Precise widths of the 3089 and 3684 keV levels in ^{13}C

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The widths of the 3089 keV and the 3684 keV levels in ^{13}C are precisely measured using nuclear self-absorption and employing amorphous ^{13}C absorbers and scatterers. The role of the effective temperature of carbon is discussed in some detail. The result for the 3089 keV level was found to be larger by about 25% than the compiled value.

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I. INTRODUCTION

There is a recent flurry of activity in the measurement of level widths especially in the energy region below 4 MeV where a search is being made for $M1$ transitions related to the scissors mode of the nucleus [1]. In most such measurements a bremsstrahlung beam is employed and several levels of large well-known widths are used for calibration purposes. Among those, the ^{13}C levels at 3089 and 3684 keV are also used, first because the widths of the ground state transitions of those levels are large (around 400 meV) yielding a strong scattering signal [2] and second, the reported accuracy of the compiled widths is better than 10%. Using a bremsstrahlung beam, two methods are used for level width measurements [3]. In the first, the intensity of the scattered radiation from a certain level is compared with calibration levels of known widths. Here one requires a knowledge of both the relative detector efficiency and the bremsstrahlung intensity as a function of energy. In the second, the absolute width is obtained by carrying out a nuclear self-absorption measurement. In this latter method, there is no need to know the absolute intensity of the incident photons which usually contributes the largest uncertainty in the measured width. The determination of the ground state level width Γ_0 of the ^{13}C levels by self-absorption requires, however, an accurate value of the effective temperature T_e of the scattering atom [3,4] in the particular sample. The value of T_e is related to the Doppler width $\Delta = E(2kT_e/Mc^2)^{1/2}$ where E is the nuclear level energy, and M is the nuclear mass. Because of the importance of the value of T_e for the results of the present work, we hereby discuss it in more detail.

The notion of the effective temperature T_e was first introduced by Lamb to take into account the actual vibrational motion of the atoms in a lattice by viewing them as Planck oscillators having a continuous frequency distribution, $g(\nu)$, given by the Debye approximation $g(\nu)d\nu \propto \nu^2 d\nu$ with an upper cutoff frequency ν_m related to characteristic Debye temperature Θ by the relation $h\nu_m = k\Theta$. Thus instead of the classical average energy per mode of vibration in a solid, kT, Lamb obtained $\epsilon = kT_e$, where T_e is given by [4]

$$\frac{T_e}{T} = 3\left(\frac{T}{\Theta}\right)^3 \int_0^{\Theta/T} x^3 \left(\frac{1}{e^x - 1} + \frac{1}{2}\right) dx. \quad (1)$$

The normal procedure for calculating T_e, due to Lamb, is to find an experimental value of Θ for the particular ^{13}C sample and substitute it into Eq. (1). However, this procedure can yield a variety of values of T_e markedly different from each other depending on the particular choice of Θ. This in turn depends, however, not only on the particular chemical form of the sample but also on its crystallographic structure. The most common forms of pure carbon are graphite and amorphous carbon or a combination of both. In the literature [5–10] numerous values of Θ for graphite and carbon were reported, ranging from 530 to 1967 K depending on the method of measurement. Furthermore, it was found that the above procedure of calculating T_e is not applicable to light elements such as boron [11] where the atomic binding is very strong and the phonon spectrum of the lattice contains *discrete* optical high frequency vibrations which are usually not accounted for by the Debye model. A similar situation is expected to hold for the case of a carbon target. We decided therefore not to use this procedure because it may yield a wide range of values depending on the choice of Θ. The choice of the particular value of T_e can best be made by first considering its physical meaning which essentially expresses the *total* kinetic energy of the atom including that of its zero-point motion. This may be deduced by integrating over all frequencies of the vibrational spectrum of the carbon atoms namely over the phonon spectrum $g(\nu)$ of the atomic lattice. Thus T_e may be expressed as

$$T_e = \frac{1}{k} \frac{\int_0^{\nu_m} g(\nu) h\nu\alpha d\nu}{\int_0^{\nu_m} g(\nu) d\nu} \quad (2)$$

where

$$\alpha = \left[\exp\frac{h\nu}{kT} - 1\right]^{-1} + \frac{1}{2} = \frac{1}{2}\coth\frac{h\nu}{2kT}. \quad (3)$$

For the case of graphite, the phonon spectrum $g(\nu)$ was

calculated by Nicklow *et al.* [12], hence the value of T_e may be obtained by carrying out a numerical integration using Eq. (2); the resulting value at 295 K is $T_e = 773$ K. It is of interest to compare this T_e with values ranging between $T_e = 341$ and 755 K which are obtained from Eq. (1), using graphite Debye temperatures in the range 530–1967 K reported by various authors using graphite and other types of carbon [5–8,10]. It can thus be seen that the use of the large value of T_e in a self-absorption measurement leads to a larger value of Γ_0 by a factor $(755/341)^{1/2} = 1.49$. This illustrates the kind of deviations which one could obtain when using the first approach contained in Eq. (1) for calculating T_e. Such an effect may also occur in a *scattering* experiment because of the finite thickness of the target which also has a nuclear self-absorption effect. It should also be added that by using $T_e = 773$ K obtained from Eq. (2) it is possible to deduce the corresponding Debye temperature from Eq. (1) yielding $\Theta = 2018$ K.

In the present work, we used amorphous carbon both as a target and as a nuclear absorber. This is because, in the present experiment, we used isotopically enriched elemental ^{13}C (both as an absorber and scatterer); it is commercially supplied only in an amorphous form and not in a graphite form. It was thus necessary to get a quantitative measure of T_e for amorphous carbon. This cannot be obtained, however, by using Eq. (2) because the phonon spectrum of amorphous carbon is not known. In view of the above we decided to determine the T_e of the amorphous ^{13}C by carrying out an independent experiment [13]. It turned out that the measured value of T_e is surprisingly high as briefly discussed in Sec. III A.

II. EXPERIMENTAL PROCEDURE

Experimentally, the ^{13}C levels were photoexcited using a bremsstrahlung source obtained by an electron beam hitting a 4 mm thick gold radiator plate containing small holes (1 mm diam) through which pressurized water was passed for cooling purposes. This radiator thickness ensured a complete stopping of the beam. The electron beam energy was 4.1 MeV with average currents varying between 150 and 250 μA, depending on the run number; it was obtained from the Dynamitron accelerator of the University of Stuttgart having a 100% duty cycle. The beam was passed through a 3 mm lead hardener and then to a 1 m long lead collimator (having a 1.0 cm through hole) before striking the target. Two separate runs were carried out. In the first, the target consisted of 0.396 g/cm^2 of 98% enriched amorphous ^{13}C inserted inside a thin walled cylindrical plastic container having 2.0 cm internal diameter; the scattered radiation was detected using two hyperpure germanium (HPGe) diodes having efficiencies of 85% and 40% and placed at distances of 20 cm from the target. In the second run, a thicker target of amorphous ^{13}C, 0.590 g/cm^2, was used in a similar arrangement but with the 85% HPGe detector placed at an angle of 127° and another HPGe detector of 23% efficiency placed at 90°. In both runs the scatterers were positioned with the symmetry axis coinciding with the axis of the photon beam. For self-absorption, three separate measurements were carried out using different absorbers all containing amorphous ^{13}C (98%) placed inside a copper cylinder of 16.0 mm inner diameter with thicknesses of 2.424, 1.571, and 1.251 g/cm^2. The comparative nonresonant absorbers consisted of an equivalent weight of powdered natural graphite containing 98.89% ^{12}C and 1.11% ^{13}C. In both runs, a 2.5 cm lead filter was placed in front of the 85% HPGe detector, while lead (2.5 cm) and copper (1 cm) filters were placed in front of the other detectors. These filters helped to attenuate markedly the intense low-energy scattered radiation. Care was taken to shield the detectors from the radiation scattered by the ^{13}C absorbers by using a total of 20 cm thick plates of lead. Great care was taken in aligning the electron beam, the bremsstrahlung beam, the collimators, the absorbers, and the target to ensure that the entire photon beam would pass through the amorphous ^{13}C absorbers before hitting the sample. This was important, because any fraction of the photon beam which could reach the target without passing through the absorber may severely distort the measured self-absorption effect.

III. RESULTS AND DISCUSSION

A typical scattered spectrum from the amorphous ^{13}C target is shown in Fig. 1 which also displays the effect of nuclear attenuation of two ^{13}C absorbers of different thicknesses on the scattered intensity. In fact by using ^{13}C absorbers of thickness 2.424, 1.571, and 1.251 g/cm^2 the scattered intensity ratio (relative to equivalent ^{12}C absorbers) were 45.4%, 57.4%, and 67.2%, respectively, for the 3089 keV level while the corresponding values for the 3684 keV level were 48.6%, 59.5%, and 70.5%. The radiative widths obtained from the weighted average of the above three independent measurements are given in Table I where the errors include both the statistical contributions and an estimate of other uncertainties. The table also lists previous results obtained using (γ,γ') and (e,e') excitations. The present results were obtained using the following values of the excitation process: $\Gamma_0/\Gamma = 1$ and T_e= 930 K for both levels, $J(3089)$=1/2, $J(3684)$=3/2. The high value of the effective temperature used here was determined experimentally as explained below.

A. Determination of T_e of amorphous ^{13}C

The value of T_e for amorphous ^{13}C was obtained by a separate experiment which will be published in detail elsewhere. Here we outline briefly the method used. The amorphous ^{13}C (98%) sample whose T_e is to be deter-

TABLE I. Level widths (meV).

	3089 keV	3684 keV
Ref. [2]	424 ± 41	408 ± 26
(e,e') [18]	680 ± 230	362 ± 47
Present	537 ± 42	403 ± 30

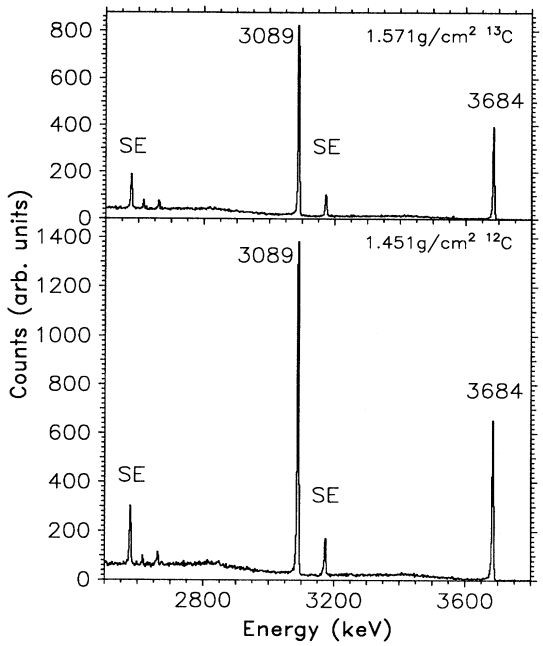

FIG. 1. Scattered radiation spectra obtained using an amorphous ^{13}C scatterer with ^{13}C absorbers of various thicknesses. The spectra are normalized to the same photon flux and show the influence of the nuclear absorption on the scattered intensities. The figure at the bottom was taken with a 1.451 g/cm^2 natural carbon while the other spectrum was taken with a 1.571 g/cm^2 ^{13}C amorphous absorber. Lines marked by SE correspond to single escape peaks.

mined was used as an absorber in a self-absorption experiment in which the scatterer consisted of a highly oriented pyrolytic graphite (HOPG) sample of natural abundance (1.11% ^{13}C). Here the scattered intensity from the ^{13}C levels were compared for the two orientations (parallel and perpendicular) of the graphite planes of the HOPG with respect to the photon beam. In this manner the anisotropy of the scattered radiation with respect to the HOPG target was determined. It should be added that this measurement was carried out in a similar fashion to that described in Ref. [14] but with two differences. The absorber and scatterer of Ref. [14] were replaced by amorphous ^{13}C and HOPG, respectively. From the measured value of the anisotropy and from a knowledge of the effective temperatures $T_\perp$ and $T_\parallel$ of carbon in the two perpendicular directions of HOPG, it was possible to determine the T_e of amorphous ^{13}C which was found to be $T_e = 930\pm70$ K. It should be noted that the input data in the above were $T_\perp = 550$ K and $T_\parallel = 1050$ K which were taken from Ref. [15] where the effective temperatures were determined experimentally using "Compton" scattering of epithermal neutrons. The above experimental value of T_e is high and was entirely unexpected; however, recent studies by Tersoff [9] carried out on amorphous carbon seem to strongly support the above findings. This high value of T_e leads to large Doppler widths (at 296 K), namely, $\Delta(3089)=11.94$ eV and $\Delta(3684)=14.24$ eV to be compared with $\Delta(3684)=8.4$ eV used in Ref. [16]. It should be emphasized that some of the Θ and T_e values quoted above are for the ^{12}C which is the most abundant isotope and can be corrected to that of ^{13}C by multiplying by the mass factor being, $(12/13)^{1/2}$.

B. Comparison of level widths

It is of interest to compare the present value of Γ for the 3684 keV level with previous results. Rasmussen and Swann [16] measured the gamma-ray width of the 3684 keV level by comparing the scattered intensity with that of levels in ^{6}Li and ^{31}P. To avoid large self-absorption corrections they used what seems to be an *amorphous* carbon sample enriched to 58% ^{13}C which corresponds to a thin (0.1 g/cm^2) ^{13}C target. They assumed a small Doppler width, $\Delta=8.4$ eV , obtained by assuming a very small value of T_e namely 360 K. This resulted in a gamma width $\Gamma = 0.44 \pm 0.04$ eV, which is about 10% higher than the present value. It is very remarkable to note that when the correction for self-absorption in their thin target is recalculated by using the present value of T_e, the resulting gamma width of the 3684 keV level is very close to our value (Table I). Those authors [16] were aware of the importance of the value of T_e and in a footnote to their paper they mentioned the fact that if one would have taken the Debye temperature to be 1800 K which yields $\Delta=11.8$ eV, the resulting width would have been lower than their reported value, namely 0.42 eV.

The deviation of the present result of the 3089 keV level from that of Robinson *et al.* [17] is quite large; it could have been caused by the fact that they used a large, 380 g graphite target consisting of natural carbon (1.11% ^{13}C) yielding a small signal to noise ratio. This together with the fact that they used a higher Z nonresonant target consisting of Mg for their background measurement has very probably contributed to the enhancement of the background leading to a small net scattered signal.

It may be noted that the present measured width of the 3089 keV level is medium between the photoexcitation measurement [17] and that obtained using the (e,e') technique [18]. It is very important to emphasize that the fact that the nuclear absorption of the 3089 keV level is larger than that of the 3684 keV level sets a lower limit to the width of the 3089 keV. Thus even if we were to use a much lower value of T_e of amorphous ^{13}C such as $T_e = 420$ K [obtained using Eq. (1) above with some average Debye temperature for graphite of say $\Theta = 900$ K] and normalize the deduced width of the 3089 keV level to the adopted width of the 3684 keV level , namely to $\Gamma_0(3684) = 0.41$ eV (taken from Ref. [2]), the result would be $\Gamma_0(3089) = 0.55$ eV which is in essential agreement with the result of the present work listed in Table I.

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