5.8 Polarized Targets: Pointing to New Directions

Tapio Niinikoski

In Polarized Targets (PT) nuclear spins are polarized dynamically in a solid material containing a high density of the nucleons of interest. Such targets are required for some scattering experiments where the spins of the beam and/or target particles have to be aligned with respect to a static magnetic field. To develop, build and operate solid PTs draws on several fields of physics and technology. In this highlight we address advances where CERN has made a major contribution.

Quantum statistics to describe Dynamic Nuclear Polarization (DNP)

Particles with spin have an associated magnetic moment that couples with external and internal magnetic fields. Spin polarization is observable by magnetic resonance methods, whereby a small oscillating magnetic field, transverse to a strong static field, is absorbed by the system of magnetic moments.

Spins in thermal equilibrium with the lattice have a small natural polarization because the magnetic energy levels of the moments have tiny difference in a static external magnetic field. For proton spins this is only a few tenths of a percent at 1 K temperature and 2.5 T magnetic field. Electron spins, on the other hand, under the same circumstances, have about 99% polarization, because their magnetic moment is about 1000 times higher. This large polarization can be transferred to the nuclear spins by certain types of magnetic resonance: the double resonance of electron and nuclear spin pairs, or by cooling of the whole spin system using off-resonance microwave irradiation. The former requires a strong magnetic component of the oscillating microwave field, at 70 GHz frequency, that is parallel to the steady field. The latter requires a much weaker transverse microwave field. The concept of “spin temperature” helps to understand this mechanism.

The spin temperature T_s can be seen in the populations of the magnetic energy levels E_m that are proportional to the Boltzmann factors $\exp(-E_m/k_BT_s)$, after relaxation transitions have established thermal equilibrium among the levels m. This is the classical static view. With a transverse field oscillating at a frequency close to Larmor precession, the spin system reaches a new equilibrium spin temperature that is positive, zero or negative, respectively, and can be much lower than the temperature of the lattice. We may then speak of “cooling of spin system”.

The effects are measurable and dramatic: the new “dynamic” spin temperature is transmitted to all other non-resonant spin systems by spin-spin relaxation transitions, assisted by the oscillating field. Quantum statistics must then be used to predict the thermodynamic parameters such as spin temperature, polarization and entropy. At high temperatures this is relatively easy, because the quantized

Boltzmann factors can be linearized. At low temperatures this approach does not work. It was resolved with the formalism of "Spin Temperature Model of DNP", which gives numerically solvable formulae [38].

The development of this model was one of the major original contributions of CERN to polarized target physics It explains the previously obtained, but poorly understood, results in hydrogen-rich materials by extending the early quantum statistical treatment of magnetic resonance saturation to electron spin systems at low temperatures where the electron polarization is high. The quantum statistical formalism was developed to properly describe and evaluate spin temperature and polarization for the regime of PT applications, where the simplifications of the so-called "high temperature" approximation are not valid. The Polarized Target team at CERN also validated experimentally [39] the key prediction of the model, namely that all nuclear spin species cool towards a common temperature. This common temperature is that of the electronic spin system under a saturating microwave field. It can be as low as one thousandth of the lattice temperature, which is typically 0.2 K to 0.7 K. This new formalism pointed the way to obtain proton polarizations over 99% and deuteron polarizations of about 90% in large targets with corresponding spin temperatures below 0.001 K.

The double resonance method was limited to small targets, owing to the high microwave power required, and to exotic single crystal materials that contain relatively few protons, the target nuclei of interest. In the dynamic cooling method, the microwave power can be reduced so much that very little heat is generated in the material, thus allowing the target to be cooled with ^{3}He evaporation refrigerators at 0.5 K temperature, and even lower with ^{3}He–^{4}He dilution refrigerators, with large gains in the polarization.

The DNP described by the new model benefits from lower coolant and lattice temperatures, and can be extended to a large class of materials that are rich in hydrogen or deuterium. Importantly, the much lower temperatures available by ^{3}He–^{4}He dilution refrigeration (Fig. 5.20) enable "freezing" the polarization. A lower and less homogeneous "holding" field of a spectrometer is sufficient to maintain the polarization of the target after DNP in an external, strong and homogeneous field. Such target technology was developed at CERN where the first frozen spin target was constructed and operated in 1974 [40].

Dilution refrigerators were first introduced to the polarized targets at CERN in the 1970s, with horizontal [40,41] and vertical [42] designs. For these targets CERN developed sintered counterflow heat exchangers [41], which have had a substantial impact on current industrial design of machines for reaching down to temperatures of 0.002 K.

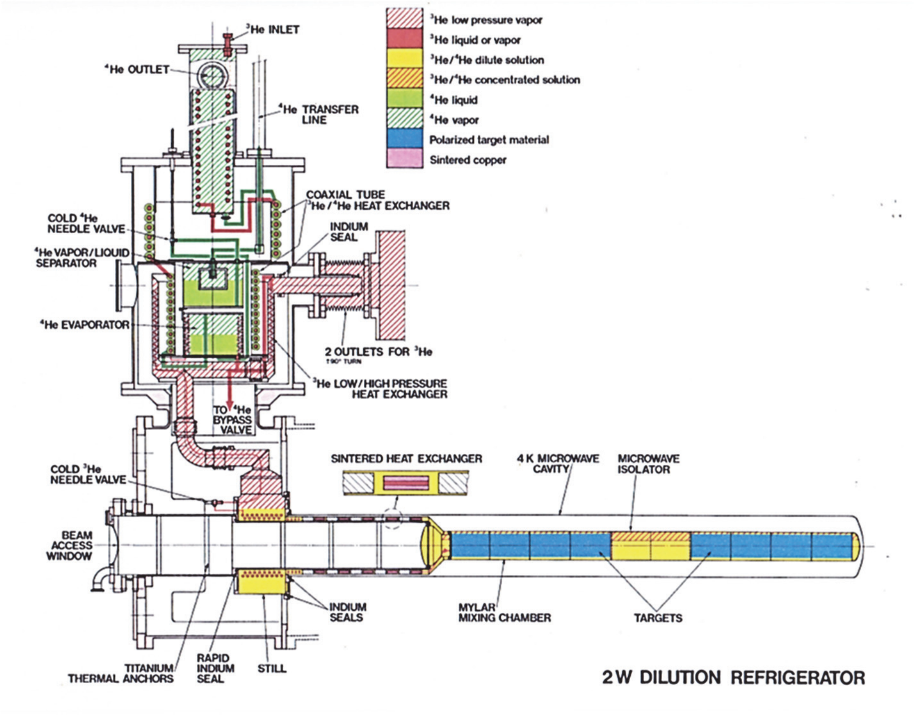

Fig. 5.20. Cross-section of EMC PT cooled with a dilution refrigerator absorbing 2 W power generated by DNP. The target is split in halves polarised in opposite directions, and has 1 m total length. The superconducting solenoid magnet is not shown, for clarity.

Development of materials and magnet technology for polarized targets

DNP in hydrogen-rich chemically doped materials requires the uniform dispersion of suitable paramagnetic impurities. Such materials were initially developed by trial-and-error until the CERN team discovered that they share the common property of being excellent glass formers [43]. The glass "solidifies" by becoming increasingly viscous already at high temperature, which prevents, upon fast cooling, the phase separation of the dissolved dopant as microcrystals.

Another way of doping PT materials uniformly is to create free radicals by suitable irradiation. A technique was developed at CERN to prepare and irradiate solid ammonia, which is richer in H_2 than any hydrocarbon (except methane). Over 90% polarization was reached in the first samples tested by the CERN team [44].

Large polarized targets were designed for the deep-inelastic muon scattering experiments of EMC (NA2), SMC (NA47) and COMPASS (NA48). The NA2 PT was made of irradiated ammonia, while the NA47 target [45] used doped deuterated butanol. The low lattice temperature enabled reaching > 60% deuteron polarization in a 2.5 T magnetic field. Even higher deuteron polarizations have been achieved in materials doped by new trityl free radicals [46], in irradiated deuterated butanol [46, 47], and in irradiated deuterated ammonia [48]. Common to these and to irradiated ^{6}LiD is a narrow "Electron Spin Resonance" (ESR) line that allows one to reach a low deuteron spin temperature by dynamic cooling of the spin–spin interactions of the unpaired electrons, as had been predicted in earlier studies by the PT team at CERN [49].

For the large targets an axial field geometry was required, with a field uniformity in the range of 10^{-5}. Superconducting solenoid magnets were designed with improved coil winding techniques, using rectangular wire to reduce the number of compensation and trimming coils. The rectangular wire fabrication technique was developed in collaboration with industry. The technology for achieving a uniform field in superconducting solenoids has found other applications, including magnetic resonance imaging (MRI).

While this highlight focused on technical development at CERN, clearly other laboratories also contributed to the field and CERN profited from exchanges with them. This development has now enabled us to reach over 90% polarization, positive and negative, of almost any nuclear spin. Targets can be operated in frozen spin mode in a relatively low field of any orientation, and in DNP mode for high intensity beams. Beyond experiments in nuclear and particle physics, applications of DNP are emerging in macromolecular chemistry and in MRI.

5.9 The Silicon Age: Micrometre Precision Millions of Times a Second

Erik Heijne

Silicon sensors and custom-designed integrated circuits ("chips") are essential components in today's particle physics experiments. These silicon devices replaced earlier tracking instruments such as spark chambers and bubble chambers which recorded the particle trajectories photographically. While gaseous wire chambers remain preferred for covering large surfaces [Highlight 4.8], they are no longer competitive in spatial resolution and signal speed for the smaller areas close to the interaction region. The characteristic features that contributed to the breakthrough of silicon (Si) detectors between 1980 and 2000 were: (i) the small, stable and well-defined dimensions of the sensor cells of typically around 100 μm; (ii) the potential to resolve several particles, incident simultaneously on mm-size area; (iii) the short signals of less than 20 nanoseconds (ns); and (iv) the progressive miniaturization of the associated electronics for the processing of the particle signals: by 2010, 65 000 signal amplifiers, digitizers and memory could be