POLARIZED TARGET WITH DILUTION REFRIGERATOR:WHY AND HOW^{**}

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Abstract

Polarized targets using dilution refrigerators have several advantages over targets of He^3 -cryostats for some polarization experiments.

One of the advantages is in the long nuclear spin lattice relaxation time in quite low temperatures. It permits to hold the target polarization in a magnetic field different from the polarizing field.

Another merit is in the fact that we can obtain higher polarization in a dilution refrigerator than in a He^3 cryostat, especially in the case of deuterons.

These facts suggest various applications of the target with a dilution refrigerator, such as a spin frozen target for spin rotation parameter measurements, a target for spin effects in inelastic scatterings, and highly polarized deuteron target and so on.

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Furthermore it will be hopeful to make highly polarized HD target with further improvements of the dilution refrigerator. The possibility of the solid hydrogen polarization is also discussed in this report.

Finally we describe briefly the principle of the dilution refrigerator and the special features of the refrigerator for the polarized target.

§1. Introduction

The polarized-proton target opened the way for the measurement of polarization parameters of high-energy reactions. Particularly the polarized target of organic materials with a He^3 cryostat is currently used for many experiments. These experiments suggest the importance of the further study of the spin dependence of the reactions'. The ordinary polarized target, however, gives several difficulties for some experiments.

One of the problems comes from the restrictions on access angles for incident and scattered particles. The access on the plane, including the polarization direction, is especially limited by the polarizing magnet which produces a homogeneous high field at the target point. It was found that the high polarization of protons can be held in a lower and less homogeneous magnetic field, after polarizing the nuclear spins in a dilution refrigerator, since the relaxation time of the nuclear spin is long in quite low temperatures.

Secondly, the polarization experiment needs higher polarization of the target and lower background from complex nuclei. It is known that a higher polarization can be obtained in a dilution refrigerator than in a He^3 cryostat because of the lower temperature. This fact plays a remarkable role in some cases, especially in the deuteron polarization. The polarization

of the deuterons in organic materials is substantially lower than the proton polarization, owing to the small magnetic moment. It can be increased by lowering the temperature.

Furthermore, the polarized target of solid HD or ammonia is hopeful, if we go to a lower temperature. Such a material is important for future experiments, for example, inclusive reactions, large-angle scatterings, etc. at very high energy, as lower background from complex nuclei is expected in these targets than in existing polarized targets.

For these purposes we have to build a dilution refrigerator specially designed for a polarized target. It should have a large cooling power to overcome the heating with the microwaves at $0.4 \sim 0.2$ K for polarizing the target. The temperature must be reduced quickly from a polarizing temperature to a temperature lower than 0.1 K for holding the polarization.

This report attempts to study some applications of the polarized target with dilution refrigerator to high-energy physics experiments. Then it gives a few comments on the dilution refrigerator which should have special features for a polarized target. The possibility of the polarization of solid hydrogen by the brute force method is also discussed.

§2. Spin-Frozen Target

Polarized proton targets with iron magnets are currently used for polarization experiments, because it is convenient to make a magnetic field of 25 kG with uniformity of 10^{-4} which is necessary for the dynamic polarization of protons in the organic materials. However, it has a restriction on access in the plane including the direction of the polariza-

tion because of the pole pieces, yokes and coils. On the other hand, superconducting coils of a Helmholtz configuration or a solenoid configuration, have large access including the direction of the polarization at the expense of the aperture perpendicular to the direction of the polarization.

It is known that the nuclear spin lattice relaxation time in organic materials depends strongly on the temperature. For example, the relaxation time of protons in ethylene glycol or in propane diol with a few percent of Cr^{V} complex is roughly proportional to T^{-4} , T^{-3} , and $T^{-1.7} \sim -2$ in the temperature regions of $1 \sim 0.3$ K, 0.3 K ~ 0.1 K and $0.1 \sim 0.03$ K respectively, where T is the temperature of the target material. Typically, the spin-lattice relaxation time of protons in ethylene glycol with 7×10^{19} $\text{Cr}^{\text{V}}/\text{ml}$ is about 1 week at 0.1 K in a magnetic field of 10 KG.¹ Actually, it was confirmed that the polarization can be kept unchanged within the accuracy of NMR measurements (relative accuracy of about 2 %) for 4 hours without microwave irradiation in 0.1 K and 10 KG.² This fact suggests a possibility of holding the target polarization in a lower and less homogeneous magnetic field after polarizing nuclear spins dynamically in another uniform magnetic field of 25 kG. The lower and less homogeneous holding field allows large access angles to both the incident and scattered particles. It is expected that a field homogeneity of about 10 % is tolerable to keep the homogeneity of the polarization within 2 % for 8 hours at a temperature of about 80 mK. This type of polarized target is often called the spin-frozen target. It is of a great use in some measurements of spin-dependent parameters in such a case that the conventional polarized target cannot be used because of its geometrical restriction.

We show a few examples of possible applications of the spin-frozen target. In order to measure the spin-rotation parameters, we have to polarize the target protons in the scattering plane. For example, the measurement of the A-parameter of meson-nucleon scattering requires a target polarized parallel to the beam direction. In the measurement of the R-parameter, the target should be polarized perpendicular to the beam direction in the scattering plane. In both cases, we have to have enough aperture for analyzing the polarization of recoil particles.

A Saclay Group measured spin rotation parameters of π^+p elastic scattering at $6 \sim 40$ GeV/c,³ using a polarized target with a Helmholtz superconducting coil (HERA) and a carbon analyzer for recoil particles. There is no experimental data in lower or higher energy regions other than $6 \sim 40$ GeV or higher $|-t|$ than 0.5 (GeV/c)². It was pointed out that the measurement at very high energy is interesting for the investigation of the hadronic structure,⁴ while the lower energy data is desirable for the complete phase shift analysis.⁵ For these experiments the spin-frozen target plays an important role, because it has a large aperture for incident and scattered particles in a holding field.

In a very high energy region an interesting application of the spin-frozen target for the measurement of the spin-rotation parameter was proposed.⁶ After polarizing the target in a small solenoid coil, target spins are held parallel to the beam in a large spectrometer having a field component perpendicular to the recoil proton direction to process the longitudinal spin component into the transverse direction (rotation of 90°), so that a second scattering by a carbon analyzer can be a measure of R and A. In the second scattering, we can measure R and A simultaneously as an azimuthal scattering angle, which has scattering

asymmetry on carbon. This is possible because R and A are related by the equation

$$A^2 + R^2 \sim 1,$$

if P-parameter is very small in very high energy. The attainable experimental error in R of this measurement can be reduced to about 1/4 of the classical method.

The measurements of spin-rotation parameters of the reactions

$$\pi^- p \rightarrow K^0 \Lambda, \quad K^- p \rightarrow \pi^0 \Lambda, \quad \pi^+ p \rightarrow K^+ \Sigma^+, \quad K^- p \rightarrow \pi^- \Sigma^+,$$

give complete data for model-independent-amplitude analysis of each reaction, because the reactions have a pure isospin state. In these measurements it is not necessary to make double scatterings, if the target is polarized in the scattering plane. Since the polarization of recoil particles can be determined by decay asymmetry of Λ and Σ^+ .

In these measurements, we have to detect 3 or 4 particles which are going almost to 4π angles. The amplitude measurement of the reaction $\pi^- p \rightarrow K^0 \Lambda$ was performed at 6 GeV by a spin frozen target in the ETH magnet (so-called small Ω) at CERN.^{7,8} Similar measurements are being planned at KEK and Rutherford Laboratory with spin-frozen targets.⁸

Several spin-dependent parameters of p-p scattering were measured with a polarized proton beam and a polarized proton target at Argonne, and significant and exciting physics results were discovered.⁹⁻¹³ They suggest the importance of further measurements of spin parameters of the reaction. The analysis of the p-p amplitude requires a complete set of

the measurements including double- and triple-spin parameters with a target polarized in the scattering plane, although some of them have been made using a Helmholtz-type superconducting magnet (so-called R and A magnet). The spin-frozen target is well-suited for these measurements, because it has enough access angle in the plane including the target spin direction. A spin-frozen target for the measurement of spin rotation parameters of the following configuration was proposed at KEK (Fig.1).⁸ The proton in organic materials is polarized in a solenoid coil of 25 kG with the homogeneity of 1×10^{-4} at the temperature of about 0.3 K in a horizontal dilution refrigerator. Then the solenoid coil is moved horizontally about 30 cm to take the target material out of the coil. A combination of the fringing field of the polarizing solenoid coil and the field of a small auxiliary coil can be used for holding the polarization. At this point, the target is kept in 80 mK and 10 kG. We can put the target in a place where there is enough access for beam and scattered particles, by adjusting the relative current of two coils in order to get enough homogeneous field for holding the polarization. It is possible to cover almost all of the angle with combinations of relative geometry and currents, because the geometry of the 2 coils is asymmetric. For the measurement of R-parameters, the beam will be put perpendicular to the axis of the solenoid coil. For the measurement of the A-parameters, the beam is put on the axis of the coil. The measurement of P-parameters can be performed using a holding magnet with large access perpendicular to the direction of the spin. The length of the polarizing solenoid coil should be as short as possible in order to take the target out of the coil easily.

The measurement of the P-parameter of inelastic scatterings with 3 or more final particles also has difficulties of aperture of the polarized target magnet. Since scattered particles go to the direction far from a plane perpendicular to the direction of the target spin, even though the scattering plane is perpendicular to the spin direction. The first spin-frozen target was built in order to solve such a problem in a measurement of the P-parameter of $\pi^- p \rightarrow \pi^0 n$ reaction at Rutherford Laboratory using a He^3 cryostat.^{14, 15} Another one is a large aperture spectrometer at KEK. It is a smaller version of the multi-particle spectrometer for low momentum particles having a spin-frozen target. The target is polarized in a narrow gap of pole pieces which is placed at a corner of the spectrometer magnet. Then, it is moved horizontally to be used in a beam at the center of the spectrometer magnet where the high polarization can be held at the temperature lower than 80 mK and about 10 kG⁸ (Fig.2). At that point, it is surrounded by scintillation counters, multi-wire proportional chambers and drift chambers. As the first experiment with it, polarization measurements of $K^+ n$ elastic and charge exchanged scattering will be performed in the energy region of 1 ~ 2 GeV, using a deuteron polarized target. The measurement is important not only for discrimination of solutions of the phase shift analysis, some of which exhibit resonance-like behavior, but also for the test of several theoretical models of the strong interaction. This spectrometer will be used for measurements on the polarization of $\pi^+ N$, $K^+ N$, pp, pn and $\bar{p}p$ reactions in the future.

53. High Polarization in the Dilution Refrigerator

An advantageous feature of the polarized target with a dilution refrigerator is in higher polarization than that with a He^3 refrigerator. This is not very helpful for the conventional polarized-proton targets, because protons in organic materials can be polarized about 80 ~ 90 % at 0.45 K and 25 kG in a He^3 cryostat. However, it is known that even in a lower magnetic field we can get high polarization in a lower temperature. A magnetic field lower than 25 kG is favorable for some experiments in order to minimize the spin precession as well as bending of the particles in the field of the polarizing magnet, especially for lower-momentum particles. In addition, lower magnetic field is rather profitable for large aperture and high field homogeneity. Such a polarized target can be realized in a magnetic field of 12.5 kG with microwave of 35 GHz using a dilution refrigerator, in which protons are expected to be polarized almost the same as in 25 kG and 0.5 K.

The dilution refrigerator plays a remarkable role for the polarization of deuterons. The polarized deuteron target is useful as a polarized-neutron target. Measurements of polarization parameters with the polarized-neutron target, for example K^+n and pn reactions, are very important for the investigation of hadron interaction.

We will recall some properties of the deuteron spin polarization. The polarization of the deuteron (Spin = 1) is defined as follows:

$$P_D = \frac{N_+ - N_-}{N_+ + N_0 + N_-}$$

where N_+ , N_0 and N_- are the numbers of the nucleus on the magnetic substates of $m = +1, 0, -1$ respectively. As shown in Fig.3 three magnetic

substates are shifted with the quadrupole interaction. Two transitions between three states overlap each other in the case of deuterated organic material, and the actual deuteron magnetic resonance (DMR) line (16.34 MHz in 25 kG) is a superposition of them which is also shown in Fig.3.

Deuterons in the deuterated organic materials can be polarized dynamically with the same method as protons, that is, with the microwave of 70 GHz in a 25 kG magnetic field. The polarization of deuterons is substantially smaller than the polarization of protons. The relation of the polarization of protons and of deuterons is consistent with a model in which it is assumed that the nuclear spins share a common spin temperature. The nuclear polarization corresponding to this model is given¹⁶ by

$$p_H = \tanh (\hbar \nu_H / 2kT_S)$$

$$p_D = 4 \tanh (\hbar \nu_D / 2kT_S) [3 + \tanh^2 (\hbar \nu_D / 2kT_S)]^{-1}$$

where P_H and P_D are proton and deuteron polarization, ν_H and ν_D are proton and deuteron Larmor frequencies, respectively and T_S is a common nuclear spin temperature. For example, deuteron polarizations of 26 % and 40 % correspond to proton polarizations of 85 % and 96 % respectively. It was shown that the obtainable polarization of deuterons in deuterated ethylene-glycol is about 40 % or higher in the dilution refrigerator, whereas 26 % in the He^3 cryostat. The difference of the polarization gives significant effect on the experiment, because the figure of merit of polarization experiments is proportional to the square of the polarization of the target.

The polarized deuteron targets with dilution refrigerators were constructed for experiments of K^+n scattering at CERN and at KEK.⁸

§4. Toward the HD Target

The measurement of the spin dependent parameters at very high energy is important for the investigation of the hadronic interaction. It is not easy to distinguish between events from hydrogen and complex nuclei in some cases at very high energy. Therefore, it is desirable to polarize all the nucleons in the target material as high as possible.

Investigations of solid HD directed toward polarized proton and deuteron targets have been carried out by several authors.

Dynamic polarization of protons and deuterons in radiation-damaged solid HD with a small oxygen impurity was investigated by G. Rebka and J. Solem. They obtained a proton polarization of 3.7 % at 1.2 K and 12.7 kG,¹⁷ and a deuteron polarization of 0.5 % at 1.2 K and 8.53 kG.¹⁸ If we extrapolate the results to lower temperature and higher magnetic field, we expect to obtain 30 % ~ 50 % polarization of protons and about 10 % of the polarization of deuterons. The nuclear spin lattice relaxation time is too short immediately after irradiation because of the ortho-hydrogens which are produced during irradiation. Therefore, we have to wait a few weeks for the decrease of the ortho-hydrogen due to the ortho-para conversion and resulting long relaxation time.

On the other hand, A. Honig proposed solid HD,¹⁹ in which the spins of proton and/or deuteron are kept polarized at ordinary liquid He⁴ temperature after polarizing by the brute-force method at quite a low temperature and a high magnetic field. The relaxation time of proton spins depends strongly on the ortho-H₂ concentration in HD through the

temperature range of $0.02 \sim 4$ K, whereas the ortho-para conversion rate of hydrogen molecules is independent of the temperature. The relaxation time of a sample whose initial concentration of ortho- H_2 is 1.5×10^{-4} is approximately 1 day at 25 mK and 100 kG. In such a condition the proton spin polarization builds up from an initial value toward the equilibrium value, $P_0 = \tanh \frac{\mu_H}{2kT}$ or 0.38 at 100 kG and 25 mK. They obtained 32 % polarization after 6 days. Due to the ortho-para conversion, the concentration of the ortho- H_2 decreases continually and the relaxation time of the proton increases with time. An additional wait of 6 days at 25 mK and 100 kG is sufficient for a relaxation time of 1 day at 1 K and 3 kG. They expect a possibility of polarizing protons about $60 \sim 70$ % at 150 kG and 16 mK, if the dilution refrigerator has enough cooling power to overcome the heat of the ortho-para conversion, and the thermal resistance is not too large. The deuteron polarization is very small because of its smaller magnetic moment and a longer relaxation time. They proposed to polarize deuterons dynamically via their dipolar coupling with the highly-polarized proton on the analogy of the dynamic polarization of protons via coupling to polarized electrons.

In spite of several difficulties, the polarization of the HD target is desired for very high-energy polarization experiments. It will be hopeful to have a highly polarized HD target in the future with new ideas and improvements of cryogenic technology, especially with the development of the high cooling power dilution refrigerator.

§5. Possibility of Solid Hydrogen Polarization

In this section we discuss the possibility of the polarization of solid hydrogen by the brute force method in the dilution refrigerator.

The ground state of H_2 remains unpolarized, because it has $J = 0$ (para hydrogen), whereas the spin state with $J = 1$ (ortho hydrogen) converts to the $J = 0$ state, generating heat of conversion. Ortho-para conversion rate is

$$\frac{dC}{dt} = -kC^2$$

where C is the concentration of ortho-hydrogen and k is $1.8 \times 10^{-2} \text{ (hour)}^{-1}$. The heat of ortho-para conversion is 1430 joule/mol (ortho). Therefore, the necessary cooling power to overcome the heat of conversion is $7.2 \text{ C}^2 \text{ mW/mol}$. For example, the heat of conversion of 2 gr of hydrogen with 50 % ortho concentration is about 1.8 mW. This value is almost the limit of the cooling power of existing dilution refrigerators at 0.11 K .

The polarization of proton in ortho-hydrogen is

$$P_{\text{ortho}} = \frac{3}{2} \coth \left(\frac{3}{2} \frac{2\mu_p H}{kT} \right) - \frac{1}{2} \coth \left(\frac{1}{2} \frac{2\mu_p H}{kT} \right).$$

where μ_p is the magnetic moment of the proton, T is the temperature and H is the magnetic field. The temperature of 0.11 K and the magnetic field of 150 kG correspond to the polarization of 20 % of the ortho hydrogen. Therefore, obtainable average polarization of protons is about 10 % for 2 gr of the solid hydrogen with 50 % ortho concentration, taking into account of the maximum cooling power of the existing dilution refrigerator.

The mass of the solid hydrogen will be able to be enlarged by a few times, if the cooling power of the dilution refrigerator will be improved.

However it is not so easy to obtain higher polarization than 30 % because of the difficulty of cooling the solid hydrogen, overcoming the Kapitza resistance even with a very high cooling power dilution refrigerator.

The polarization of protons can be kept for 1 or 2 days in almost the same value. The decrease of the concentration of ortho-hydrogen is compensated by the increase of the polarization of ortho-hydrogen, due to lower temperature which can be achieved by less ortho-para conversion heating.

The relaxation time of ortho-hydrogen was measured at 22 MHz²⁰. The relaxation time for ortho content of 50 % decreases with decreasing temperature down to about 0.5 K (about 0.01 sec at 0.5 K) and then it shows an anomalous increase by a factor of 10^2 , that is, about 2 sec at 0.3 K and 7 sec at 0.25 K.

§6. Dilution Refrigerator for the Polarized Target

The principle of the dilution refrigerator is based on the phase separation of solutions of He^3 and He^4 below the critical temperature; the upper phase is richer than the lower phase in He^3 (Fig.4). The lower part (dilute phase) is superfluid and He^4 plays no significant thermodynamical or hydrodynamical role at a very low temperature. Therefore, He^3 of the dilute component in the lower part behaves like an ideal gas. When He^3 dilutes from the He^3 rich phase to the dilute phase, it has a cooling power of

$$\dot{Q} \approx \dot{n} (95 T^2 - 12 T_i^2)$$

where $\dot{n}$ is the flow rate of He^3 into the dilute phase in moles/sec, $\dot{Q}$ is in watts and T is the temperature (K) of a mixing chamber in which the

phase separation occurs. T_i is the temperature (K) of the incoming concentrated stream to the mixing chamber. He^3 in the dilute phase is lead to a still through heat exchangers in which the incoming concentrated stream is cooled down by the outgoing dilute solution. He^3 is pumped out from the still at a high rate at a temperature of $0.6 \sim 0.9$ K, whereas the pumping rate of He^4 is rather low because of lower vapor pressure of He^4 . The principle is shown schematically in Fig.5.

Dilution refrigerators for polarized targets should be of the following special features which are somehow different from ordinary refrigerators for solid state physics.²¹

- i) It has a large cooling power to overcome heating with microwave and incident beam. The microwave power absorbed in the mixing chamber is estimated to be about $0.5 \text{ mW} \sim 2 \text{ mW}$ to polarize 1 gr of ethylene glycol at $0.25 \sim 0.4$ K.
- ii) It is operated continuously for a long time. The polarized target must be kept unchanged for a few weeks.
- iii) The temperature of the mixing chamber must be reduced quickly from the "polarizing temperature" ($0.4 \text{ K} \sim 0.2 \text{ K}$) to the "holding temperature" (lower than 0.1 K), in the spin-frozen mode of operation.
- iv) A mixing chamber has a demountable construction in order to fill the target material easily. The material currently in use is frozen beads which are handled at liquid nitrogen temperature.
- v) In most cases experimental geometry requires a horizontal-type refrigerator which can be moved in a horizontal plane.

We are going to give a few comments on the dilution refrigerator designed for polarized targets.

Precooler and He³ Pumping

Incoming gas is first precooled and liquified in a precooler attached to a He⁴ pot. It is desirable to cool down incoming gas to about 1 K ~ 2 K in a continuous flow liquid He⁴ system. The pressure of the He³ has to be kept sufficiently high for condensation by means of a flow impedance control. This type of precooler is similar to the He³ refrigerators commonly used for polarized targets. Therefore, a He³ refrigerator can be used as a precooler of a dilution refrigerator with a small modification.

One of the differences between a He³ refrigerator and a dilution refrigerator is in the flow rate. Dilution refrigerators have to have a higher flow rate than a He³ refrigerator, if the same cooling power is required at a temperature higher than 0.4 K as shown in Fig.6. Therefore, larger surface between incoming gas and liquid He⁴ is necessary to liquify He³ completely in the precooler.

A pumping system for a He³ cryostat such as Roots pumps or an ejector pump backed with a rotary pump can be used for pumping of He³ concentrated gas from a dilution refrigerator.

Still

Vapor of the He³ and the He⁴ are pumped out from the still, while incoming concentrated liquid is cooled down to the still temperature through a still heat exchanger. If an orifice is installed suitable for reducing the He⁴ film flow, the concentration of the He³ in outgoing gas is over 90 %, because the vapor pressure of the He⁴ is much smaller than that of the He³ at the still temperature. For minimizing the He⁴ concentration in the circulating gas, it is necessary to keep the still surface clean, especially the orifice, and to use high-conductivity

copper. If the He^4 concentration in the circulated gas is too high, phase separation occurs in a heat exchanger. It becomes the cause of instability of the temperature and heating of a mixing chamber.

A large boiling surface is necessary in a still in order to get a high flow rate.

Heat Exchanger

Incoming concentrated liquid is cooled down by an outgoing dilute stream through heat exchangers after passing through the precooler and the still. It is the most important part in the design of a dilution refrigerator. Many different types of heat exchangers have been constructed.

Heat exchangers of a dilution refrigerator for a polarized target must have the following features.

- i) The flow impedance is low in order to have a high circulation rate.
- ii) The heat capacity of the heat exchangers and the amounts of He^3 and He^4 are small, allowing a short cooling time.
- iii) It has a structure of horizontal flow, if the refrigerator is a horizontal type.

One of the examples of such heat exchangers can be seen in a dilution refrigerator at KEK.²¹ The higher temperature part is a continuous heat exchanger which consists of a 5 m long stainless steel double tubes. The concentrated stream goes into the inner tube and the dilute stream flows in the space between two tubes. The low temperature part consists of two coaxial double-tube heat exchangers filled with sintered copper powder (Fig.7). The inner tube is made of oxygen-free copper with an inside diameter of 4 mm. The inside of the tube is half-filled with

sintered copper of $40\text{ }\mu\text{m}$ powder and the outside of the tube is surrounded by a 0.4 mm thick layer of sintered copper of the same powder. The outer tube is stainless steel with a 6.5 mm inside diameter. The length is about 75 mm. Two pieces of such a heat exchanger are connected in series at the end of the long coaxial double tube heat exchanger.

T. Niinikoski made a special long heat exchanger with sintered copper and got high cooling power at CERN^{1,22}

Mixing Chamber

The mixing chamber must be demountable in order to fill the target material in it easily. The heat leak through the microwave guide and the coaxial cable for the NMR has to be minimized. Teflon mixing chambers were realized at CERN and at KEK for this purpose. They allow microwave exposure from the outside. The chamber at KEK is joined with a brass flange fitted with an indium gasket. The teflon part is simply demountable from the flange²¹. The mixing chamber and the heat exchangers are surrounded by a vacuum jacket. The temperature of the vacuum jacket is close to the still temperature. The 4 mm waveguide ends near the mixing chamber in the vacuum jacket to feed the microwave power to the target material.

Cooling Power

The cooling power and the lowest obtainable temperature of the refrigerator are strongly dependent on the structure of the heat exchanger, the still and the precooler and also on the pumping speed. For example, in the KEK refrigerator with an only 5 m continuous heat exchanger the lowest temperature without heat load is about 62 mK and the cooling power at 300 mK is about 1.6 mW. If the two pieces of the coaxial-

sintered copper heat exchanger are added, the lowest temperature decreases to 26 mK and the cooling powers at 50 mK and 300 mK are about 50 μ W and 2.2 mW respectively.

The cooling power of the refrigerator of Niinikoski¹ is 200 μ W and 10 mW at 50 mK and 200 mK, respectively. The lowest temperature is about 15 mK.

Another horizontal dilution refrigerator with a very long coaxial sintered copper heat exchanger is nearly at completion at KEK for a spin-frozen deuteron target.

57. Concluding Remarks

We tried to communicate some of the importance of the polarized target with a dilution refrigerator. Improvement in the target makes several new measurements of spin-dependent parameters possible, because experiments are sometimes limited by the target technology. One of the important technological aspects of the recent polarized targets is in the dilution refrigerator. It made possible the construction of the spin-frozen target and the highly-polarized deuteron target. If we are able to construct a dilution refrigerator at a cooling power ten times larger than the existing one, it will be possible to polarize not only HD, but also pure solid hydrogen by the brute-force method, overcoming the heat owing to the ortho-para conversion.

Furthermore, it is expected that the technologies of polarized targets developed for high energy physics will be applied to other fields of physics. For example, a polarized proton filter to obtain a polarized slow neutron beam is a quite hopeful application of polarized target technology for neutron diffraction experiments. The idea came from the fact that the cross section of n-p scattering through the

singlet state is much larger than the cross section for scattering through the triplet state. A filter was constructed and successfully operated to get enough polarization of the neutron beam recently at KEK and JAERI in Japan.²³ It suggests the possibilities of wide application of the polarized target for physics with new advanced technologies.

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Figure Captions

- 1) Schematic view of a proposed spin-frozen target for the measurement of spin rotation parameters at KEK. After polarizing target material

in a dilution refrigerator at the center of a solenoid coil of 25 kG, the coil is moved horizontally to take target material out of the coil.

- 2) A spin frozen target in a large aperture spectrometer at KEK. The target is polarized in a narrow gap of pole pieces which is placed at a corner of the spectrometer magnet and then it is moved horizontally to be used in a beam at the center of the spectrometer magnet.
- 3) Magnetic substates of the deuteron nuclei and the deuteron magnetic resonance line in deuterated ethylene glycol.
- 4) Phase separation diagram of mixture of He^3 and He^4 . X is the He^3 concentration. Tricritical point is at 0.86 K.
- 5) Schematic diagram showing the principle of the dilution refrigerator.
- 6) Typical cooling power of a He^3 cryostat and a dilution refrigerator as a function of temperature. It is assumed that the pumping speed is 80 l/sec.
- 7) A coaxial double tube heat exchanger filled with sintered copper powder made in KEK. Inside of the inner tube is half filled with sintered copper and the outside of the tube is surrounded by a 0.4 mm thick layer of the same powder. The concentrated stream gas goes into the inner tube and the dilute stream flows in the space between two tubes.

Fig. 1

Fig . 2

$$\delta = \frac{1}{8} \cdot eQ \cdot \frac{\partial^2 V}{\partial s^2}$$

$$\frac{\partial^2 V}{\partial s^2} = \text{field gradient}$$

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7