USE OF ENERGY SUMMING
FOR SELECTION OF COINCIDENCE EVENTS
IN POSITRON-LIFETIME SPECTROSCOPY

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A BaF_2 positron-lifetime spectrometer equipped with a coincidence system that represents a compromise between the traditional fast-fast and fast-slow arrangements is described. The main difference of the present configuration from both the fast-slow and fast-fast ones consists in use of a sum of the energy signals from the start and stop detectors to select the coincidence events. Quality of the spectrometer response function (≈ 150 ps FWHM for ^{22}Na) is very close to that observed for our fast-slow configuration with the equivalent detectors but throughput of the present apparatus is increased almost by a factor of two. Moreover, the electronic scheme becomes less complicated, which has also a positive impact on its cost.

PACS numbers: 78.70.Bj

1. Introduction

Quality of an experimental device for positron-lifetime spectroscopy (PLS) is first of all given in terms of the time-resolution power and the coincidence counting rate. The counting rates are strongly influenced by the energy intervals chosen for selection of the coincidence events and by the detector–source geometry. However, attempts to increase the rates simply by making the geometry as compact as possible or by extending the energy windows for which the coincidence events are accepted are applicable only with limitations because such measures can produce significant degradation of the spectrometer response function and the time resolution may then become unadmissible. This happens due to registration of the unwanted coincidence events caused by too wide energy windows or due to enhanced effects of pulse summation. For the same reasons and also due to scattering of photons between the detectors, shape distortions of the measured positron-lifetime spectra may occur. As a consequence, analyses of such spectra yield frequently a spurious short-lifetime component. Without going into tedious

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details, it can be stated that all the outlined imperfections are enhanced in the fast-fast (FF) rather than fast-slow (FS) coincidence systems being conventionally used in the fast-timing $\gamma-\gamma$ spectrometry.

A sufficiently precise and efficient energy selection of the coincidence events seems thus *necessary* for the attaining of a good time resolution in PLS as well as for the avoiding of the above degradation and distortion effects. In respect of this, the BaF_2 scintillation detectors of photons, introduced into PLS more than ten years ago [1], appeared to be highly convenient. They provide for an excellent timing similar to that of the best plastic scintillators and for a considerably larger γ-ray efficiency. The BaF_2 detectors exhibit also a good enough energy resolution which becomes to be sufficient for selection of the coincidence events using the well-resolved full-absorption peaks in γ-ray spectra. These features are important for both the FF and FS arrangements.

In our recent paper [2], a BaF_2 positron-lifetime spectrometer equipped with the FS scheme has been described. An excellent time resolution of ≈ 150 ps FWHM for a ^{22}Na positron source was attained with this spectrometer and kept during a long-time operation period. Simultaneously, the coincidence counting rate of $35 \div 40$ s^{-1} was reached with this device. There was, however, still feeling that a considerable loss of the coincidence events may take place due to the large dead times arising in the slow part of the FS coincidence system when the system is operated at high single counting rates in the start and stop channels. As an attempt to get an increase in the coincidence counting rate, a simplified mode of energy selection of the coincidence events (denoted as FFS) is suggested for use in PLS in the present work. It is relied upon utilizing of the *sum* of the start and stop energy signals with the energy window being adjusted at the sum of energies of the start and stop photons. A spectrometer operating on the basis of such a principle is described and the first results of its tests are given below. To authors' knowledge, this principle has not yet been applied to PLS.

2. Experimental setup

The present FFS configuration was created by modification of our previous FS spectrometer [2]. Principal scheme of the FFS apparatus is shown in Fig. 1. Its detector part consists of two BaF_2 cylindrical scintillators ($\phi 25$ mm $\times$ 10 mm) coupled to Philips XP2020/Q photomultipliers (PMT's), see Ref. [2] for details. Screening of the PMT's from the environmental magnetic field is accomplished by means of a pair of the Helmholtz coils. The detectors are positioned in face-to-face geometry with common symmetry axis. The distance between the front sides of the scintillators amounts typically 12 mm. The positron source (^{22}Na) is located between the detectors out of the axis at a radial distance slightly greater than the scintillator radius. A 2.5 mm thick lead shielding is placed in front of the start detector to suppress the detecting of the photons backscattered from the detector to its opposite partner.

The timing (fast) signals are processed in a way identical to Ref. [2]. The signal is taken from the 10th dynode and passed to a constant-fraction differential discriminator (CFDD) ORTEC Model 583. No pulse inversion is performed before the signal reaches the CFDD input. The CFDD's generate timing-output
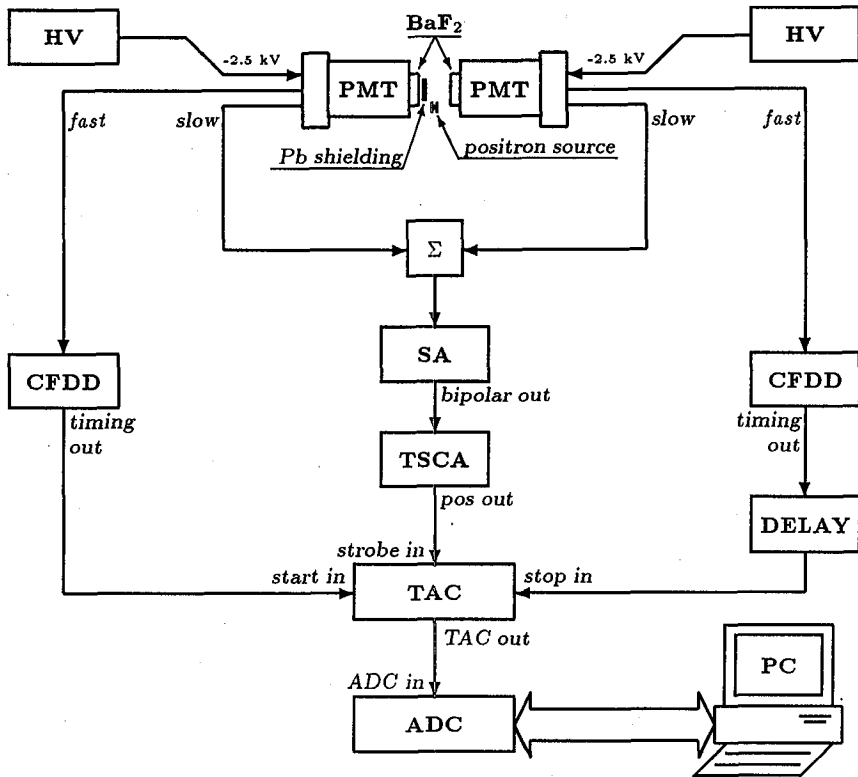
Fig. 1. Principal scheme of the FFS spectrometer. Abbreviations of the individual modules are given in text.

pulses activating the start and stop inputs of a time-to-amplitude converter (TAC) ORTEC Model 567 and provide also for a coarse filtering of the events according to energy.

The energy (slow) signals are taken from the 9th dynode and shaped to resemble signal from a semiconductor detector [2]. The signals from both the detectors are led to a passive circuit (Σ) in which they are first properly balanced in order to compensate different gains of the start and stop PMT's and then summed. The sum signal appearing at the Σ output is amplified using a spectroscopy amplifier (SA) CANBERRA Model 2020 (0.25 μs shaping time) to feed a timing single-channel analyser (TSCA) ORTEC Model 551. The window of the TSCA is adjusted at the peak of the energy sum of the start and stop photons, i.e. at 1785 keV in the case of the ^{22}Na positron source. The TSCA output signal is then used to strobe the TAC output.

The output pulses from the TAC are processed in an analog-to-digital converter (ADC) CANBERRA Model 8077 whose data output is connected either via an interface card to a personal computer (PC), see Fig. 1, or to a histogramming memory operated by means of a CAMAC auxiliary crate controller, as used in

our earlier spectrometer [2]. In both cases, data-acquisition control including the software correction for a possible slow drift of the zero-time point during measurement [2] is involved. Precise absolute calibration of the time scale of the TAC–ADC tandem has been carried out using a procedure described also in [2].

3. Test measurements and results

Several measurements of positron-lifetime spectra have been carried out for the purpose of tests of the FFS apparatus described in the preceding section. The results of decompositions of the spectra have been compared with the data obtained by means of the FS device [2] for the same specimens, positron source as well as detector–source geometry. The two reference materials were chosen for testing: (i) The well-annealed pure α-iron which represents a known defect-free system exhibiting a single exponential component. (ii) The reactor pressure vessel (RPV) steel 15Ch2MFA containing trapping centres for positrons which is expected to show several components contributing to the lifetime spectrum, one of them having the positron lifetime well below 100 ps. The positron source was made of ≈ 1.3 MBq of the carrier-free ^{22}NaCl (Amersham) deposited and sealed between the two mylar foils of 2 μm thickness. Diameter of the radioactive spot did not exceed 3 mm. The source was closely sandwiched between a pair of plates made of the material studied ($1 \times 1 \times 0.03$ cm^3). At least $\approx 8 \times 10^6$ counts were collected in each of the measured spectra. An example of the spectrum taken with the aid of the FFS apparatus for the α-iron is given in Fig. 2. The spectra were decomposed into the three or four exponential components by means of a procedure [3] based on the maximum-likelihood method and assuming that measured intensities of positron-lifetime spectra fluctuate according to the Poisson distribution. The results of decompositions are summarised in Table in terms of positron lifetimes τ_i and intensities I_i of the individual components and full width w_{tot} at the half maximum of the time-resolution function, obtained from the simultaneous fit. In the case of the RPV steel, average lifetime τ^{av} over the two shortest components, i.e. $\tau^{av} = (\tau_1 I_1 + \tau_2 I_2)/(I_1 + I_2)$, was also included in the table. Quality of fit was characterised through weighted sum of squared residuals reduced to the number of degrees of freedom, $\overline{\chi}^2$, see Table. Also residuals patterns illustrated in the upper panel of Fig. 2 were taken into account. The total numbers of counts and the coincidence counting rates are shown in the last two rows of Table, too.

It can be seen from Fig. 2 and Table that the α-iron positron-lifetime spectra measured by means of both the FFS and FS spectrometers could be satisfactorily decomposed into the three exponential components while the four components should be included in the model fitted to the experimental RPV steel spectra. The two components, labelled with subscripts 3 and 4 in Table, can be apparently attributed to positrons annihilating in the source and the covering foils. Hence, a single exponential component is assigned to positron annihilation in the well-annealed α-iron specimen, as expected for this defect-free material. Its lifetime, $\tau_1 = 107.9 \pm 0.2$ ps, is in reasonable agreement with the data known from literature, see e.g. Ref. [4]. In the RPV steel, the two short-lived components could be clearly identified suggesting most probably occurrence of the non-saturated positron trapping in the specimen. This result seems obvious for such a complex
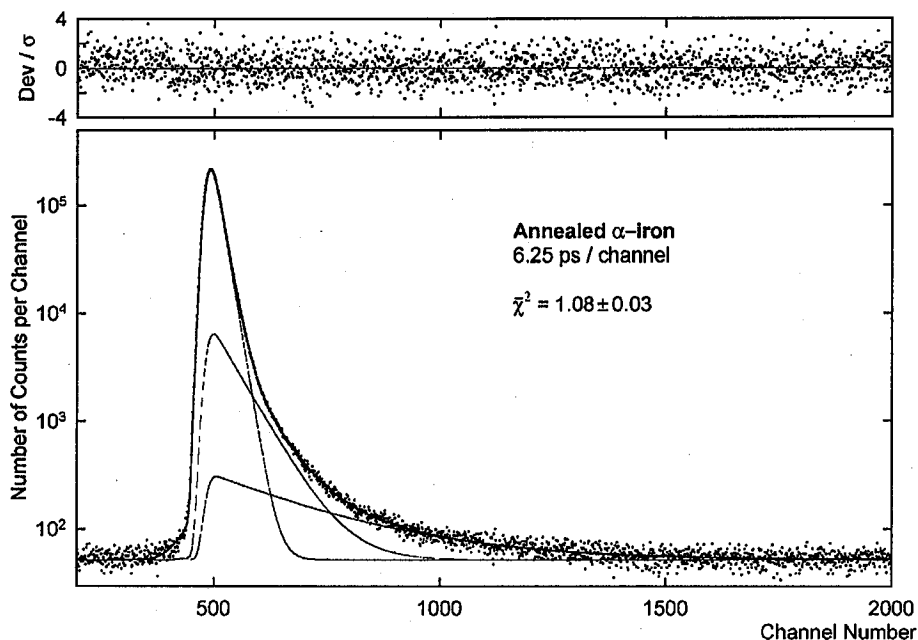
Fig. 2. An example of the α-iron positron-lifetime spectrum measured with the FFS spectrometer. The experimental and fitted spectra are shown in the lower panel together with the individual components (each component is imposed upon the same background level). In the upper panel, normalised deviations of the experimental data from the fitted model are seen.

system, however, a more detailed discussion of nature of the components is out of scope of the present contribution.

It is clearly implied by the data of Table that there is no significant difference in the positron lifetimes and relative intensities observed by means of the present FFS apparatus or the FS spectrometer [2]. Also the time resolution expressed through w_{tot} in Table has appeared to be closely similar for both the devices which demonstrates no loss of the time-resolution power of the FFS configuration compared to the FS one. Hence, the FFS system utilising the 1785 keV energy sum for the energy selection of the coincidence events can appear equally adequate and efficient in avoiding distortions of shapes of the positron-lifetime spectra as the FS arrangement. The FFS coincidence counting rate has been increased nearly by a factor of two with respect to the FS system. This is to be outlined as a clear advantage of the FFS apparatus which can obviously be understood as a consequence of much lower counting rate at the TSCA output with respect to outputs from the TSCA's in the FS configuration. It was observed in the test measurement that a proper setting of the CFDD coarse energy windows is naturally of more importance for the FFS arrangement than for the FS one. In the FFS system, moreover, suppression of the backscattering and pulse-summation effects with the aid of the lead shielding placed between the scintillators turned out to be necessary. This was demonstrated in a separate run, performed with the

TABLE

Decompositions of the α-iron and RPV steel positron-lifetime spectra into the individual components. Standard deviations resulting from the fits are shown in parentheses in units of the last significant digit.

Material	α-iron		RPV steel	
Spectrometer	FFS	FS	FFS	FS
τ_1 [ns]	0.1079(2)	0.1073(3)	0.075(8)	0.061(9)
I_1 [%]	93.3(1)	93.2(2)	14(2)	13(1)
τ_2 [ns]			0.153(3)	0.151(2)
I_2 [%]			79(2)	79.8(8)
τ^{av} [ns]			0.141(2)	0.139(3)
τ_3 [ns]	0.372(5)	0.364(6)	0.38(2)	0.36(2)
I_3 [%]	5.9(1)	6.0(1)	6.3(6)	6.9(7)
τ_4 [ns]	1.49(5)	1.53(5)	1.50(7)	1.43(5)
w_{tot} [ns]	0.153	0.149	0.149	0.148
$\overline{\chi}^2$	1.08(3)	0.95(3)	1.00(3)	0.96(3)
Tot. counts [$\times 10^6$]	9.3	7.8	10.2	8.3
Counting rate [s^{-1}]	58	35	61	36

α-iron specimen when the shielding was removed and the other circumstances unchanged. Such a run revealed visible distortion of shape of the spectrum, expressed as remarkable shortening of effective positron lifetime τ_1 by ≈ 2 ps.

4. Conclusions

The FFS coincidence system developed for use in PLS in the present work can be regarded as a compromise between the traditional FF and FS schemes. In comparison with the FF configuration, it utilises also the slow signal from the detectors to perform a simplified energy selection of the coincidence events. Contrary to the FS arrangement, in which the energy signals are processed and analysed *separately* in two SA–TSCA tandems, the *sum* of the balanced start and stop energy signals is used in the FFS system to generate the strobe condition for the TAC.

Positron lifetimes and intensities of the individual components obtained in test measurements with the FFS spectrometer were found to reproduce well those observed by means of our FS device [2] if proper shielding preventing the FFS system against the scattering of photons between the detectors and pulse-summation effects is used. Also the time resolution of the FFS apparatus appeared to be similar to the FS one which is ≈ 150 ps FWHM for the ^{22}Na positron source [2]. In these respects, the FFS and FS configurations become to be equally powerful. At the same time, the present work has demonstrated that the throughput of the FFS system may be considerably increased compared to the FS arrangement, almost

twice in our case. Moreover, the FFS electronic scheme becomes less complicated than that of the FS systems which has a positive impact on its reliability and cost.

Acknowledgment

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