Experiment 815, 816 and 817: β-NMR

(W.A. MacFarlane and R.F. Kiefl, TRIUMF, UBC)

In the past year we have made significant advances in developing the β-NMR technique at ISAC. A major part of this progress is the successful development of the ^{8}Li optical polarizer, which is described elsewhere in this report. The main result of this is that we now have available a high spin polarization (50% routinely and up to 70%) in the ^{8}Li beam. In addition we have demonstrated that in a high magnetic field (3 T) we can maintain a well-focussed beam while decelerating from 30 keV to at least 1 keV. This was shown by imaging the beamspot with a CCD camera viewing a scintillator target. Advances were also made in understanding the beam transport through the β-NMR optics. The Einzel lenses are now operated in a focus-to-parallel mode minimizing beam "snaking" through the optics and simplifying the field and energy dependence of the beam transport. In addition specific advances in understanding the ^{8}Li β-NMR probe are summarized in the following sections.

Deceleration and Range Straggling

To demonstrate that we can stop the ^{8}Li beam in a thin structure, we undertook a study of thin noble metal films with the objective of comparing the range straggling to state of the art Monte Carlo calculations embodied in the SRIM2000 program. Noble metals were selected because their simple structure (Face-Centred Cubic) yields simple resonances as we have already found in thick metal foils.

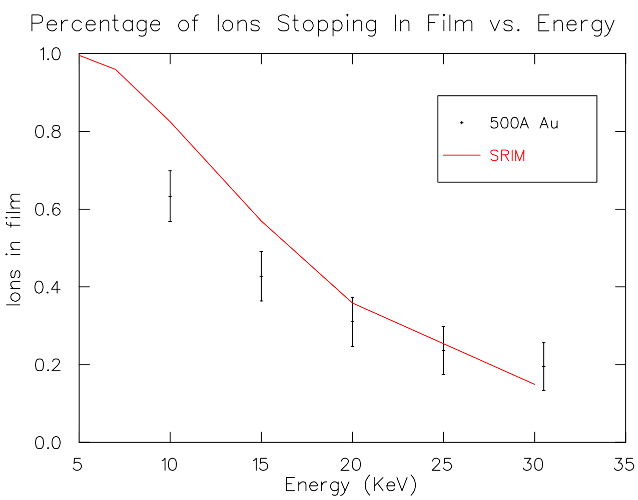

Fig. 1. A comparison of the relative ^{8}Li β-NMR resonance amplitude to the stopping fraction predicted by the SRIM program as a function of the Li beam energy for a 500Å film of Au.

The dramatic contrast in the resonance signals between the metals which have a single narrow resonance near the Larmor frequency and the film substrates allowed us to clearly distinguish the signal coming from the thin film. The resonances were observed for several platform voltages, i.e. varying the beam energy from 30 keV down to 1 keV.

Range straggling was performed on a 500 Å Au film on $SrTiO_3$ substrate, using $^{8}Li^{+}$. The resulting spectra were appropriately scaled and fit to Gaussians. Amplitudes of these fits were then normalized against spectra at similar energies in an Au foil (which is thick compared to the implantation depth of the $^{8}Li^{+}$), and compared to SRIM2000 predictions. It should be noted that this process of normalization against Au foil provides only a lower bound on pecentage of ions stopped in the film. One reason for this is that the resonance is broader in the thin film, possibly a consequence of disorder or a finite–size effect. Future work will involve obtaining spectra in thick Au films (> 2000Å), and normalizing against these spectra instead of the foil spectra.

Thin Metallic Films

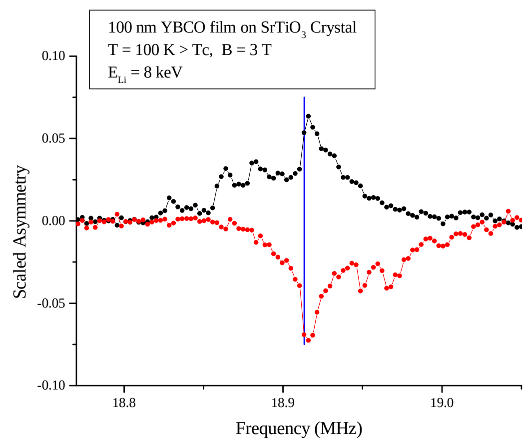

Fig. 2. The ^{8}Li β-NMR resonance in a 1000 Å film of YBCO in the two polarization channels. The line indicates the resonance frequency in MgO.

Aside from the demonstration of range straggling presented above, the results in thin metallic films are of interest in their own right. One motivation for this is that thin noble metal films are components of interesting heterostructures such as giant magnetoresistive multilayers. However, we also plan to use them as an integral part of the β-NMR probe in some circumstances. When we are investigating magnetism at the surface of a complex material, our idea is to use the simple ^{8}Li resonance in a thin noble metal overlayer to probe the magnetic field near but outside the sample. One clear reason for this is that the ^{8}Li resonance in a complex material may be complicated, for example, Fig. 2 shows the resonance in a 1000Å film of the orthorhomic high temperature superconductor YBCO. In such a circumstance it may be easier to extract the interesting information from the simpler overlayer resonance.

Initial room temperature measurements of the ^{8}Li β-NMR resonance in the cubic noble metals Ag and Au showed a single narrow line, indicating a single site of cubic symmetry for Li. Surprisingly, as we cooled films of these metals, a second resonance appeared, and grew in amplitude at the expense of amplitude of the high T line. An example of this is shown in Fig. 3. Both lines appear at frequencies higher than the Larmor frequency in an insulator. Specifically in Ag, the 2 resonances are at +144 ppm and +242 ppm from the resonance frequency in MgO.

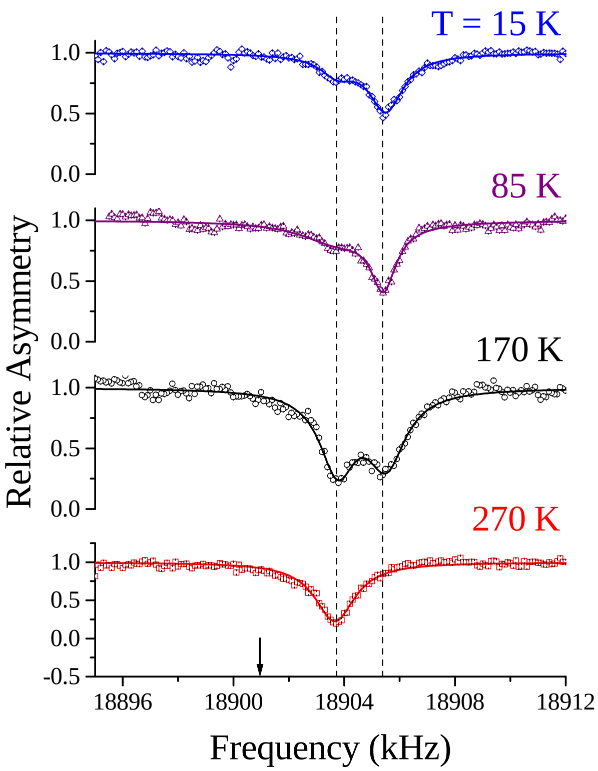

Fig. 3. The temperature dependence of the ^{8}Li β-NMR resonance in a thin film of silver. The two lines correspond to distict crystallographic sites for Li in Ag. The arrow indicates the resonance position in the insulator MgO.

This data suggests that there are two distinct sites for Li in the FCC structure of Ag. In this scenario, we ascribe the small positive shifts to a Knight shift, i.e. to a direct coupling of the ^{8}Li nucleus to the Pauli spin susceptibility of the conduction band. This is a common effect in the NMR of metals, yielding significant temperature independent shifts. There are 2 cubic symmetry interstitial sites in the face-centred cubic lattice, the large octahedral(O) site and the smaller tatrahedral(T) site. Additionally there is the cubic substitutional(S) site. It is likely that the two observed lines correspond to the O and S sites as the T site probably too small to accomodate Li. We plan experiments to confirm this scenario in the near future.

In fact this is the first time that the Knight shift has been used to resolve two sites for an implanted β-NMR probe. The reason we are able to accomplish this is the high magnetic field (3 Tesla) used in this measurement. Lower field studies in Cu did not observe such an effect[1].

Insulators

Strontium Titanate ($SrTiO_3$) is an important substrate material for films of oxide materals such as high temperature superconductors. It is a transparent insulator with the cubic perovskite structure and exhibits a structural phase transition at $\sim$ 100 K to a low temperature tetragonal phase. This phase transition has been studied extensively and is considered a prototype of soft-mode structural phase transitions. Interestingly, neutron and syncrotron x-ray diffraction measurements indicate that there is distinct critical behaviour associated with this transition in a region near the surface of the crystal[2].

We have studied ^{8}Li β-NMR in $SrTiO_3$, and find that although it is cubic there is a significant quadrupolar splitting of the lines indicating that the local symmetry of the Li site is non-cubic. Fig. 4 shows an example of the resonance in $SrTiO_3$. The electric quadrupole moment of the ^{8}Li nucleus couples the nuclear spin to the electric field gradient (EFG) at the Li site causing the Larmor resonance to be split into a quartet of lines for the spin 2 nucleus. However, the high degree of polarization implies that only the $m = \pm 2$ states are populated appreciably. The applied RF magnetic field can then induce $\Delta m = 1$ transitions, and we will observe only two lines of the quartet. However, instead, we find 4 lines - two distinct ones in each polarization channel, the inner 2 having higher intensity.

[1]F. Ohsumi *et al.*, Hyp. Int. **120-121**, 419 (1999).
[2]K. Hirota *et al.*, Phys. Rev. B **52**, 13195 (1995).

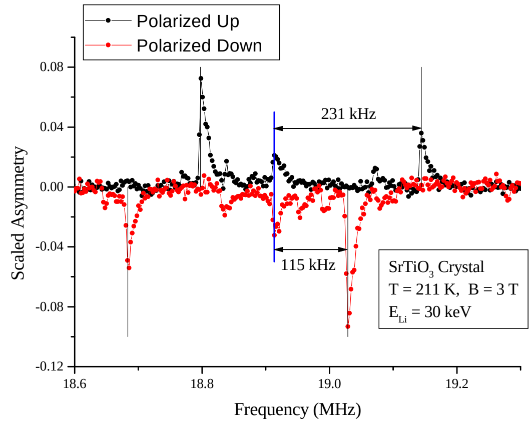

Fig. 4. The ^{8}Li β-NMR resonance in $SrTiO_3$. The central line indicates the Larmor frequency. The resonance is split by the quadrupolar interaction, with a characteristic frequency of $\nu_Q \sim 115$ kHz.

The likely explanation for this effect is that the Li site has a [100] symmetry axis, thus there are in fact 3 sites with [100], [010] and [001] principle axes in the cubic structure. The field applied along [001] distinguishes the [001] site from the other 2. In fact the first order quadrupolar splitting for an axially symmetric EFG depends on the angle of the magnetic field relative to the EFG axis (θ) as

$$\delta\nu \propto 3\cos^2(\theta) - 1 \qquad (1)$$

So the 2 large resonances correspond to the [100] and [010] sites with $\theta = 90°$ and the outer lines to the [001] site with $\theta = 0°$.

The results in $SrTiO_3$ indicate that not only can ^{8}Li β-NMR be used as a local magnetic probe, but in some cases it is also sensitive locally to electrostatic fields in solids.

Spin Lattice Relaxation

In addition to measuring the ^{8}Li resonance, we have measured the spin lattice relaxation. The relaxation is due to coupling of the ^{8}Li to the conduction electrons of the metal (Korringa relaxation) and demonstrates our ability to measure magnetic dynamics.

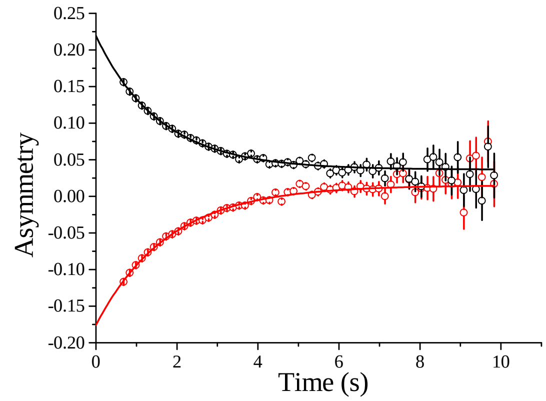

Fig. 5. The spin lattice relaxation of ^{8}Li in Pd. In the experiment the beam was on for the first 0.5 seconds, then the decay of the asymmetry was monitored.

Theses:

Undergraduate Co-op Reports:

"Range Straggling and β-NMR of Spin Polarized ^{8}Li in Ultra-thin Metallic Films" by T.R. Beals, UBC

"Simulated Magnetic Field Distributions Near the Surface of a Superconductor for β-NMR Experiments" by K. Mitra, UBC

Appendix D and Appendix E update:

Updated Collaboration List:

P. Amaudruz, R. Baartman, T.R. Beals, J. Behr, J.H. Brewer, s. Daviel R.F. Kiefl, S.R. Kreitzmann, T. Kuo, C.D.P. Levy, R.I. Miller, W.A. MacFarlane, M. Olivo, R. Poutissou, G.D. Wight, TRIUMF/UBC

C. Bommas, University of Bonn

A. Hatakeyama, Y. Hirayama, T. Shimoda, Osaka University

K.H. Chow, University of Alberta

S.R. Dunsiger, R.H. Heffner, G.D. Morris, Los Alamos National Lab

L.H. Greene, University of Illinois, Urbana–Champagne