE*10μ expected to have a refrigeration power of 10 μW at

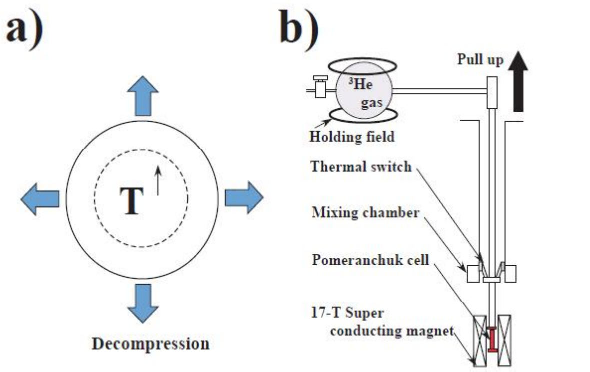


Figure 4. Conceptual view of the rapid melting: a) Temperature increase by decompression of the solid $^3$He since the decompression process, i.e., the reverse process of the Pomeranchuk cooling produces a thermal energy. b) Schematic picture of an equipment for the rapid melting method. Small helical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

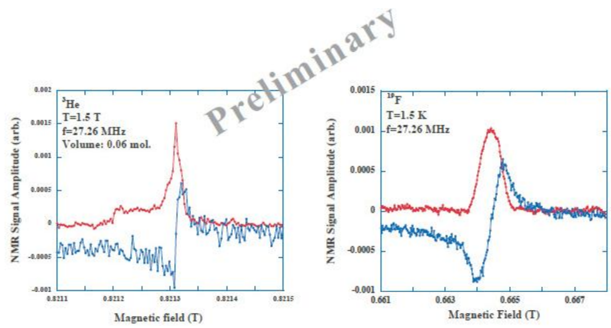


Figure 5. NMR spectra observed for $^3$He (liquid) and $^{19}$F (solid), where the red and blue curves correspond to the imaginary and real parts of the magnetic susceptibility, respectively.

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 modern software system employing a cutting-edge digital technology for the fast ADC and re-writable logic circuits with a high speed computer which has been developed for the HD target project [17, 18]. In Figure 5, the first observation of the NMR spectra is plotted 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 TE (thermal equilibration) is 0.04 %.

## 4. Future Prospect

After a possible success in producing a hyperpolarized $^3$He gas, we will have a test experiment of MRI lung imaging with animals and then with human beings. Meanwhile, production of heavier nuclei, in particular



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$^{13}C$ at first will be tried. With the hyperpolarized $^{13}C$, we will start a basic study on the biomolecular reaction mechanisms of the metabolic compounds like glucose by using the NMR spectrometer for facilitating the future hyperpolarized MRI.

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