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Development of 17T-NMR system for measurement of polarized HD and 3He targets

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Polarized targets for hadron experiment and medical imaging have been developed at RCNP, Osaka University. Concerning the former project, the LEPS group at SPring-8 has studied hadron photo-production experiments of the ϕ, K, η, and π^0 mesons by using the linear polarized Back Scattering Compton (BCS) γ-rays and unpolarized target in the energy range of Eγ=1.5 - 2.9 GeV. An experiment with a complete set of spin observables is, in particular, favorable to investigate the nucleon hidden structure and hadron photo-production dynamics for our future LEPS experiments. This is a major reason why a polarized Hydride Deuterium (HD) target is under development by means of the Brute force method, where a high magnetic field (17 T) and an extremely low temperature (10 mK) are employed. The polarized HD target is produced at RCNP and transported to the LEPS beam-line at SPring-8 by the ground transportation. To simplify and upgrade the quality for measurement, 700 MHz frequency sweep NMR system was developed allowing the measurement at any magnet field and any frequency without a tuning circuit.

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1. HD target project in Osaka

The hadron physics needs the spin observation in order to understand the fundamental structure of elementally particles. Polarized targets for hadron experiments and medical imaging have been developed at RCNP, Osaka University. Concerning the former project, the LEPS group at SPring-8 has studied hadron photo-production experiment of the ϕ, K, η, and π^0 mesons by using the linear polarized Back Scattering Compton (BCS) γ-rays and unpolarized target in the energy range of Eγ=1.5 - 2.9 GeV. An experiment with a complete set of spin observables is, in particular, favorable to investigate the nucleon hidden structure and hadron photo production dynamics for our future LEPS experiments [1] and reaction mechanisms [2, 3]. For this purpose, we have developed a polarized Hydrogen-Deuteride (HD) [4] target for future experiments at SPring-8/LEPS. Polarized Hydride Deuterium (HD) target is under development by the Brute force method, where a high magnetic field ($\sim$17 Tesla) and an extremely low temperature ($\sim$ 10 mK) are employed [5]. The polarized HD target is produced at RCNP and transported to the LEPS beam-line at SPring-8 by the ground transportation. The polarization degree should be checked not only at RCNP, but also during the transportation and at SPring-8. 5 years ago, we constructed a digital processing NMR system with a digitizer and software for NMR measurement enabling a magnetic field sweeping [6]. This system was the innovative NMR measurement instruments in terms of portability and low cost. Recently, we improved the NMR system working with a frequency sweep instead of a magnet field sweep which caused many problems associated with the heat production due to the change of electric current of the superconducting solenoid coil. Another improvement was that this frequency range is extended up to the 1 GHz by introducing digitizer modules commercially available working in the GHz range. The proton NMR measurement becomes possible with frequency of 700 MHz at 17 Tesla. This success is very important in on-line observation of the target polarization growth at 17 T. This instrument enable us to monitor the polarization degree for a period of three month which are needed for production of the produced polarization target. Meanwhile, this new NMR circuit system will also be used for the hyperpolarized ^{3}He project aiming at medical imaging, where the the Brute Force method and Pomeranchuk cooling are employed for production of the hyper-polarized ^{3}He target. This is somewhat in detail described in this workshop by one of our group [7].

In order to achieve high polarizations and long relaxation time of proton and deuteron in the HD target, HD target is kept in the DRS (Dilution refrigerator system) working at low temperature (10 mK) and at high magnetic field (17 T). HD polarization gradually grows up in the spin-flip process between HD molecules and a small amount of ortho-H_2 with spin 1 by spin flip [8, 9]. After a long period of cooling, ortho-H_2 molecules are converted to para-H_2. Since the para-H_2 has a total spin 0, the spin-flip process will stop when all the ortho-H_2 molecules are converted to the para-H_2. If ortho-H_2 does not remain in the HD sample, the relaxation time of hydrogen polarization becomes very long even at a temperature higher than 1 K. The expected polarization exceeds 84% for proton after an aging process for 2-3 months.

The polarized HD system consists of five refrigerators called SC (Storage Cryostat), TC1 (Transfer Crryostat), DRS , TC2 (Transfer Cryostat 2) and IBC. All polarization measurements are performed by using the SC. The flow chart of the target transportation is shown in Fig. 1. The DRS is main refrigerator for polarized HD production and having a cooling power of 2500 μW at 100mK.. The IBC will be operated under the condition with a magnetic field of 1 Tesla and a temperature of 300 mK during the physics experiment for a few months.The three cryostats SC, TC1, TC2 are liquid-^{4}He cryostats used during the transportation of the HD target. At RCNP, pure HD gas with an amount of 1 mole is produced by using the HD gas distillator. The HD gas is solidified in the DRS, and the polarization of the reference HD is measured at 4.2 K. The polarization of the solid HD is grown and frozen by aging at B=17 Tesla and at T=14 mK in the DRS. After polarization is frozen, the target is transferred from the DRS to the SC by using the TC1 and transported to SPring-8/LEPS by a truck. At SPring-8/LEPS, the polarized HD is transferred from the SC to a dilution refrigerator, IBC by using the last ^{4}He refrigerator, TC2.

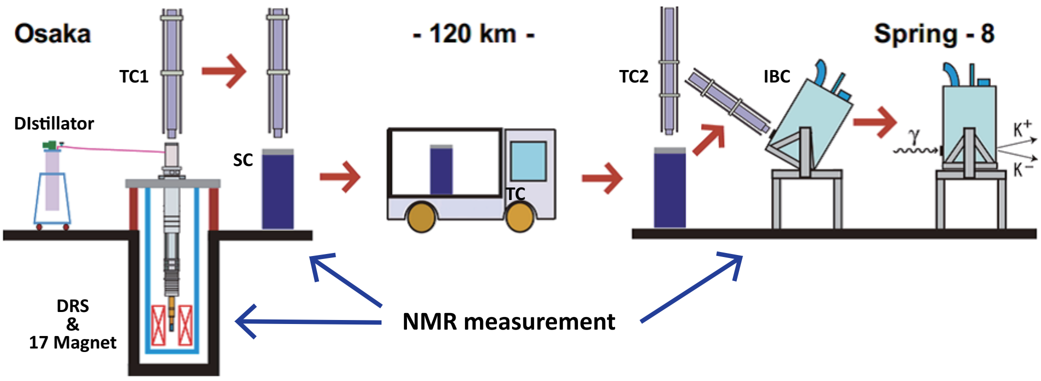

Figure 1: Transportation diagram for Polarized HD target from production to installing IBC

2. 17 Tesla magnet and Dilution refrigerator

The NMR measurement was performed inside DR where the 17 Tesla is produced by the super conducting magnet and DRS. The DRS consists of a liquid nitrogen (LN_2) bath, a liquid helium (LHe) bath, and a dilution circular line. The DRS has a hole in the center. The HD target is put and extracted by this hole and transferred to SPring-8 for hadron experiment. The superconducting magnet cooled by LHe provides the maximum magnetic field of 17.0 T. The homogeneity, $\Delta B/B$, of the magnetic field is 1.0×10^{-4} in the central region over 300 mm long and 30 mm diameter. The HD gas is solidified in a cell made of Kel-F® (PCTFE:Poly-Chloro-Tri-Fluoro-Ethylene), a hydrogen-free material. We can also observe a Fluorine and Chlorine NMR signals. Since The number of mole of Fluorine and Chlorine unchanges, those NMR signals are used as an relative indicator of proton and deuteron in the HD target.

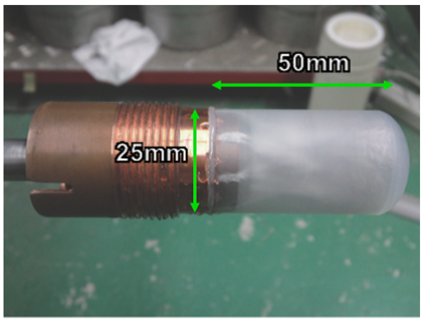

Figure 2: The HD target cell without coil for the LEPS experiments. The geometry of the cell is 2.5 cm in diameter and 5 cm in length. The coil frame is covered this target when NMR measurement is performed.

3. 700 MHz NMR system operated with the frequency sweep

The NMR system constructed this time, consists of an RF signal generator module and an ADC module. These modules are put in slots in a PXI (PCI eXtensions for Instrumentation) chassis and controlled by the software, LabVIEW on the laptop PC with high-speed transmission [10]. This system consists of PXIe-1073 (Chassis), PXIe-5650 (1.3 GHz RF signal generator), and PXI-5162 (10 bit, 2.5 GSample/s Digitizer) which are produced by the National Instruments Company (Fig. 3). The LabVIEW has a role as a controller and calculation for signals. The NMR system has a function as an oscilloscope, a lock-in amplifier and a network analyzer on the software. The network analyzer is used for minimizing the power reflection of the NMR circuit by tuning variable capacitors at off-resonance frequencies. The oscilloscope is used to observe the returning signal from the NMR coil. The lock-in amplifier is used to pick up the small RF amplitude with a frequency equal to the frequency of the input signal, then separates detected signal into the absorption and dispersion signal. Even if a noise level is several thousand times higher than a true tiny NMR signal, a signal with a specific frequency can be detected by using a phase sensitive processing in the software. The noises with frequencies other than the reference frequency are rejected. As a result, we can greatly reduce the noise effect in the NMR measurement. As shown in Fig. 4, we introduced a special circuit to cancel the output signals in the case of the non-resonance. The sinusoidal wave output from the signal generator is divided into two components. One is sent the RF signal to the NMR coil and the other is for a reference signal. When the nuclear magnetic resonance occurs, the HD target absorbs an RF energy from the coil, and the absorption signal is measured with the lock-in amplifier when magnetic field (or frequency) is swept. We apply a cross coil method for the NMR measurements [11, 12]. A Teflon coated silver wire with a diameter of 0.1 mm is wounded to form a saddle coil by 1 turn on the coil support frame which is also made of Kel-F®. The polarization of H in the HD is 0.005% at 4.2 K and 1 Tesla. Fig. 5 shows NMR signals obtained in various magnetic fields by the frequency sweep method. The characteristic feature of this NMR system has no tune circuit to measure with the broaden frequency range. On the other hand, the signal to noise ratio becomes bad. Nevertheless NMR signals were visible from 50 MHz (1.17 Tesla) to 727 MHz. During the polarization growth, the NMR measurements keep working for 3 month and monitor the polarization every day. This result shows us that this monitoring is possible irrespectively of the magnetic field.

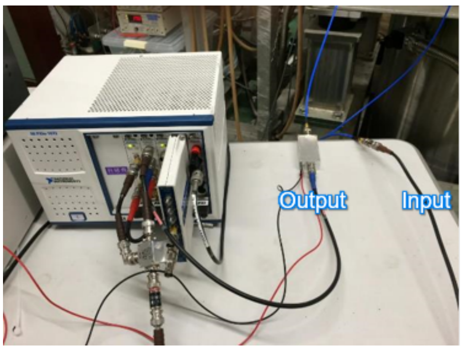

Figure 3: Photo of 17 tesla NMR monitor.

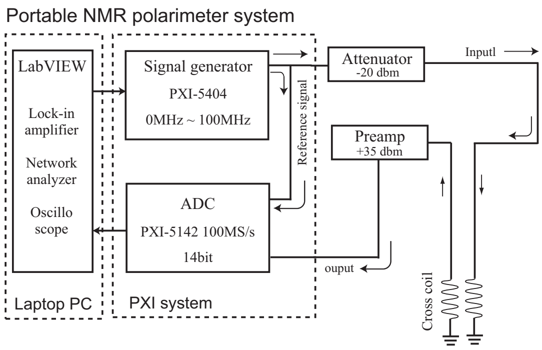

Figure 4: NMR circuit for using 17 tesla NMR monitor

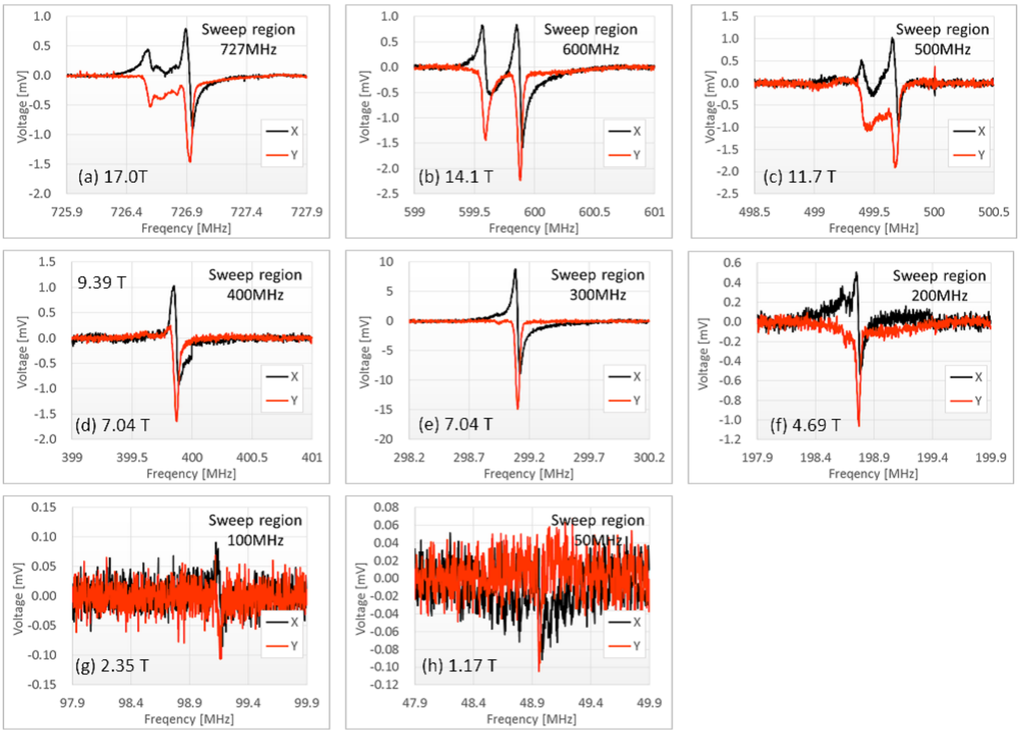

Figure 5: Measured NMR signals by frequency sweep from 50 MHz (1.17 Tesla) to 727 MHz (17.0 Tesla). Red curves are absorption signals, and black curves are dispersion signals.

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