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Positron annihilation in boron nitride

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Abstract. The positron lifetime and Doppler shift of boron nitride have been studied. A positronium yield was indicated by the lifetime being longer than 700 ps and by the magnetic quenching of the Doppler shift. An orientation dependence of the Doppler spectrum was observed and this is explained in terms of two-dimensional motion of positronium between basal planes. It is deduced that a proportion of the positrons are trapped by defects and that these annihilate within a lifetime of about 355 ps, which is nearly equal to the lifetime for the defects of graphite.

1. Introduction

Boron nitride and graphite have crystal structures that are almost the same—they comprise stacks of hexagonal-network planes and the lattice constants are almost equal. Their electronic constants are distinctly different, however—boron nitride is an insulator whose energy gap between the valence band and the conduction band is relatively wide, while graphite is a semiconductor with a nearly zero-gap band structure.

The positron annihilation in graphite has been extensively studied since the first report by Berko *et al* (1958). Dominant positrons injected with a high energy annihilate in the form of free positrons or positrons trapped by defects (Iwata *et al* 1981, Jean *et al* 1984, Rice-Evans *et al* 1986, Kanazawa *et al* 1987, Saito *et al* 1988). A positronium yield was detected with slow positrons (Sferlazzo *et al* 1988). In contrast, little work on boron nitride has been reported (Chiba and Akahane 1988).

We are interested in positron annihilation in boron nitride because its crystal structure almost coincides with that of graphite while its electronic properties are very different. In the study reported here, we examined the positron annihilation lifetime and Doppler shift of boron nitride and discussed the annihilation modes, comparing them with those of graphite.

2. Experimental procedure

Pyrolytic boron nitride (PBN) sheets of approximate area $5 \times 5\ mm^2$ were piled up to a height of about 4 mm. A positron source, $^{22}NaCl$, $\sim 10\ \mu Ci$, was set in the centre of the pile. Lifetime measurements were carried out using a fast–fast system with a BaF_2 scintillator. The time resolution was 210 ps, using the two photons from ^{60}Co through

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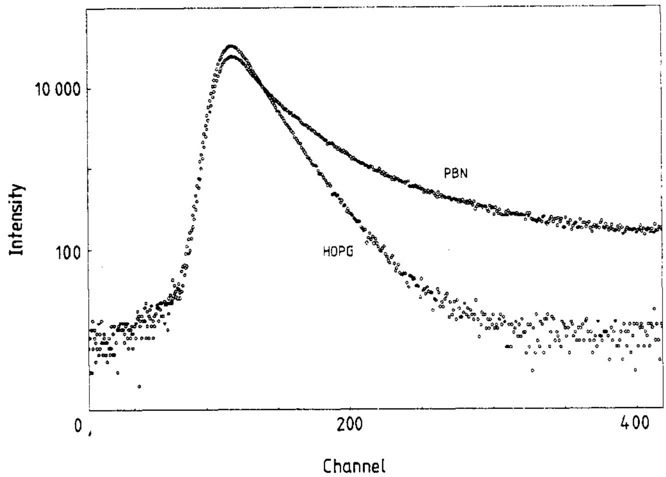

Figure 1. Lifetime spectra of PBN and HOPG (14 ps/channel). An extremely long lifetime component is found in the spectrum of PBN.

Table 1. Components of lifetimes and intensities calculated from lifetime spectra of *pyrolytic boron* PBN and HOPG.

	Lifetime (ps)				Intensity (%)			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
PBN	155 ± 10	355 ± 10	850 ± 150	6000 ± 1000	24	44	20	12
HOPG	210 ± 10	390 ± 10	—	—	91	9	—	—

energy windows for positron annihilation. The lifetime spectra were analysed using a computer program based on the formulation proposed by Kirkegaard and Eldrup (1974). Doppler-broadened spectra were obtained with a pure Ge detector system whose energy resolution was 0.98 keV at FWHM of 512 keV mono-energetic γ-rays from ^{106}Ru. In order to study the effect of magnetic quenching, the sample was set in a magnetic field of about 10 kG. The Doppler spectra were deconvoluted by a Fourier transformation method (Saeffer *et al* 1984).

3. Results and discussion

Extremely long lifetime components clearly appear in the spectrum of PBN as shown in figure 1, where a spectrum of highly orientated pyrolytic graphite (HOPG) is also plotted. The results of the lifetime analyses are listed in table 1. Two lifetime components, 6000 and $\simeq$850 ps, are assigned to the 'pick-off' annihilation of ortho-positronium. The two annihilation modes may be understood by considering some of the ortho-positronium to annihilate through a pick-off mechanism on the crystal surfaces and the internal surfaces, and the others to annihilate in the interlayer spaces between network planes.

The average electron density of boron nitride is almost equal to that of graphite. It is thought that the lifetimes in states trapped by defects are similar in the two materials.

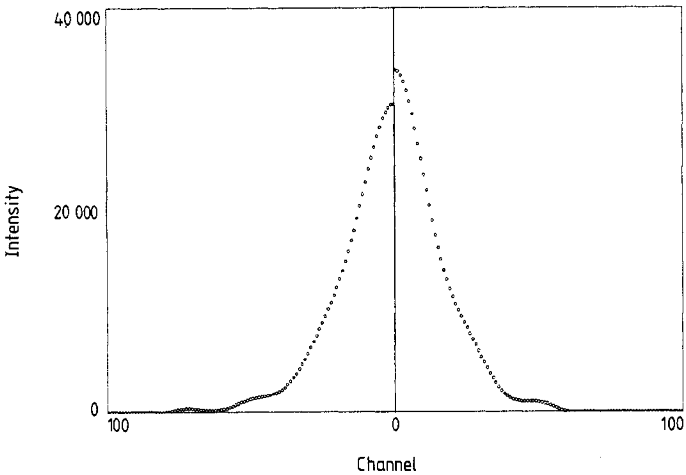

Figure 2. The Doppler spectrum of boron nitride in a magnetic field of ≃10 kG (right-hand panel) and out of the field (left-hand panel). The effect of magnetic quenching is clear.

The lifetime of 355 ± 10 ps in boron nitride is comparable to that of 390 ± 10 ps in graphite, which has been assigned to the annihilation in states trapped by defects (Iwata *et al* 1981, Jean *et al* 1984). We consider that the component ≃355 ps is attributable to the annihilation of positrons trapped by defects.

Taking into consideration the active yield of ortho-positronium, para-positroniums are also formed at a considerable rate. The shortest components, 155 ± 10 ps, is considered to be related to annihilation of both free positrons and para-positronium. However, it is not worth decomposing this component further because of the time resolution limit.

Doppler-broadened spectra were measured in the magnetic field and out of the field and are shown in figure 2. The spectra are roughly decomposed into two Gaussian

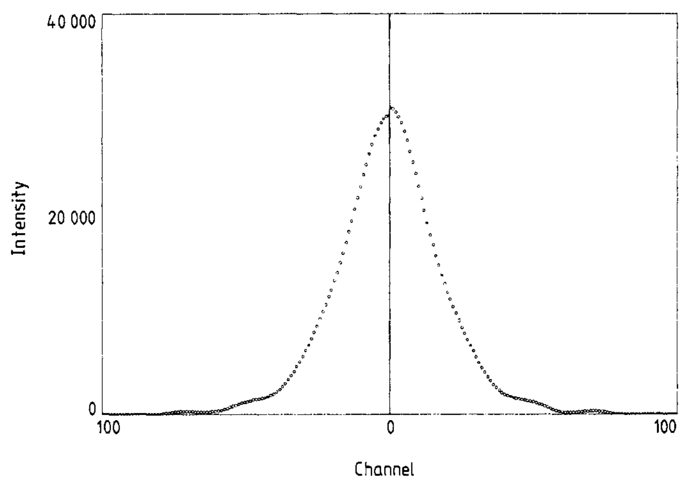

Figure 3. The orientation dependence of the Doppler spectrum. The peak height of the spectrum measured perpendicular to the *c* axis (right-hand panel) is higher than that parallel to the axis (left-hand panel).

spectra. The values of the FWHMs and the integrated intensities are $\simeq$18 channels ($\simeq$1.26 keV) and $\simeq$12% for a narrow component, and $\simeq$40 channels ($\simeq$2.94 keV) and $\simeq$88% for a broad component when the sample is out of the magnetic field. When the sample is in the field, the intensity of the narrow component increases to $\simeq$20% and that of the broad component decreases to $\simeq$80% while no change in FWHM is detected in either component. The enhancement of the narrow component by the magnetic field—the magnetic quenching—is clear. It is revealed that a relatively high proportion of positrons annihilate as para-positroniums in boron nitride.

The peak of the Doppler spectrum measured in the direction perpendicular to the *c* axis is higher than that in the parallel direction as shown in figure 3. One possible origin of this anisotropy is the positronium motion being restricted to the two-dimensional space between basal planes, as pointed out by Chiba and Akahane (1988).

4. Conclusions

The yield rate of positronium in boron nitride is considerably higher than that in graphite. The lineshape of the Doppler spectrum depends on crystal orientation and the dependence can be explained in terms of the two-dimensional motion of positronium. The lifetime of positrons trapped in defects is $\simeq$355 ps—nearly equal to that in defects of graphite, $\simeq$390 ps.

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