

# EFFECTIVE TEMPERATURE OF AMORPHOUS CARBON STUDIED USING NUCLEAR RESONANCE PHOTON SCATTERING

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## Introduction

The effective temperature of <sup>13</sup>C in the form of isotopic amorphous carbon (AC) was measured at 295K by employing the nuclear resonance photon scattering (NRPS) technique [1] in a self-absorption mode [2,3]. The photon beam was in the form of bremsstrahlung obtained from an electron beam of the Stuttgart Dynamitron (E=4.1 MeV) and the resonance scattering from the 3089-keV and 3684-keV levels in <sup>13</sup>C was measured. In the NRPS method, one measures the effective temperature  $T_s$  by monitoring the Doppler broadening of the nuclear level caused by the *total* kinetic energy of the scattering C-atom. The scattered intensity is related to the directional binding strength of the scattering atoms. The Doppler width is given by  $\Delta_s = E(2kT_s/M_s C^2)^{1/2}$  where E, the nuclear level energy,  $M_s$  is the nuclear mass, and  $T_s$  is the effective temperature of the scattering atom; it is related to its *total* kinetic energy in the sense that it includes the part which is due to its internal zero-point motion.

## Experimental

The NRPS method is illustrated in Fig. 1 which, from left to right, depicts an incident bremsstrahlung beam obtained when 4.1 MeV electrons strike a high Z gold radiator. This incident 'white' beam is modified by passing it through an AC absorber (98% <sup>13</sup>C) which generates narrow nuclear absorption dips caused by the resonance excitation of the 3089-keV and 3684-keV levels in <sup>13</sup>C. The particular shape and width of those dips which are Doppler broadened are determined by the atomic binding properties of the <sup>13</sup>C absorber. Similarly, the levels of the scatterer are also Doppler broadened with widths defined above. The shapes of those lines carry the lattice dynamical information of the scattering atoms, which is of our concern here. When this artificially modified photon beam strikes a nuclear scatterer (containing <sup>13</sup>C nuclei), the Doppler broadened dips, created by the absorber, act as shape-analyzers of the broadened levels of the scatterer. The overlap of the two shapes (described by the shaded areas in Fig. 1) is proportional to the scattered intensity which in turn depends on the effective temperature of the scatterer. For

two <sup>13</sup>C samples with effective temperatures ( $T_{s1} < T_{s2}$ ) struck by such a modified beam, the corresponding scattered intensities will be related as  $I_1 < I_2$ .

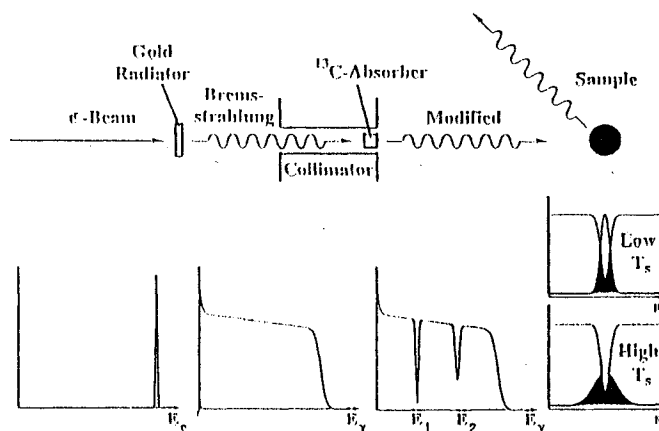


Fig. 1. The upper figures describe the sequence of events in the NRPS technique. The lower figures represent the corresponding energy spectra of electrons and photons.

Experimentally, we measure the self-absorption ratio  $R$  defined as  $R=(N_0-N_n)/N_0$  with  $N_n$  and  $N_0$ , the scattered intensities from a sample obtained by passing the incident photons through a resonant and non-resonant absorber, containing <sup>13</sup>C and <sup>12</sup>C respectively before hitting the sample. In such measurements the thicknesses of the resonant and non-resonant absorbers are chosen to have the same atomic attenuation. It is reasonable to expect a larger experimental self-absorption ratio  $R$  for a nuclear self-absorber with low effective temperature  $T_a$ , and hence a better accuracy in the resulting measured value  $T_s$ . This was achieved using liquid <sup>13</sup>CO ( $T_a = 346K$  at 78K), as a nuclear absorber. The <sup>13</sup>C AC scatterer was in a powder form having an effective thickness of 0.429 g/cm<sup>2</sup>. We made two sets of nuclear absorption experiments; in one set we used liquid <sup>13</sup>CO resonant absorber. In the other set we used 2.424 g/cm<sup>2</sup> AC absorber (98% <sup>13</sup>C).

## Results and Discussion

A typical scattered radiation spectrum from a  $^{13}\text{C}$  AC sample as measured using a hyper-pure Germanium detector (HPGe) is given on Fig. 2 and shows the  $\gamma$ -lines corresponding to nuclear resonance scattering from the two levels in  $^{13}\text{C}$ .

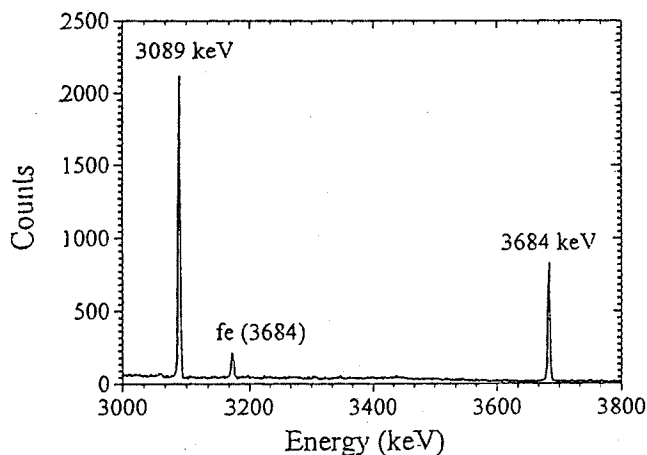


Figure 2. Typical scattered radiation spectrum from enriched (99%  $^{13}\text{C}$ ) AC sample.

The effective temperature  $T_s$  was deduced from the measured self-absorption ratio [2,3]. The deduced value is strongly dependent on the experimental values of the nuclear level widths [11]. Adopting the values  $\Gamma_0(3089 \text{ keV}) = (0.500 \pm 0.042) \text{ eV}$ ,  $\Gamma_0(3684 \text{ keV}) = (0.403 \pm 0.030) \text{ eV}$ , we obtain after averaging:  $T_s = (790 \pm 118) \text{ K}$  for the effective temperature of  $^{13}\text{C}$  in AC. The corresponding value for a natural AC sample (98.89%  $^{12}\text{C}$ ) is deduced by multiplying by the inverse square root of the mass ratio, yielding:  $T_s = (822 \pm 123) \text{ K}$ . The high difference between  $T_s$  and  $T = 295 \text{ K}$  is due solely to the effect of the zero-point kinetic energy of the C-atoms. The present result was obtained at  $T = 295 \text{ K}$ , using isotopic ( $^{13}\text{C}$ ) AC. This measured value may be compared with  $T_s = 720 \text{ K}$  and  $T_s = 743 \text{ K}$  calculated at  $295 \text{ K}$  by integrating over the vibrational density of states (VDOS) of the C-atom as measured in sputtered AC and glassy carbon [4]. It is interesting to note that the above calculated values of  $T_s$  in AC are close to those of graphite where the VDOS were reported in references [5-7]. The corresponding calculated values at  $295 \text{ K}$  are:  $T_s = 717 \text{ K}$ ,  $773 \text{ K}$  and  $725 \text{ K}$ . Our measured value of  $T_s$  is within a little more than one standard deviation of the calculated values. It compares nicely with the average obtained for graphite at  $295 \text{ K}$  using the neutron Compton scattering (NCS)

method [8-10] which yielded:  $T_s = (883 \pm 63) \text{ K}$ ,  $(834 \pm 63) \text{ K}$  and  $(838 \pm 23) \text{ K}$ . The large deviation between the measured and calculated values is not clear yet and could be caused by some unknown high frequency modes in graphite which are not observed yet.

## Conclusions

We have measured the effective temperature of  $^{13}\text{C}$  in amorphous carbon using the NRPS technique using bremsstrahlung. The result strongly depends on the known accuracy of the radiative width of the 3089 and 3684 keV nuclear levels of  $^{13}\text{C}$ . It is not clear however, why the measured effective temperature is higher by about 13% than those calculated using the phonon spectrum of AC. This deviation between the measured and calculated values of  $T_s$  in the case of graphite and amorphous carbon remains an open question.

## Acknowledgements

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