DYNAMIC TEMPERATURE AND VELOCITY MEASUREMENTS USING NEUTRON RESONANCE SPECTROSCOPY.


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1. Introduction

The challenge of measuring the internal temperature of a system undergoing dynamic loading is one whose successful solution is of great interest to the shock physics and industrial communities. Existing methods of temperature measurement in dynamic systems have various inherent limitations. Optical methods interact with sample surfaces, and during dynamic events the surface may be obscured from view by reaction products. Even if the surface can be clearly viewed, temperatures at the surface may not equal those present in the interior. Sensors for pyrometric techniques, such as thermocouples placed in the interior of the sample, are short lived and often destroyed or altered during the dynamic event. Furthermore, the presence of invasive diagnostics may change the dynamics of the very interaction one desires to study.

The use of Doppler broadening in neutron resonances as a quantitative way to measure temperatures has been proposed \[1,2\] and investigated for cases of static or quasi-static temperature measurements. Neutrons are temperature probes that can penetrate a sample to view its interior. At the same time products that may shield a sample optically are not opaque to neutrons so that temperature measurements can be made in their presence. When neutrons are attenuated by a sample material, the time-of-flight (TOF) spectrum of the transmitted neutrons exhibits a series of characteristic dips or resonances. These resonances appear when neutrons are captured from the beam in the formation of excited states in the \( A+1 \) nucleus \((\text{n}+A \rightarrow (A+1)^*\)). Subsequent de-excitation of these states, by gamma emission or particle emission into \(4\pi\) steradians, effectively eliminates the captured neutrons from the transmitted beam. The resonance locations and lineshapes which appear in the TOF spectrum are unique to each isotopic element, and temperature determinations can be localized through the positioning of resonant tags.

2. Neutron Resonance Spectroscopy

In Neutron Resonance Spectroscopy (NRS), the temperature of an irradiated sample is determined from changes to the Lorentzian lineshape of a resonance. Neutrons in the epithermal energy range between 1 and 100 eV are typically used. The energy available when neutron and nucleus interact is dependent on the relative velocity of the two bodies. As a result, the observed lineshape is a convolution between a Lorentzian and a temperature-dependent Gaussian of width, \(\sigma = (2E_kT/A)^{1/2}\). One must also be aware, however, that other factors which do not depend on temperature may also influence the resonance lineshape. First, in the production of epithermal neutrons the moderation of fast neutrons to lower energies is a statistical process, and not all neutrons of a given final
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energy will leave the moderator at the same time. Second, scintillation detectors such as 6Li-loaded glass can possess phosphorescent tails in their light emission which will affect the resonance lineshape. And third, motion of the sample’s center of mass can result in changes to a resonance’s centroid location. Hence, velocity distributions within the sample can superimpose shifts of different amounts to produce a distortion to the lineshape.

3. Neutron Beam and Experimental Setup

At the Los Alamos Neutron Science Center (LANSCE), one source of neutrons for NRS measurements is the neutron production target of the Manual Lujan Neutron Scattering Center (MLNSC). Protons accelerated by the 800-MeV linac are accumulated in a proton storage ring (PSR) and then released as short (125 ns) and intense (2.2 x 10^13) pulses at a 20-Hz repetition rate. In normal operation, these pulses strike a tungsten target at MLNSC and produce neutrons which become moderated and distributed to time-of-flight (TOF) beam lines.

A second neutron source for NRS measurements is a special target/moderator assembly placed by our group in the “Blue Room” at LANSCE. When this assembly is installed, single PSR beam pulses are delivered to the “Blue Room” to provide short, intense bursts of neutrons. The advantage of the “Blue Room” neutron source is that samples under study can be placed in much closer proximity to it (within 1 meter) than is possible at MLNSC, where the source-to-sample minimum distance is 6 meters. The radiation shielding of the “Blue Room”, however, is not designed to handle the same intense neutron production rates as is the shielding at MLNSC, and therefore the delivery of single PSR pulses is restricted to a maximum delivery rate of one pulse every 7 minutes. The present beam transport systems also do not permit simultaneous beam delivery to both MLNSC and the “Blue room”.

A schematic of the apparatus used in the MLNSC resonance spectroscopy measurements is shown in Fig. 1. The moderated neutron beam travels through a radiation shield to a sample located 6.5 meters away. Neutrons transmitted by the sample are detected by a 6Li-glass/phototube array positioned further downstream - at 6m, 25m, or 58m from the neutron source. In order to handle the high count rates of a large neutron flux, rather than attempting to count individual neutrons we integrate the neutron signal in a transient digitizer (current mode detection) [3]. For geometries with low count rates, where individual neutron pulses are detected without overlap, we have the option to discriminate and count individual neutron pulses in a multiscaler (pulse-counting mode) so as to eliminate the contribution of phosphorescence in the Lithium glass.

4. Measurement Time Scale

The time scale of a dynamic temperature measurement using is determined by the time for resonant neutrons to pass through the sample being studied. For the temperature measurement to be meaningful, this transit time must be short compared to the time scale of changes in the dynamic system of interest. In other words, the dynamic system must remain quasi-stable during this time of passage: the more rapid the dynamic event to be studied – the shorter the transit time required.

Neutron resonances typically have natural widths of order 100 meV. In a TOF measurement, an energy spread ΔE will, at the sample, translate into a time spread directly proportional to the distance between the sample and the neutron source:

$$\Delta t = \frac{1}{2} \frac{t \Delta E}{E} \sim \frac{L}{E^{3/2}}$$

where L = distance source to detector
As an example of the time scales involved, Fig. 1 shows the resonance profile for the 30.4-eV resonance in $^{109}$Ag as measured at MLNSC. The fwhm of the resonance is 1.2 μs for a sample 6.5 meters from the source. In the case of MLNSC, this sample-to-source distance cannot be decreased because of limitations imposed by the existing biological radiation shielding, and the shortest time scales that can be probed with this resonance are in the 3 to 5 μs range. In the “Blue Room”, a 6-times smaller sample-to-source distance is feasible and consequently it is possible to study dynamic systems in the sub-microsecond range.

5. Contributions to the Final Lineshape

In neutron-nucleus interactions, the basic Lorentzian lineshape of an isolated neutron resonance is modified by the motion of target nuclei because the energy available to the interaction depends on the relative neutron-nucleus velocity. If one assumes that the target nuclei have a Maxwellian velocity distribution, then the resulting Doppler-broadened cross section has the form of a convolution of a Lorentzian and Gaussian (Voight profile):

$$\sigma(\nu) = \int \sigma(\nu - V) P(V) dV = \frac{\sigma_0}{\Delta \sqrt{\pi}} \int_0^\infty \frac{e^{-\left(\frac{E_{CM} - E_{LAB}}{\Delta}\right)^2}}{1 + \left(\frac{E_{CM} - E_0}{\Gamma/2}\right)^2} dE$$

where $$\Delta = \frac{4mEkT}{M}$$

and then $$\sigma(E) = \sigma_0 \frac{1}{2t\sqrt{\pi}} \int_0^\infty \frac{e^{-\left(\frac{x-y}{2}\right)^2}}{1 + y^2} dy \quad \text{where} \quad t = \frac{\Delta}{\Gamma}$$

In addition, the observed lineshape can possess contributions from other, non temperature dependent sources. One is the energy-dependent background that is due to gammas and non-resonant neutrons that have their source in room radiation and fast neutrons moderated in the beam line between sample and detector. We determine the shape of this background by performing thick absorber runs that measure the count rates in the bottom of black resonances. At neutron energies of 1.5 eV, we have found that our MLNSC beam line has background rates which vary from less than 1% for a detector that is 60 meters from the source to 10% for the same detector located only 11 meters from the source.

A second contribution to the resonance lineshape is the time-dispersion properties of the neutron moderator/reflect assembly of the MLNSC target. We have used measured lineshapes of resonances in a $^{238}$U - cooled, $^{1}$N$_2$ target to determine these source properties. The lineshape measurements were made at low counting rates with a detector in pulse-counting mode. Eliminating phosphorescence components in these measurements was accomplished through pulseheight discrimination. The moderator measurements show the presence of both short ($2.4/E^{0.367} \mu s$) and long ($8/E^{0.367} \mu s$) time-dispersion components.

A third contribution to the resonance lineshape is the presence of phosphorescent tails in the light emitted by the lithium-glass scintillators of the detector array. To determine the contributions of these tails, lineshapes recorded by detectors in current-mode were curve fit while intrinsic resonance parameters and moderator time-dispersion parameters were fixed to previously measured values. In addition, using a radioactive Californium source
we studied the lineshape of time-averaged detector pulses. The analysis shows the presence of phosphorescence tails with approximate 4-μs and 15-μs time constants.

6. Static Measurements

Although the snapshot taken in a dynamic measurement is limited to using single beam pulses, static measurements of oven-heated samples using multiple beam pulses are useful for calibrating the system. We have studied the observed resonance broadening in static samples as they are heated over a wide range of temperatures in a controlled oven.

We also performed tests with single beam pulses and an oven-heated sample to determine the statistical limitations for single-pulse temperature determination at present MLNSC neutron-flux levels. Figure 3 shows results for an indium sample at two temperatures differing by 100°. The spread in the measured values at each temperature indicates that a rms uncertainty of approximately 30° K was achieved.

7. Metal-Jet Experiment

NRS is now being used to determine temperatures in a wide range of dynamically-changing systems. Systems whose temperatures are of interest include: in a metal behind a shockwave, in shock-driven pore collapse, at a shocked frictional interface, and in a metal jet. Figure 4 shows experimental data taken in one such system, during the formation of a metal jet. In the comparison between a silver sample at room temperature and the heated silver in a jet, it is easy to see the resonance broadening resulting from the large temperature difference. Figure 5 shows a fit to the lineshape from which the jet temperature is extracted. Radiographs provide additional information on variations in jet thickness and jet velocity as a function of time, and we include their effects in our analysis of the data.

8. Future Plans

The NRS project is currently testing a new target/moderator designed to produce increased neutron flux. At the same time we are studying ways to reduce non-resonant background contributions to the measured spectra. We also experimenting with prototypes of ³He detectors that possess low sensitivities to gammas and that are free of phosphorescence in their signals. We are continuing to develop our program of dynamical experiments. For the longer term future, we are pursuing the development of improvements to beam transport which would improve beam sharing with other LANSCE users and consequently greatly increase the availability of high-intensity beam pulses to "Blue-Room” experiments at NRS.

References


Figure 1. Experimental Setup.

Figure 2. 30.4-eV resonance in $^{109}\text{Ag}$

Figure 3. Histogram comparison of single-pulse temperature runs for Indium samples at 299°K and 407°K.

Figure 4. Comparison of 30.4-ev ($^{109}\text{Ag}$) resonance width for room temperature Ag sample (blue profile) and for metal jet Ag.

Figure 5. Fit to 30.4-eV ($^{109}\text{Ag}$) resonance to determine temperature in metal-jet experiment. Thickness shown in figure is approximate.