

BIOLOGICALLY-EQUIVALENT DOSIMETRY FROM
NITROGEN-14 NUCLEAR QUADRUPOLE RESONANCE

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ABSTRACT

A new method for measuring the damage to biological systems from ionizing radiation has been developed based upon the principles of ^{14}N Nuclear Quadrupole Resonance (NQR). NQR studies have been performed on several biologically-equivalent materials. Variations of NQR parameters are presented for materials exposed in gamma and neutron fields. The radiation induced structural changes are modeled and quantitatively correlated with photon and neutron fluxes and absorbed dose rates. Radiation induced changes in the NQR spectra provide a sensitive measure of potential biological damage.

INTRODUCTION

The NQR technique provides a sensitive probe of electron bonding configurations around the nitrogen sites for a number of organic, biologically-significant compounds. Detailed information on radiation effects is obtained by monitoring the interaction between the electric field gradient produced by the electron bonding configuration and the nuclear quadrupole moment of the probe nucleus. Studies have been performed on the simplest compounds of the urea family, urea and thiourea. By utilizing biological materials as dosimeter material, and monitoring the radiation induced changes, a representation of potential biological damage is obtained.

THEORY AND EXPERIMENT

The bonding configuration around ^{14}N nuclei produces an electric field gradient (EFG) at the nuclear site which causes splitting of the nuclear energy levels due to an interaction with the nuclear electric quadrupole moment (eQ). Observable transition frequencies between the energy levels are

$$\nu_+ = \frac{(3+\eta) e^2 q Q}{4h} \quad \nu_- = \frac{(3-\eta) e^2 q Q}{4h}$$

where η is the asymmetry parameter measuring deviation from axial symmetry, eq is the EFG component with maximum amplitude, and h is Planck's constant. These transitions are forced by the application of radiofrequency (RF) energy at the appropriate transition frequency. Single pulses of $14\mu\text{s}$ duration were used to excite the spin system at 77 K and the resulting free induction decays (FID's) were characterized to determine the radiation response of the material. All resonance frequencies for urea and thiourea were observed to occur at previously

reported frequencies between 2 and 3 MHz, using pulsed NQR techniques with a pulsed spectrometer commercially available.¹

RESULTS AND DISCUSSION

The initial radiation response of urea and thiourea has been characterized using gamma and neutron radiation fields. Gamma irradiations were performed with a ^{60}Co irradiator² providing a delivered dose rate of 0.122 Gy s^{-1} . The response of the NQR parameters of urea have been investigated with the urea in two physical forms. Dry polycrystalline urea does not exhibit any detectable change in its NQR

parameters for delivered doses of ^{60}Co radiation up to 2000 Gy. Hydrated polycrystalline urea exhibits pronounced changes in several NQR parameters when exposed to ^{60}Co radiation. The most pronounced effects are manifest as a decrease in the spin-spin relaxation time, T_2 , as the delivered dose increases, figure 1. These changes may be related to small changes in the chemical bonding configuration of the urea, and not large-scale structural rearrangement³. Urea studies demonstrate that the response of these materials may be greatly enhanced when water is incorporated into the polycrystalline matrix. A comparison of the response of the dry and hydrated urea samples demonstrates that radiolytic products created in the water subsequently attack urea molecules. This is the dominant mechanism for radiation effects, not direct interactions with urea molecules.

Thiourea has a molecular structure similar to that of urea, with the oxygen atom in urea being replaced by a sulfur atom to form thiourea. The NQR and radiation responses of these two materials would be expected to be quite similar. The incorporation of sulfur instead of oxygen, however, causes the two nitrogen sites in the molecule to become nonequivalent, and the sites experience different EFG's and resonate at slightly

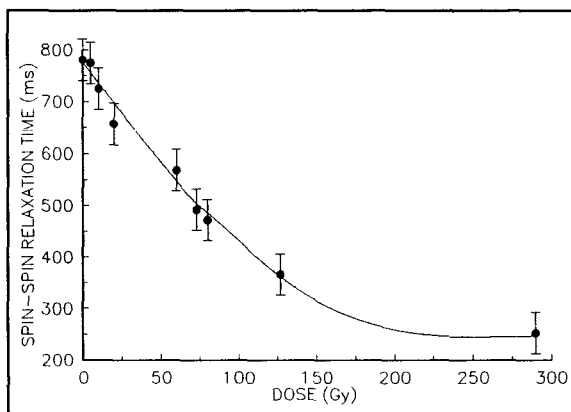


Figure 1 Urea T_2 response to gamma irradiation

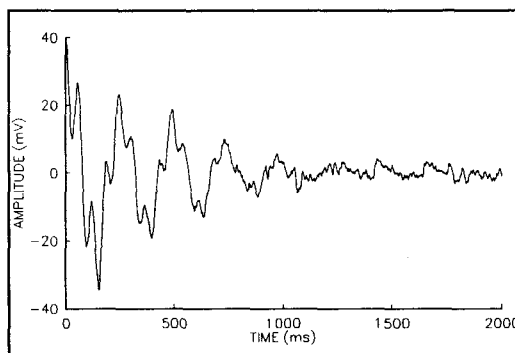


Figure 2 FID of thiourea

different frequencies. The thiourea FID is therefore complicated by the superposition of two FID's from independent nitrogen sites, and exhibits a more complex shape, figure 2. This requires that sophisticated data analysis methods be utilized. In this case a non-linear curve fitting program was developed and used to separate the T_2 's associated with each of the two components of the FID.

Studies analogous to those performed on urea were attempted on thiourea. Although dry polycrystalline samples were irradiated to much higher doses than the urea, no radiation induced changes were observed. Hydrated polycrystalline samples of thiourea cannot be studied because water reacts with the thiourea molecules and eliminates any NQR response. Dry polycrystalline thiourea was characterized for changes induced by exposure to neutron radiation. The samples were irradiated in the central beam port of the University of Florida Training Reactor with a fission neutron spectrum of flux $1.2 \times 10^{16} \text{ m}^{-2} \text{ s}^{-1}$. Neutron irradiation resulted in a

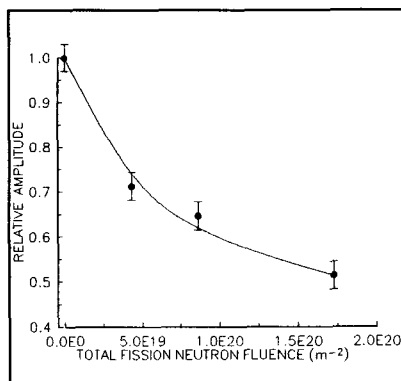


Figure 3 Thiourea response to fission neutrons.

dramatic decrease in NQR signal intensity as illustrated in figure 3. A much greater fraction of ^{14}N nuclei are prevented from contributing to the NQR signal than would be expected from calculations of the number of thiourea molecules damaged by the delivered neutron fluences. This indicates that the NQR parameters are sensitive enough to be affected by radiation induced changes at least several molecules away.

More complex molecules, such as guanidine sulfate, are expected to provide more sensitive probes of radiation induced changes using NQR techniques. Due to the superposition of several nitrogen sites, however, the quantization of contributions from each site requires more sophisticated data analysis methods. Traditionally, data analysis for magnetic resonance spectra has been done by discrete Fourier Transform (FT) of the time series data via the Cooley-Tukey Fast Fourier Transform algorithm.⁴ The FT power spectrum in frequency space is used to isolate the appropriate resonance frequencies and the FT absorption spectrum yields the spin relaxation times which are proportional to the inverse of the line widths. In pulsed NQR the loss of frequency-dependent phase information due to the spectrometry electronics results in a mixing of absorption and dispersion modes in the cosine portion of the FT. We have been unable to characterize the missing phase information and thus the individual line widths cannot be determined by this method.

The Marquardt method⁵ of non-linear least squares curvefitting was used to overcome this problem. The experimental FID is fit to a Lorentzian line in the time domain:

$$v(t) = \sum_{i=1}^N a_i \cos(\omega_i t + \phi_i) e^{-t/T_{2i}}$$

with $v(t)$ being the composite time domain signal, N the number of different ^{14}N sites, a_i the signal amplitude, ω_i the difference frequency between the applied RF and the resonance frequency, and ϕ_i the phase shift. A data reduction method recently applied to magnetic resonance spectra, HSVD⁶, which converts the non-linear problem of exponentially damped sinusoids in the time domain into a linear problem in state space and solves by linear least squares, will be used in future work on more complex molecules.

CONCLUSIONS

This work represents the first observed detection of gamma and neutron radiation effects in bio-molecules using ^{14}N NQR. Neutron radiation is capable of producing direct effects in the compounds studied, while gamma radiation effects on the molecular structure occurred as a result of indirect interaction with radiolytic products formed in hydrated samples. While the system has yet to be optimized to maximize the response to ionizing radiations, more sophisticated data analysis methods are being developed to improve the detection limit of this dosimetry technique. Ultimately ^{14}N NQR is expected to provide a sensitive method for radiation dosimetry and the study of the response of fundamental biological systems to ionizing radiation.

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