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Positron annihilation in flight: experiment with slow and fast positrons

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Abstract. A novel digital coincidence Doppler broadening (D-CDB) spectrometer was employed for energy resolved investigations of two-quantum annihilation-in-flight (TQAF). The TQAF phenomenon was studied using monoenergetic positrons produced in a slow positron beam and also using fast positrons. Because of a low background the measurements on the slow positron beam could be performed in a close geometry and the TQAF contribution in the two-dimensional gamma ray energy spectra fills a 'bowl-like' area delimited by a hyperbolic curve and a kinematical cut-off determined by the kinetic energy of positrons. With decreasing positron energy the area of TQAF contribution becomes smaller and disappears completely for slow positrons with energies below ~ 100 eV. The measurements with fast positrons were restricted to a limited range of angles between the annihilation gamma rays and the TQAF events contribute to a hyperbolic band in gamma ray energy spectrum.

1. Introduction

An energetic positron implanted into a solid loses rapidly its kinetic energy in collisions with electrons and reaches quickly thermal equilibrium with the surrounding medium. As a consequence positrons are annihilated predominantly in thermalized state. However, a small fraction of positrons is annihilated before reaching the thermal equilibrium. These so called annihilation-in-flight (AiF) events differ significantly from annihilations of thermalized positrons because the positron momentum substantially exceeds the momentum of electrons and causes a large Doppler shift of the annihilation radiation. Two-quantum annihilation-in-flight (TQAF) is the dominating AiF channel known for a long time [1]. Coincidence Doppler broadening (CDB) technique introduced by Lynn et al. [2] is based on a precise measurement of the Doppler shift of annihilation radiation and becomes nowadays widely used for characterization of the chemical environment of defects. Weber et al. [3] demonstrated that CDB technique is a suitable tool also for investigation of the TQAF phenomenon. Since TQAF events occur rarely a low background measurement is crucial. A novel (D-CDB) spectrometer [4] developed recently enables to achieve an extremely low background because of detailed shape analysis which eliminates pulses distorted by pile up or by slow charge collection (ballistic deficit). In the present work a D-CDB spectrometer was employed for investigations of the TQAF phenomenon using monoenergetic slow positrons and also fast positrons with continuous energy spectrum.

2. Experimental details

The CDB investigations were performed using a D-CDB spectrometer [4] equipped with two HPGe detectors. To improve the signal-to-noise ratio detector pulses were amplified and sharpened to semi-Gaussian shape in spectroscopy amplifiers. Shaped pulses were sampled by a two channel 12-bit digitizer Acqiris DC 440. Analysis of sampled waveforms was performed off-line by software using the algorithm described in Ref. [4]. The CDB spectra are presented as two-dimensional plots of the sum of energies of annihilation gamma rays $E_1 + E_2 - 2m_0c^2$ (the rest energy of annihilating pair subtracted) versus the difference of these energies $E_1 - E_2$.

TQAF events were investigated using positrons from various sources: (i) monoenergetic positrons with energy adjustable in the range from 0.03 to 36 keV created in a variable energy slow positron beam SPONSOR [5], (ii) fast positrons emitted by ^{68}Ge/^{68}Ga positron generator and exhibiting a continuous energy spectrum with the end-point-energy of 1897 keV, and (iii) fast positrons with a continuous energy spectrum up to 16 MeV created from bremsstrahlung radiation by pair production in a target, so called gamma-induced positron spectroscopy (GiPS) [6].

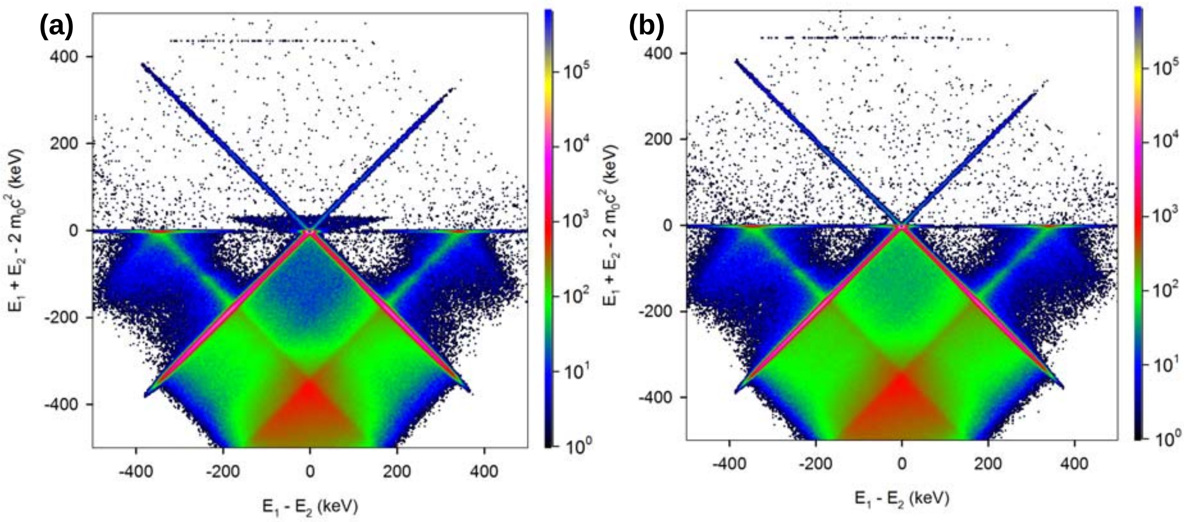

Figure 1. CDB spectra for Fe target obtained using positrons with energy of 35 keV (a) and 27 eV (b).

3. Results and discussion

The CDB spectra measured on the slow positron beam using a 0.5 mm thick Fe target are plotted in Fig. 1. In these measurements HPGe detectors were positioned face-to-face in a distance of 45 mm from the target and perpendicularly to the beam direction. Fig. 1(a) shows the CDB spectrum for positrons with kinetic energy of 35 keV. The TQAF contribution is clearly visible as a 'bowl-like' area located above the main annihilation peak of thermalized positrons. From the conservation of energy and momentum it follows that the sum of energies of gamma rays emitted in a TQAF event is related to the difference of these energies through the relation [7]

$$E_1 + E_2 - 2m_0c^2 = \sqrt{(E_1 - E_2)^2 + \left(\frac{2m_0c^2}{1-\cos\theta}\right)^2} + \frac{2m_0c^2\cos\theta}{1-\cos\theta}, \qquad (1)$$

where θ is the angle between the two gamma rays. The sum $E_1 + E_2 - 2m_0c^2$ cannot be higher than the kinetic energy of incident positrons, i.e. 35 keV in Fig. 1(a). This upper limit can be seen as the kinematical cut-off of the TQAF contribution. Since the kinetic energy of a positron implanted into the target is progressively lowered in electronic collisions some positrons lost portion of their kinetic energy prior to the TQAF process and contribute to the 'bowl area' below the kinematical cut-off. The annihilation gamma rays emitted in anti-parallel directions ($\theta = 180^\circ$) exhibit the largest difference of energies. From Eq. (1) it follows that such TQAF events fall on a hyperbolic curve determining borders of the ‘bowl-like’ area in Fig. 1(a). Projection cuts from the CDB spectra of Fig. 1 are plotted in Fig. 2. The TQAF contribution is clearly visible above the main annihilation peak and exhibits a sharp drop at 35 keV corresponding precisely to the kinetic energy of positrons in the beam. The inset in Fig. 2(a) shows that shape of the TQAF profile is well described by theoretical curve calculated using the TQAF cross section [8] and the positron stopping power [7]. From Eq. (1) one can calculate that for positrons with kinetic energy of 35 keV the TQAF contribution extends to the range $E_1 - E_2 = \pm$ 192 keV, which agrees well with the horizontal projection in Fig. 2(b). The shape of the horizontal projection is again well described by the theoretical curve. The minimum angle between the TQAF gamma rays is related to the maximum kinetic energy of positron $T_{+,max}$ by the relation $(\cos\theta)_{min} = (T_{+,max} - 2m_0c^2)/(T_{+,max} + 2m_0c^2)$ [8], i.e. for $T_{+,max}$= 35 keV, θ_{min}=159°. Taking into account the geometry of the experiment and dimensions of detectors, if one photon falls into the centre of one detector then the second one can be detected if θ>115°. Close geometry used here ensures that TQAF events can be detected in the full range of angles θ = 180°-159° allowed for positrons with $T_{+,max}$= 35 keV.

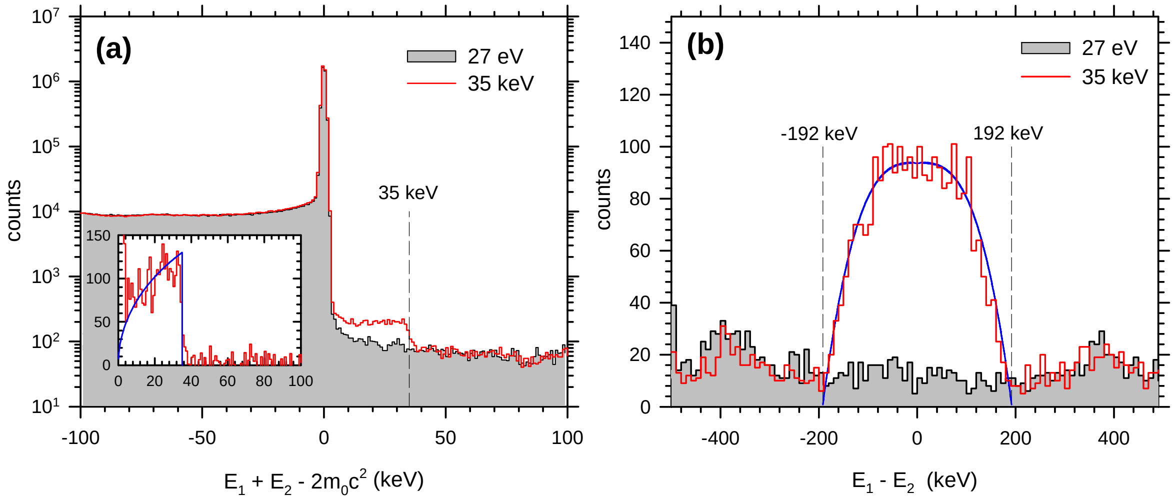

Figure 2. One-dimensional projections from CDB spectra of Fig. 1: (a) vertical cut integrated in the range -192 < $E_1 - E_2$ < 192 keV, inset shows the detail of the TQAF contribution and the theoretical shape calculated within QED, (b) horizontal cut integrated in the range 5 < $E_1 + E_2 - 2m_0c^2$ < 35 keV, solid line shows the theoretical shape of the integrated TQAF contribution calculated within QED.

With decreasing energy of incident positrons the kinematical cut-off decreases and the ‘bowl’ area becomes smaller. In Fig. 1(b) one can see that the TQAF contribution completely disappeared in the CDB spectrum for slow positrons with energy of 27 eV. Hence the present experiment can be used as a benchmark test to verify the absence of fast positrons in the slow positron beam.

Side peaks visible in Fig. 1 on both sides of the main annihilation peak are caused by the events when annihilation gamma ray in one detector is back-scattered into the second detector. If the backscattering angle is 180° the energy difference between the Compton electron (341 keV) registered in one detector and the backscattered gamma ray (170 keV) detected in the second detector together with the second annihilation photon (511 keV) is ± 340 keV which corresponds well to the maxima of the side peaks in Fig. 1. The horizontal line at $E_1 + E_2 - 2m_0c^2$ = 438 keV comes from events when a gamma ray emitted by a ^{40}K radioisotope from background is scattered between the detectors.

The CDB spectra for fast positrons from ^{68}Ge/^{68}Ga radioisotope and GiPS are plotted in Fig. 3(a) and 3(b), respectively. The detectors were again positioned in face-to-face geometry but because of a significantly higher count rate the distance of detectors from the target was much higher than in the measurements on the slow positron beam. As a consequence, only the TQAF events with θ in a narrow range 177-180° can be detected and these events fall on a hyperbolic curve which is clearly visible in

Fig. 3 and represents the border of the TQAF 'bowl'. Obviously the TQAF contribution in Fig. 3 extends to significantly higher energies due high energies of incident positrons. Moreover, from comparison of Figs. 1 and 3 it becomes clear that the background above the main annihilation peak in the CDB spectra measured using fast positrons is higher than for slow positrons. In case of $^{68}Ge/^{68}Ga$ radioisotope the background is caused mainly by Compton scattering of gamma rays with energy of 1078 keV in the detectors. In case of GiPS the background is rather high due to Compton scattering of bremsstrahlung radiation in the target. Asymmetry of background in Fig. 3(b) is caused by the fact that one detector was positioned in the forward direction while the second one in the backward direction with respect to the beam. Since the source of this background is not in pile up events and the corresponding pulses have proper shape they cannot be removed by the shape analysis.

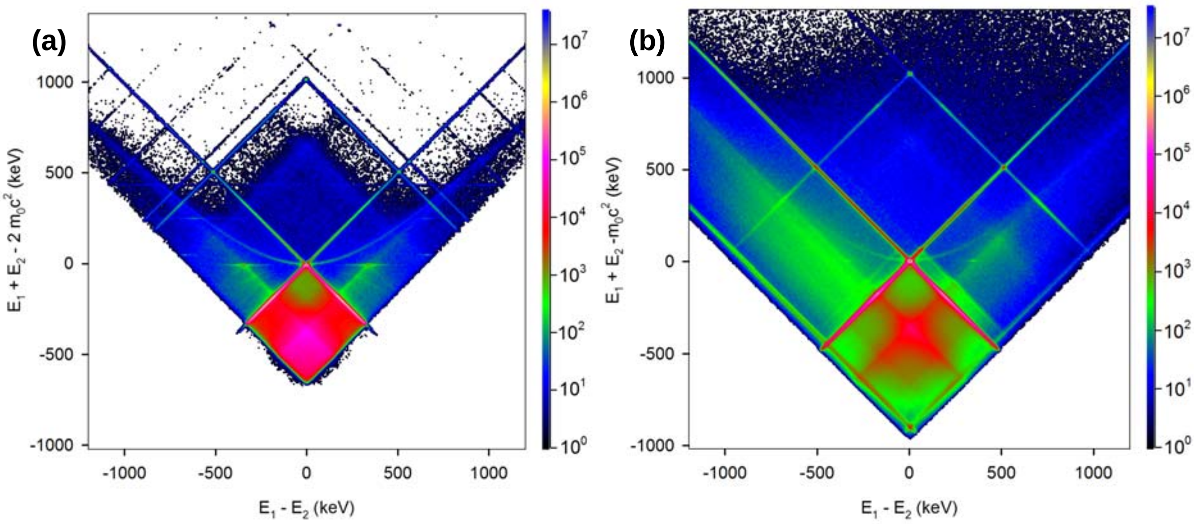

Figure 3. Two-dimensional CDB spectra measured using fast positrons (a) Mg target, positrons emitted by a $^{68}Ge/^{68}Ga$ positron generator, (b) W target, positrons created by GIPS.

4. Conclusions

A novel D-CDB spectrometer was employed for investigation of the TQAF process. The CDB spectra measured on slow positron beam exhibit low background and a 'bowl' shape TQAF contribution was detected for positrons accelerated to 35 keV. Analysis of the TQAF contribution provides information about positron thermalization in the target. The CDB spectra measured using fast positrons exhibit a remarkably higher background but even here the TQAF contribution was clearly visible.

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5. References

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