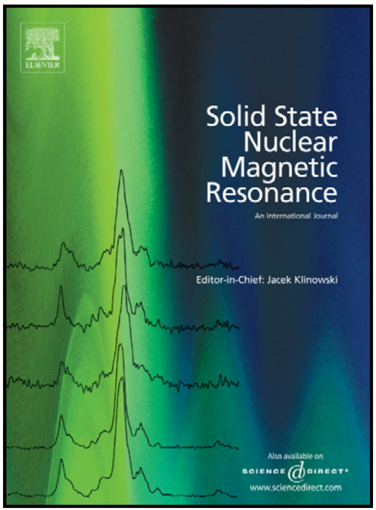

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Implanted-Ion βNMR: a New Probe for Nanoscience

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Abstract

NMR detected by radioactive beta decay, β-NMR, is undergoing a renaissance largely due to the availability of high intensity low energy beams of the most common probe ion, ^{8}Li$^+$, and dedicated facilities for materials research. The radioactive detection scheme, combined with the low energy ion beam, enable depth resolved NMR measurements in crystals, thin films and multilayers on depth scales of 2 to 200 nanometers. After a brief historical introduction, technical aspects of implanted-ion β-NMR are presented, followed by a review of recent applications to a wide range of solids.

Keywords: β-NMR, 8Li, interfaces, thin films, radioactive ion beams, muon spin rotation

1. Introduction

The original theoretical proposal by Lee and Yang[1] that the weak interaction responsible for radioactive β-decay might not conserve parity was quickly verified experimentally in the decay of ^{60}Co nuclei spin-polarized at sub-Kelvin temperatures in the high internal magnetic field they experience in ferromagnetic cobalt[2], and also, almost simultaneously, in the decay of the muon μ^+ that is produced naturally polarized[3]. These results were revolutionary in particle physics, but also opened the way for applications of this special property of β-decay. The effect of parity violation is simply that the *direction* of the high energy β-particle ejected in the radioactive decay is probabilistically correlated with the direction of the nuclear spin at the instant of decay. The detection of nuclear magnetization of stable nuclei by NMR was by this time growing rapidly, and it was not long before asymmetric β-decay was used to detect NMR in an applied magnetic field in the first β-NMR experiment[4]. The main application of this new technique was to measure the dipole and quadrupole moments of many unstable nuclei, whose values can be used to test models of nuclear structure. However, there was also a growing interest in using these radioactive spin probes to study problems in condensed matter physics, materials science and chemistry. In the case of the muon, this flourished in the 1980s into the field of μSR[5, 6, 7, 8]. Due to the extra difficulty of polarization, and the lack of dedicated facilities, β-NMR remained a much lesser known method, but one that is currently enjoying a resurgence of interest, due largely to the β-NMR facility developed at TRIUMF, a medium energy particle accelerator in Vancouver, Canada, whose ISAC facility provides beams of short-lived radioisotopes for nuclear, materials and life sciences.

Here I will review highlights of the recent progress using β-NMR to study materials, mainly based on results from TRIUMF using the heavy isotope of lithium, ^{8}Li. Numerous other reviews precede this one, including the old but comprehensive Ref. [9]. More specialized reviews on applications of β-NMR to crystal surfaces[10, 11, 12], defects in semiconductors[13, 14], solid state diffusion[15, 16, 17] and cross-relaxation[18], as well as from various β-NMR groups around the world, including ISOLDE at CERN[19, 20], Osaka[21, 22], Moscow[23] and TRIUMF[24, 25, 26] are also available.

2. Implanted-Ion β-NMR

2.1. Production of the Polarized Radioactive Ion Beam

β-NMR, as implemented at the ISAC facility at TRIUMF, uses a low energy radioactive ion beam (RIB), rather than *in situ* neutron activation or high energy scattered beams. The primary 500 MeV proton beam from the TRIUMF cyclotron produces a wide variety of nuclides, both stable and radioactive, via spallation nuclear reactions in a solid production target[27]. Following production, the species of interest must migrate out of the target and be ionized in order to be extracted as a secondary RIB. The principle β-NMR nuclide is ^{8}Li with radioactive lifetime $\tau = 1.21$ s (half-life 848 ms). With spin $I = 2$, it has a gyromagnetic ratio $\gamma = 6.3015$ MHz/T, and a small electric quadrupole moment $Q = +31.4$ mb. A typical production target for ^{8}Li$^+$ is formed from the refractory metal tantalum. The target is operated at temperatures in excess of 2000 K to facilitate thermal diffusion of ^{8}Li out of the target to a surface ionization tube, where it is thermally ionized. The entire target assembly in high vacuum is held at a high positive voltage, and cations from surface ionization are expelled and extracted to form a high intensity beam with a cross section on the mm scale and

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