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A 1.5 - 4 Kelvin Detachable Cold-Sample Transfer System:
Application to Inertially Confined Fusion with Spin-Polarized
Hydrogens Fuels

N. Alexander, J. Barden, Q. Fan and A. Honig,
Department of Physics, Syracuse University, Syracuse, NY 13244.

ABSTRACT

A compact cold-transfer apparatus for engaging and retrieving samples at liquid helium temperatures (1.5 - 4K), maintaining the samples at such temperatures for periods of hours, and subsequently inserting them in diverse apparatuses followed by disengagement, is described. The properties of several thermal radiation-insulating shrouds, necessary for very low sample temperatures, are presented. The immediate intended application is transportable target-shells containing highly spin-polarized deuterons in solid HD or D₂ for inertially confined fusion (ICF) experiments. The system is also valuable for unpolarized high-density fusion fuels, as well as for other applications which are discussed.

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INTRODUCTION

An apparatus for convenient transfer of cold (4K) samples from one system to another (entry-retrieval), followed by disengagement, is indispensable for some applications and desirable for many others. By freezing condensable gases such as 'hydrogens' in a separate apparatus instead of in situ for a given experiment, the reduction in complexity allows greater freedom in carrying out and monitoring the solidification process, for example the production of single crystals. In certain situations, a condensable gas of very high density is sought, but high pressures are inconsistent with other constraints. This is the case for hydrogens filled target shells for inertially confined fusion (ICF) experiments, where desirable low atomic density (for instance, polystyrene) fuel-containing shells are mechanically quite weak¹. One solution is to diffuse gas into the shells under conditions of low pressure differentials, and subsequently condense the material, maintaining low pressure differentials throughout the cooling process². This is easier to carry out in an apparatus separate from the fusion chamber, following which the frozen encapsulated material can be transferred to the fusion chamber³. This procedure also permits separate control and characterization of the formation of the solid target, very important for optimizing ICF fusion reaction yields. In another class of applications, irradiation of a solid can produce defects whose properties are to be investigated in various instruments, such as infra-red (IR), electron paramagnetic resonance (EPR) or nuclear magnetic

resonance (NMR) spectrometers. These defects are stable against recombination only at low temperatures, frequently in the liquid helium range, where the defect diffusion rates are low. The apparatus we describe here permits transfer of the cold, irradiated sample, with the defect system intact, to the desired analytical instrument. Another example in this same category, namely where a sample is prepared in a state which survives only at very low temperatures and is later utilized in another apparatus, is that of condensed hydrogens with highly spin-polarized nuclei^{3,4}. The utilization can be as a polarized target for external or internal⁵ particle beams, or as fusion reactants. The resultant highly spin-polarized state can survive for a (generally) required time of the order of hours only in the temperature regime near or below 4K, where the nuclear spin-lattice relaxation time can be very long. In this example, it is virtually essential for the elaborate polarization-preparation apparatus (in our case, a ^3He - ^4He dilution refrigerator with a high-field superconducting magnet) to be unencumbered by other equipment. In fact, our principal impetus for designing and developing the cold entry-retrieval apparatus described in this paper was the desire to investigate ICF fusion reactions with highly spin-polarized D in HD and D_2 , and eventually with highly spin-polarized D and T in DT or $\text{D}_2 + \text{T}_2$, for which the considerable advantages of polarized fuels have been discussed in the literature over recent years⁶⁻⁹. The production of highly spin-polarized D in HD has already been accomplished in our laboratory at mK temperatures and fields up to 13 Tesla¹⁰, with

the polarization metastably maintained at higher temperatures (4K) for several hours by utilizing the very long spin-lattice relaxation times^{4,11-13}. Upon bringing these polarized samples out of the polarization-production apparatus into the fusion chamber, they must not be subjected to any appreciable temperature rise above 4K, since generally the spin-lattice relaxation time decreases drastically with increasing temperature or change of phase¹²⁻¹⁴. With a version of the cold-transfer system described here adapted to the dilution refrigerator, we intend to implement a two stage cold-transfer procedure to study ICF with polarized D in the OMEGA fusion chamber of the Laboratory of Laser energetics (LLE) at the University of Rochester. The first stage is cold transfer from the dilution refrigerator to a storage-transport dewar operating between 1 and 4K and equipped with an 8T superconducting magnet to increase the polarization retention time of the spin-polarized state, and the second stage is cold-transfer from the storage-transport dewar to the OMEGA chamber, with the sample always in a modest magnetic field of at least a few hundred gauss, provided by small permanent magnets in the cold-transfer tubes and by an installed magnet in the OMEGA chamber. With this combined procedure, one solves not only the polarization retention but also the achievement of dense targets in the fragile polymer target cells^{2,15}. In the case of unpolarized high-density hydrogens condensed targets, the high density condensed sample can be formed directly in the storage-transport dewar, and only a single entry-retrieval operation is required. This is usually true for

other experimental usages referred to earlier, such as retention of irradiation-induced defects.

We turn now to the essentials of a typical entry-retrieval tube, with the necessary features for removing and reinserting a 4K sample into a storage dewar. The particular prototype we describe here is indeed the apparatus which mates to the OMEGA fusion chamber, but the detailed description of that interface is deferred to a future report. We present performance data on various radiation-insulating shrouds, and describe an insertion-disengagement-retrieval process, using a sample-slug containing a thermometric resistor, in order to point out some of the elements associated with engagement-disengagement and to monitor the temperature to be expected with real samples, which will be discussed in the last section of this paper. We include in that discussion section additional features which are utilized in special apparatuses such as the dilution refrigerator or a fusion target chamber.

THE APPARATUS

The cold entry-retrieval system is a compact set of vacuum-separated stainless-steel coaxial tubes which contain liquid nitrogen (N_2) and liquid helium. These are movable with respect to each other with both translatory and rotary degrees of freedom. The translatory motion allows cocooning the sample within, and separating the sample from (in its destination environment) a thermal-radiation-shielding shroud. The rotation motion allows removing and implanting the sample in any device

with a commonly employed left-hand, right-hand screw coupling and decoupling mechanism. Either the translational or rotational freedom permits carrying out other mechanically-actuatable operations, such as engaging a heat switch which can thermally connect the liquid helium reservoir to the shroud, so that the latter in its inserted position in a high vacuum, cold destination apparatus can be brought to temperatures much lower than its usual 77K value when operating as a separate unit. Fig. 1a depicts the assembled system, and Figs. 1b and 1c illustrate the basic construction of the liquid helium and the liquid nitrogen tube sets, respectively. The total length of this unit is 2.5 meters, and the diameter of the lower section is 19.0 mm. Thermal conduction isolation of the liquid helium tube from the inside tube of the liquid nitrogen dewar is maintained by carefully constructed nylon "stars" with sharp touch points. Similar nylon stars are used between the tubes maintaining the vacuum in the liquid N₂ dewar. A bellows protects the nitrogen dewar from the stresses of differential contraction. Both interior and exterior (shown in Fig. 1c) bellows have been used. The latter is preferable because the liquid nitrogen containing space is then more easily sealed, permitting lowering the temperature of the nitrogen bath and even freezing the nitrogen by pumping on it, a useful and sometimes necessary provision as will be seen. A separate vacuum region with its own pumping port prevents freezing of the sliding o-rings, which are located near the upper part of the helium dewar and which effect the vacuum seal between the helium and nitrogen dewars while permitting the

translatory and rotary motion. To the bottom of the liquid N₂ dewar is welded a threaded cap, enabling attachment of a thermal-radiation-shielding shroud, which is maintained near liquid N₂ temperatures by conduction. A "lock" tube bottomed with a gate valve, as seen in Fig 1d, seals the entire system as a separate entity when the gate valve is closed, and allows sliding entry of the entire dewar set into a high vacuum system when the gate valve is opened. The sliding lock tube is sufficiently long (25 cm) so that the corresponding length of the outermost stainless steel tube provides enough thermal insulation from the liquid N₂ temperature (or colder) shroud connection point to prevent freezing of the o-rings. The liquid helium tube is sealed at the bottom with an Indium o-ring to a cold finger, which is provided with hermetically sealed feed-throughs permitting electrical connections from the sample region to the top of the liquid helium tube. The sample itself is conductively attached to the liquid helium temperature cold-finger via a left-hand screw. When screwed into its right-hand threaded destination system, continued clockwise turning after it is fully seated results in detachment from the sample. Reversing the procedure engages and detaches the sample from its destination holder. Fig. 2 illustrates one version of the shroud, in this case a structure which accommodates a sapphire cylinder and a spring-loaded relatively light-tight diaphragm-like shutter. We discuss the shroud design and performance in detail in the following sections. A schematic of a normally closed, inward-opening spring-loaded shutter, designed and built here, is shown in Fig.

3. Shutters of similar basic design, having three stable positions (outward-opening, closed, and inward-opening) without spring-loading, are also used, in particular for the OMEGA fusion chamber mating. The outward-opening position is used when fetching a cold sample, after which the shutter is closed by a mechanically actuated variable-aperture diaphragm operating in the cold environment. The inward-opening position is then used for insertion into the apparatus of interest, for example the OMEGA chamber. In that case, since no further retrieval is required, restoration of the shutter to the closed position is unnecessary.

SHROUDS

The essential function of a liquid-N₂ cooled shroud surrounding the sample is to shield the sample from the radiation flux associated with room temperature background radiation, so that the required low temperature of the sample can be maintained. Even the radiation emitted from the liquid N₂ temperature environment may be too large if the thermal link of the sample to the liquid helium temperature point is very weak. This issue will be addressed below. An all-metal shroud keeps out the 300K background radiation, and remains at a temperature near 77K because its thermal conductance to the liquid N₂ bath is sufficient to carry away the heat it absorbs from the background radiation. However, variants of an all-metal shroud are necessary for certain applications, such as the OMEGA fusion chamber, where accurate target positioning demands a partially transparent

shroud. The trick is to provide transparency near the visible blue wavelengths where the 300K background radiation is negligible, but to insure high opacity at the longer infrared wavelengths where most of the background radiation energy is concentrated. The opacity can be from high reflectance or absorption; the latter, however, results in heating which can intolerably raise the temperature of the shroud if the thermal conductance of the shroud is not high enough. Taking into account these principles, the solution we have chosen leads to the shroud design referred to earlier, depicted in Fig. 2. The principal component is the single crystal sapphire cylinder, which has a high thermal conductance in the liquid N₂ temperature region and below¹⁶ and strong absorption of radiation of wavelength greater than about 6.5 μm ¹⁷. The main problem is that it becomes increasingly transparent at wavelengths below 6.5 μm , in which region there is still a substantial amount of energy in the 300K black-body radiation spectrum. This is solved by gold plating the sapphire. In the experiments reported here, the thickness of the gold plating is 27 nm. (20 nm is almost equally effective with respect to reflectivity, but provides better transparency in the blue visible region, and thus is our preference for the fusion experiments). Such plating confers a reflectance of near 98% at all significant IR wavelengths associated with 300K (and below) blackbody radiation, but the reflectance falls off rapidly in the visible blue region near 480 nm. Thus, we effectively have transparency under blue illumination, which can be of very weak intensity since cameras of high sensitivity are available, but

opacity with respect to almost all background radiation. The other elements of the shroud shown in Fig. 2 consist of a metal top section, to connect to the liquid N_2 reservoir, and a metal bottom section, to which the shutter is attached. Copper strips hold the sapphire while allowing ample "window" space through it, and also serve as mechanical supports, additional thermal conduction links, and protection for the gold coating on the sapphire while the tubes are moved. We have also tested similarly gold-coated pyrex in place of the sapphire. Because of the low thermal conductivity of pyrex¹⁶, its average temperature under operation is considerably higher than that of the sapphire, with the limited heat conduction provided mainly by the copper strips. As will be seen, its performance is therefore not as good as that of the sapphire, but if a few degrees above 4K is tolerable (it isn't in our polarized sample experiments), it may sometimes provide a workable solution less expensive than sapphire.

TESTS

The cold-transfer system was tested by using a calibrated 1/8 W, 100 ohm, Allen-Bradley thermometric resistance as the "sample", whose (relatively weak) thermal connection to the lower extremity of the liquid helium temperature cold-finger is provided by two 10 cm lengths of 250 μ m diameter, 99.99% purity silver wire connected to the resistor's leads, and a thin layer of Apiezon N-grease between the body of the resistor and the cold-finger. The sample's surface area and temperature are denoted respectively by A_S and T_S . Because of the relatively

simple configuration, and ability to control both shroud and cold-finger temperature by pumping on either or both the liquid helium bath (4.2 to 1.5K) and the liquid N_2 bath (77K to the triple point at 63K, or lower into the solid phase of nitrogen), the thermal conductance link of the sample to the liquid helium bath, as well as the approximate leakage of 300K black body radiation through the shroud assembly, can be reasonably determined. Treating the thermometric resistor as a black body, the following heat currents affect it: absorption of black body radiation from the shroud surface at temperature T_{Sh} , absorption of room temperature (300K) black body radiation which leaks through the transparent coated shroud material or through the shutter, and the thermal cooling via the sample resistor leads and N-grease to the bottom of the liquid helium cold finger attachment. At the upper end of the liquid helium temperature cold-finger, a second similar thermometric resistor with more robust thermal attachment by means of short leads directly into the helium bath and GE 7031 varnish to the cold-finger serves to measure that temperature, T_C . Because of the tighter thermal coupling and the situation that this resistor usually sees a smaller solid angle of incident ($>4K$) thermal radiation, T_C is very close to the helium reservoir temperature. Denoting the room temperature radiation leakage factor by α , the thermal conductance linkage by Γ , and the emissivity and Steffan-Boltzmann radiation constant by e and σ respectively, we get the following equation:

$$e \sigma A_S [\alpha 300^4 + T_{Sh}^4] = \Gamma (T_S - T_C) = \Gamma (\Delta T). \quad (1)$$

Letting $H = e \sigma A_S T_{Sh}^4$, and $H' = \alpha e \sigma A_S (300)^4$,
we get

$$T = H/\Gamma + H'/\Gamma. \quad (2)$$

For $T_{Sh} = 77K$, $H' = H$ for $\alpha = 0.5 \%$. With a sealed (no shutter) all-metal shroud, H' is negligible. Our present openable shutters will be seen to have a leakage of about 2%, and our best coated transparent shrouds a fraction of a percent. Thus, with openable shutters, we expect that reducing T_{Sh} by pumping on the liquid N_2 will not have a large relative effect on ΔT , whereas when the shroud is tightly sealed against 300K radiation, we should see a significant fractional change of ΔT upon cooling the shroud.

The experimental procedure is a straightforward one. The tubes are carefully pumped out since the presence of even a slight amount of water can cause destruction of the tubes upon freezing. The vacuum-isolated liquid nitrogen space is then filled, following which liquid N_2 is poured into the liquid helium tube for precooling. After a few minutes for temperature equilibration, the liquid N_2 is emptied from the liquid helium tube by turning the tube assembly upside down. This precooling, together with employment of a single wall tube attached to the liquid helium transfer tube which extends almost to the bottom of the long helium dewar, are essential for an efficient liquid

helium transfer into the long, narrow liquid helium reservoir. The approximately 3 liters of liquid helium needed to precool and fill the 0.5 liter liquid helium reservoir is transferred within roughly 5 - 10 minutes. A desirable feature is that this system can be operated very satisfactorily at a rather small tilt angle from the horizontal. Typically, we operate at angles from the horizontal of between about 20 and 90 degrees (vertical). In Fig. 4, the experimentally obtained results for six different shroud conditions are summarized, for liquid helium bath temperatures (T_C) between 2 and 4K, and shroud spatially-averaged temperatures ranging from 63K to about 100K. It is immediately apparent that sample temperatures below 4K are easily maintained by modest pumping on the helium bath, and that even without pumping, temperatures quite close to 4K can be maintained with the best shrouds. This would be no surprise if the thermal link, Γ , were very strong, but it will be seen below that this is far from the case, and that Γ is in fact quite weak, simulating reasonably well the condition for a fusion-fuel loaded ICF target shell. The fact that $(T_S - T_C)$ does not change much with cold-finger temperature indicates that Γ does not have strong temperature dependence in this region. Fig. 5 shows the performance of the system in more detail, with a plot of ΔT vs the 4th power of the liquid nitrogen bath temperature, determined from its vapor pressure. Because of their different thermal conductances, the pyrex shroud temperature is expected to deviate considerably from the temperature of the liquid N_2 bath, the sapphire shroud much less so, and the brass shroud temperature

should be close to that of the liquid N_2 bath. From Eq. 2, we see that if Γ doesn't change much over the range of T_S associated with the T_{Sh} range (which is roughly the case), the plots in Fig. 5 should be almost linear, with an approximate value of Γ obtainable from the slope for the cases where T_{Sh} is close to the liquid N_2 bath temperature. Similarly, the room-temperature leakage can be obtained from the intercept. Putting in values for the 'sample' resistor of $e = 1$ and $A = 0.40 \text{ cm}^2$, and considering primarily the all-brass, sealed shroud, assumed to be at the temperature of the pumped liquid N_2 , we find that $\Gamma \approx 5 \times 10^{-4} \text{ w/K}$. Simple calculations based on the magnitude and temperature dependence of the thermal conductivity of N-grease¹⁸ and of silver¹⁶ indicate that most of the cooling is through the leads. The intercept for this case is indeed close to zero, with the small discrepancy explicable in terms of the shroud not being at exactly the temperature of the pumped liquid N_2 bath. The other shrouds are easily understood in a semi-quantitative way. The plot for the all-brass shroud with shutter shows a slightly smaller slope compared to the sealed brass shroud, which can be attributed to a higher Γ corresponding to its higher T_S due to H' . Its intercept yields the 2% leakage we anticipated above. The pyrex shroud exhibits a larger slope because of its poor thermal conductivity, resulting in its T_{Sh} assuredly exceeding the temperature of the liquid N_2 bath. A spatially-averaged shroud temperature of about 100K when the liquid N_2 is at 77K brings its behavior into consistency with the model. The uncoated sapphire has a very high leakage since it is relatively transparent below

6 μm , where about 20% of the blackbody spectral energy is present, leading to an α of about that amount. When coated, it behaves very well, because most of that energy is reflected. In the discussion section, we will apply these results to the ICF case using realistic target cell sizes and thermal links compatible with acceptable fusion shots, to ascertain the requirements for keeping the target sample near 4K.

SAMPLE INSERTION, DISENGAGEMENT, AND RETRIEVAL

We distinguish in this section between situations in which the sample remains attached to the liquid helium dewar cold-finger and thus remains cold by virtue of its conductive link to that tip and its isolation from everything else, and those situations where the sample is disengaged from the cold tip and subsequently stays cold because of its conductive attachment to the destination structure. An example of the former is the OMEGA fusion chamber where the cold helium dewar tube remains attached to the target shell throughout the laser shot, and of the latter is the storage-transport dewar insert, at which the sample becomes physically detached from the cold transfer tube that placed it in that insert. The former situation is simpler, and provision of a radiation-shielding shroud at about 77K and an adequate thermal linkage to the liquid helium dewar tip suffices. The latter is more complex, and is the focus of interest in this section. Several general problems arise in the process of coupling the cold-transfer tube to destination apparatuses, followed by disengagement. The most important constraint is that

the destination apparatus must be under high vacuum, particularly with respect to helium partial pressure, since even a 10^{-6} torr helium partial pressure would thermally 'short-circuit' the cold-transfer tube. This means that commonly employed helium exchange gas for keeping samples cold in a destination apparatus cannot be used, and conduction is the only cooling route. Since conduction cooling is often not as efficient as cooling with exchange gas, one must deal with the following problem. The outer wall of the cold-transfer tube is vacuum insulated from even liquid N_2 temperatures, and thus enters the high-vacuum destination apparatus at near room temperature. It has a substantial heat capacity and means must be found to cool it; otherwise, upon approach to the sample attachment assembly, it will radiatively warm the latter to unacceptably high temperatures. This is aggravated even more, albeit for only a short time interval, when physical contact takes place. Although moderate cooling to liquid N_2 temperatures might be sufficient to satisfactorily reduce the radiation problem, the practical procedure usually at some point requires physical contact of the shroud (at near-liquid- N_2 temperature) to some part of the sample-holding assembly, in order to open the shutter or for some other purpose. The insulation provided by the few millimeters of nylon or graphite possible in the tight spaces is very helpful but usually insufficient to prevent conductive sample warming of about 10K. The steps we take to minimize this warming include lowering the cold-transfer tube slowly, lining the vacuum space with styrafoam which limits the solid angle of room temperature radiation

penetration into the cold regions and also serves as a weak thermal contact brush upon the cold-transfer outer tube, and providing an additional copper "brush" to effectuate thermal contact with the inner surface of the storage dewar vacuum space can, which is at liquid helium temperatures because that can is immersed in the liquid helium bath. Furthermore, it is advantageous to pump on and solidify the nitrogen coolant in the cold-transfer tube assembly. This turns out to be especially important for bringing the temperature of the bottom region of the outer tube of the cold-transfer assembly (and hence the shroud) to below 77K, preferably to near 4K, since otherwise the liquid nitrogen is a fairly good heat transfer medium and also has a substantial latent heat of fusion which strains the heat removal ability of the conductive brushes. Typically, the liquid N₂ space of the cold-transfer tube can be rapidly pumped down to about 15 torr, corresponding to a temperature of 51K. The copper brush can then bring the temperature down to almost 4K, since the solid N₂ is in powder form and is a poor thermal conductor.

In Fig. 6, the mating assembly in the storage dewar is shown. A brief description of the thermal response from one type of engagement, insertion and disengagement procedure serves to illustrate the above discussion. The storage dewar employed is a Janis Vari-Temp model, equipped with a superconducting solenoid which produces a magnetic field of 8 Tesla with a homogeneity of 10^{-5} over 1 cm dsv, thus permitting NMR of cold-transferred samples. The mating assembly in this case contains a crossed-coil NMR probe, which has been used to detect the signal from frozen

D₂ samples. In the procedure we describe here, we replace a frozen "sample" with a thermometric resistance mounted in a sample slug similar to one which would contain a real sample, in order to monitor the "sample" temperature throughout the process. A center conductor makes electrical contact with an insulated contact on the liquid helium cold-finger after they are engaged via the left-hand threaded coupling, with the other resistor lead connected through the common ground. The thermal contact is comparable to the situation with real samples. The cold-transfer tube, precooled to liquid helium temperatures with the thermometric detachable 'sample-slug' attached, cocooned in its all-metal shroud with closed spring-loaded shutter and at a temperature near 4K, is now inserted slowly into the storage dewar. It reaches a position where a nylon sleeve over a brass cylindrical shell contacts the spring-loaded shutter. Pressing it down at that point opens the shutter. With the conditions discussed above prevailing, i.e. pumping on the N₂ bath and using a copper brush, the temperature of the NMR probe, still with sample slug unattached, rises to about 4.8K. Now, with the nitrogen dewar of the cold-transfer set fixed, the liquid helium reservoir tube is lowered until contact is made with the right-hand threaded cylinder on the cold NMR probe assembly. Turning the helium tube clockwise (right-hand screw mode), it engages the threads of the NMR probe assembly, and by continuing the screwing after total engagement, disengages the sample slug from the cold-transfer tube because of the left-hand screw coupling between the two units. At this point, the cold-transfer tube can be removed.

The sample slug remains cold by virtue of its conductive attachment to the NMR probe. Subsequent re-engagement of the sample slug by the cold-transfer tube with counter-clockwise rotation, and continued counter-clockwise rotation after engagement is completed, results in decoupling of the sample slug from the NMR mount. The whole assembly is then raised about 2 cm, causing the spring loaded shutter to close, and finally raised all the way above the gate valve of the vacuum lock, and removed from the storage dewar. Thus removed, the sample can be kept at low temperatures for about 6 hours with the original load of liquid helium, and indefinitely if the liquid helium is periodically retransferred.

DISCUSSION

The principal general features of cold-transfer operations have been outlined in the above sections. We now briefly amplify on some of these, and consider a few specific situations of interest. It was seen that the "hot" (77K) shroud could be a problem due to its thermal radiation or direct contact with an assembly required to be at 4K. For cold-transfer with the dilution refrigerator, this is even more severe. Copper cooling brushes connected to the 1K pot are expected to cool down the shroud and the considerable length of the cold-transfer assembly which enters the dilution unit. In addition, an internal cooling mechanism can be used in the form of a heat switch, already mentioned previously, which has exhibited a cooling power to the nitrogen bath of about 1 watt. Both types of heat switch,

external or internal, require pumping on the N_2 bath to solidify it and make it fairly thermally insulating, as mentioned before. Since only the bottom section, which is of quite low mass and heat capacity, is involved, the drain on liquid helium is not excessive. If necessary, liquid helium can be added to the reservoir at will. Other possibilities for getting lower shroud temperatures include substituting other liquids for the liquid N_2 . Liquid neon, or even liquid H_2 , whose large heat of vaporization makes it durable even under room temperature black-body irradiation, could also be employed in special situations.

The diameter of the lower portion of the cold-transfer assembly which we have been discussing (for OMEGA chamber mating) is 19 mm. For our present dilution refrigerator, that diameter must be reduced to 15 mm. Furthermore, the overall length must be increased from the present 2.5m to 3.4m. That apparatus is presently under construction, and no special difficulties are anticipated. However, the 15 mm diameter appears to us to be close to the manageable limit. For external irradiation experiments, a somewhat larger system was constructed, with a diameter of 25 mm. The X-irradiation will be carried out in that tube, after which the sample will be cold transferred to an EPR-NMR probe in our dilution refrigerator, suitable for dynamic polarization studies.

The geometry and thermal link of the sample were seen to be important for maintaining the sample near or below 4K. We consider now the case of target-shells containing fusion fuels. An important consideration here is to disturb the geometry of the

shell as little as possible for good fusion yields. This is of course incompatible with securing a strong thermal link. In our current compromise, a 400 μm diameter target-shell will be linked to the liquid helium temperature cold-finger by a 5 μm diameter, high purity gold wire of a few mm length, mechanically reinforced with one or more conventionally used spider silk strands¹⁹ of negligible thermal conductance. Using a low temperature thermal conductivity value of the gold wire¹⁶ of 3 w/cm K, and assuming that the entire thermal resistance is in the gold wire, we obtain a value of $\sqrt{r}$ of about 5×10^{-6} w/K, about two orders of magnitude smaller than the one measured in our shroud tests. However, the effective area of the target shell subject to thermal radiative heating is also approximately two orders of magnitude lower than that of the sample resistor used in the shroud tests, so we can expect the temperature behavior of target shells to be similar to that of the sample resistor in the described tests. Additionally, emissivity reduction of the shells is feasible with thin metal plating, and somewhat thicker heat conduction wires can be tolerated for many of the experiments. Thus, target shell temperatures near and below 4K should be attainable by pumping on the liquid helium. This can be done with well-known vibration-suppressing pumping techniques, or using a cryopump system with no moving parts.

We believe this is the first easily managed cold-transfer apparatus which can be adapted to a wide variety of applications, several of which have been mentioned. It is indispensable for passively maintained highly polarized nuclei, and it is

particularly advantageous to the inertial fusion effort requiring utilization of dense hydrogens fuels matched to the increasing laser energy outputs under development.

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REFERENCES:

1. R. Q. Gram, C. K. Immesoete, H. Kim and L. Forsley, J. Vac. Sci. Technol. A6, 2998 (1988).
2. T. M. Henderson, D. L. Melmoth, D. C. Musinski, T. R. Pattinson and G. H. Wuttke, Adv. in Cryogenic Eng. 23, 699 (1978).
3. A. Honig, N. Alexander, and S. Yucel, in Muon Catalyzed Fusion, (Sanibel Island, 1988). Proc. of the Conference on Muon-Catalyzed Fusion, AIP Conf. Proc. No. 181, edited by S. E. Jones, J. Rafelski and H. J. Monkhorst (AIP, NY, 1989).
4. A. Honig, Phys. Rev. Lett. 19, 1009 (1967).
5. A. Honig, Workshop on Polarized Gas Targets for Storage Rings, Intl. Conf. on High Energy Spin Physics, Minneapolis, Sept 10 - 16, 1988. AIP Conf. Proc. No. 187, 1554 (1989).
6. R. M. Kulsrud, H. P. Furth, E. J. Valeo and M. Goldhaber, Phys. Rev. Lett. 49, 1248 (1982).
7. R. M. More, Phys. Rev. Lett. 51, 396 (1983).
8. Y. -L. Pan and S. P. Hatchett, Nucl. Fus. 27, 815 (1987).
9. R. M. Kulsrud, E. J. Valeo, S. c. Cowley, Nucl. Fus. 26,

- 1443 (1986).
10. N. Alexander, Y. Y. Yu, Q. Fan, X. Wei and A. Honig, Bull. Am. Phys. Soc. 35, 925 (1990).
 11. W. N. Hardy and J. R. Gaines, Phys. Rev. Lett. 17, 1228 (1966)
 12. R. S. Rubins, A. Feldman and A. Honig, Phys. Rev. 169, 299 (1968).
 13. A. Honig, M. Lewis, Z. Z. Yu and S. Yucel, Phys. Rev. Lett. 56, 1866 (1986).
 14. M. Bloom, Physica 23, 237 (1957).
 15. A. Honig, N. Alexander, Q. Fan, R. Gram and H. Kim, to be published in J. Vac. Sci. and Technol. A, (1991).
 16. Thermophysical Properties of Matter, Vols. 1 & 2. Eds: Y. S. Touloukian, R. W. Powell, C. Y. Ho and P. G. Kllemens, IFI/Plenum Press, NY (1970).
 17. Handbook of Optics, McGraw-Hill, NY (1978). Eds: W. G. Driscoll and W. Vaughan.
 18. M. M. Kreitman and T. J. Callahan, Cryogenics 10, 155 (1970).
 19. B. A. Brinker, J. M. Cavese, J. R. Miller, S. G. Noyes, S. Sheble and T. Whitaker, J. Vac. Sci. Technol. A1, 941 (1983).

FIGURE CAPTIONS

Fig. 1. Cold-Transfer System. a) Assembled system. In upper region, threaded outside collar, clamps and spacers prevent helium tube from being pulled into the vacuum system. b) Liquid helium tube. Conical insert serves to guide entry of liquid helium transfer tube. c) Liquid nitrogen dewar. Double o-rings at top provide sliding vacuum seal for helium tube. d) "Vacuum-lock" with gate valve.

Fig. 2. Attached sections at bottom of nitrogen dewar and helium tube. Screwed on to nitrogen dewar is shroud, consisting of metal top section, sapphire middle section, and metal bottom section containing shutter and small permanent magnets. At bottom of liquid helium tube, from top to bottom: indium o-ring seal, cold-finger with sealed electrical feed-throughs (2 shown), and sample holder which couples to cold-finger via left-hand thread, and mates to a destination apparatus with right-hand thread. Sample-holder shown has stalk with forked end for ICF target shell.

Fig. 3. Spring loaded, inward-opening radiation-shielding shutter at bottom of shroud.

Fig. 4. Dependence of sample-resistor temperature, T_s , on cold-

finger temperature, T_C , for several shroud types and shroud temperatures. Open symbols: $T(\text{liq. N}_2 \text{ bath}) = 77\text{K}$. Filled symbols: $T(\text{liq. N}_2 \text{ bath}) = 63\text{K}$. Gold-coating is 27 nm. Sapphire and pyrex shrouds have OFHC copper supports.

- ◇ : Uncoated sapphire with light-tight end cap.
- △ : Gold-coated pyrex with light-tight end cap.
- : Gold-coated sapphire with light-tight end cap.
- : Brass with light-tight end cap.
- ▣ : Brass with shutter, $T_{\text{Sh}} = 77\text{K}$.
- ▤ : Brass with shutter, $T_{\text{Sh}} = 63\text{K}$.

Fig. 5. ($T_S - T_C$) plotted against 4th power of liquid nitrogen bath temperature, illustrating effect of shroud temperature black body radiation on sample temperature for various shroud types having different ambient temperature heat loads. Open symbols: $T_C = 4\text{K}$. Filled symbols: $T_C = 2\text{K}$. Gold-coating is 27 nm. Sapphire and pyrex shrouds have OFHC copper supports.

- ◇ : Uncoated sapphire with light-tight end cap.
- △ : Gold-coated pyrex with light-tight end cap.
- : Gold-coated sapphire with light-tight end cap.
- : Brass with light-tight end cap.
- ▣ : Brass with shutter.

Fig. 6. Cut-away drawing of NMR probe assembly in storage-transport dewar with cold-finger and sample assembly shown engaged. Upper probe assembly: nylon-sleeved conical

shroud guide and nylon-sleeved cylinder which opens the shroud shutter as the cold-transfer assembly descends; the cylinder contains the right-hand thread mating for the sample holder. Middle probe assembly: NMR coils. Bottom probe assembly: copper pedestal with indium o-ring seal to bottom of vacuum can. Cold-transfer system: Shroud with open (to inside) shutter, liquid helium cold-finger showing (from top to bottom) liquid helium reservoir, indium o-ring seal, cold-finger temperature-measuring resistor, leads from sample thermometric resistor, left-hand screw coupling of cold-finger to sample slug, right-hand threaded coupling of sample-slug to NMR probe assembly, and thermometric "sample" resistor.

FIG. 1

FIG. 2

FIG.3

FIG.4

FIG. 5

FIG. 6

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