Nuclear Bragg Scattering Studies in ^{57}Fe with Synchrotron Radiation*

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ABSTRACT

Studies of nuclear Bragg x-ray scattering of synchrotron radiation, using crystals of α-$^{57}Fe_2O_3$, have been carried out at the NSLS at Brookhaven National Laboratory and at the Cornell University CHESS facility. These studies have demonstrated that nuclear resonance states can be used to produce filtered x-ray beams which have extremely narrow bandwidth, small angular divergence and unique polarization and temporal properties. This combination of characteristics, unobtainable with radioactive sources, makes synchrotron-based Mössbauer spectroscopy feasible and is an important complement to existing methods. A review of the experimental methodology is presented, as well as some suggestions for fuller exploitation of this new technique.

1. Introduction

Synchrotron radiation sources, which now exist in several countries, can provide intense continuum beams of x-ray radiation. These are sufficiently intense to be able to excite low-lying nuclear levels and, as such, provide an interesting *non-nuclear* way to perform nuclear Bragg scattering (NBS) experiments and Mössbauer spectroscopic studies. Nuclear resonantly filtered beams can thus be obtained which have extremely narrow bandwidth, small angular divergences, and unique polarization and temporal properties. These attributes, *which are unobtainable with radioactive sources*, arise from the properties of synchrotron x-ray radiation and its interaction with low-lying nuclear levels.

2. Experimental Requirements

A major experimental requirement which must be met, when using synchrotron x-ray radiation to excite Mössbauer nuclei, is the suppression by large factors of off-resonance photons from the x-ray continuum. Line widths of Mössbauer states are typically a few microvolts. Conventional x-ray monochromators of the type used at synchrotron sources, e.g. reflection from Si (1,1,1) crystals, yield energy selected beams with bandwidths of several-to-tens of electron volts. Without additional energy discrimination, observation of the nuclear resonance signal is extremely difficult. To achieve additional improvement in the experimental signal-to-noise ratio, one employs enhanced energy filtering of the incoming x-ray beam and uses highly perfect crystals of isotopically enriched α-$^{57}Fe_2O_3$ as the scattering medium. This allows the observation, between synchrotron beam bursts, of nuclear resonance excitation without additional electronic suppression.

3. Instrumental Developments

Special instrumentation at Brookhaven National Laboratory, specifically optimized for NBS studies, has evolved from the development of a nuclear Bragg scattering monochromator that operates by multiple reflections from high quality silicon crystals[1]. Six stages are employed. The first two are from a conventional, water cooled, premononchromator that operates by x-ray reflection from Si (1,1,1). Following this is a four stage device that operates via backangle scattering from the (10,6,4) planes of Si. This device yields an energy bandwidth of 5 meV and small angular width (0.4 arcsec) at the 14.4 keV transition energy of the well known ^{57}Fe Mössbauer state. Its characteristics have been described fully elsewhere[2].

4. Typical Experimental Studies

A convenient way to provide additional suppression of prompt incoherent scattering of the remaining, off-resonance x-rays is to employ a highly perfect crystalline nuclear scatterer. Alpha hematite, $^{57}Fe_2O_3$, is ideal for this purpose. Large crystals of this material (prepared by AT&T Bells Labs and isotopically enriched to 93% ^{57}Fe), scattered the x-ray beam; plastic scintillators or LEPS Ge detectors were used to measure the scattered radiation. Reflections of odd-order, e.g. (7,7,7) are allowed for nuclear Bragg scattering, but ordinary electronic scattering is forbidden. Even-order reflections, e.g. (6,6,6) proceed by conventional electronic x-ray scattering. Indeed, when rocking curves of such reflections are scanned, the energy width of the (6,6,6) reflection is found to be approximately 250 meV and is consistent with a 3 arcsec rocking curve which is associated with small crystal imperfections. An energy width of just 5 meV is found for the pure nuclear (7,7,7) reflection and this width mirrors the intrinsic resolution of the premonochromator. While this suggests that nuclear excitation has been observed, conclusive evidence[3] comes from the time evolution of the nuclear reflection, which has been used to verify features of the dynamical theory of nuclear resonant scattering of synchrotron radiation.

Additional studies[4] have centered on the polarization mixing in NBS. Here one exploits the differences between σ and π polarization that arises from the non-degeneracy of the $\Delta m = 0, \pm 1$ hyperfine levels in ^{57}Fe. Polarization switching of the synchrotron beam has been observed using a nearly perfect single crystal of Be as a polarization analyzer and a Sm-Co permanent magnet which perturbed the small ferromagnetic moment of α-hematite.

5. Future Applications

Besides the ^{57}Fe system, synchrotron excitation of other isotopes has been reported recently, e.g. ^{119}Sn[5] and ^{169}Tm[6]. While these are among the "classic" Mössbauer nuclei, the NBS technique can also be applied to those cases where there is no convenient parent nuclide in nature. Some examples include ^{45}Sc, ^{61}Ni, ^{73}Ge and ^{201}Hg.

An interesting future application of nuclear resonantly filtered x-ray beams is in the area of x-ray interferometery[7]. Coherence lengths of filtered beams (related to $\Delta\lambda$ versus λ) can be very long, e.g. tens to hundreds of meters. This property could be exploited to perform interferometric measurement of the type done at visible wavelength by the method of Hanbury Brown and Twiss[8], but now at x-ray wavelengths.

6. References

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