ELECTRON–POSITRON PAIR SPECTROMETERS WITH HIGH EFFICIENCY FOR ANGULAR CORRELATION MEASUREMENTS*

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A new electron–positron pair spectrometer has been designed and constructed for the simultaneous measurement of the energy and angular correlations of e^+e^- pairs from internal pair creation processes (IPC) of energetic nuclear transitions. Experiments were carried out to validate the performance of the spectrometer using the e^+e^- pairs from M1 transitions in the $^7\mathrm{Li}(p,\gamma)^8\mathrm{Be}$ and an E0 transition in the $^{19}\mathrm{F}(p,\alpha,e^+e^-)^{16}\mathrm{O}$ reaction. Comparison with Geant4 Monte Carlo simulations demonstrates that the angular correlations of e^+e^- pairs can be determined with sufficient resolution and efficiency between a correlation angle of 40° and 180° degrees.

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1. Introduction

Electron spectrometers have been playing a central role in ATOMKI's research, initially developed for atomic physics studies to detect very low-energy electrons. In 1988, ATOMKI constructed its first spectrometer, a superconducting magnetic spectrometer for nuclear physics, which aimed at observing electrons from internal conversion processes in nuclear transitions. The spectrometer was later used to study the internal pair creation (IPC) process in high-energy nuclear transitions as well [1].

The development of the present detector array has been motivated by the multi-detector system originally constructed for simultaneous energy and angular correlation measurements of electron–positron pairs produced in IPC

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of nuclear transitions up to 18 MeV [2]. Although this early system was capable of observing the IPC over a broad angular range and provided valuable experimental data, its efficiency was rather low, limiting its sensitivity, especially in the search for deviations from the IPC theory that could signal the presence of a hypothetical, short-lived neutral boson. This limitation has driven the need for an optimized system with improved detection efficiency to enhance sensitivity in such high-precision measurements.

More recently, a new generation of electron–positron pair (e^+e^-) spectrometers was developed at ATOMKI to efficiently detect e^+e^- pairs and measure their angular correlation using position-sensitive detectors [3] based on the original concept of a multi-segmented array of Ref. [2]. Our development was also motivated by the search for new light particles, such as axions and dark photons, that could decay into e^+e^- pairs; when a particle decays into two equal mass particles (two-body decay), the angle between the emitted particles reflects the kinematics of the decay process, which, in combination with the known total energy of the system, allows for the determination of the mass of the decaying particle. However, the extremely low production probability (10^{-6}) relative to the γ emissions requires a high suppression of the background γ photons. The original version of our spectrometer [3] utilized multiwire proportional counters (MWPCs) for measuring the location of electron and positron impact, thin plastic scintillators for γ suppression, and thick scintillators for the measurement of the kinetic energies of electrons and positrons. This detector array facilitated the detection of an anomaly in the 18.15 MeV transition of ^{8}Be that signaled the existence of a new particle, later named $X17$ [4].

2. The upgraded e^+e^- spectrometer

We retained the previously optimized six-fold configuration of our spectrometer [3]. However, to improve the homogeneity and stability of angular measurements, the MWPC units were replaced with double-sided silicon strip detectors (DSSSD) with dimensions of 50 mm $\times$ 50 mm $\times$ 500 μm. In addition, the setup was extended with a second detector layer as an inner ring of six DSSSD units with a size of 25 mm $\times$ 25 mm $\times$ 300 μm. The DSSSD detectors of the inner ring were installed at a distance of 5.5 cm from the target. EJ-200-type plastic scintillators with dimensions of 8.6 cm $\times$ 8.2 cm $\times$ 8 cm were used as electron calorimeters, optically coupled to Hamamatsu photomultiplier tubes. The six telescope arms are positioned perpendicularly to the beam axes, separated by angular intervals of 60°, 120°, 180°, 240°, and 300°. Figure 1 displays the layout of the detector array as modeled in our Geant4 simulations.

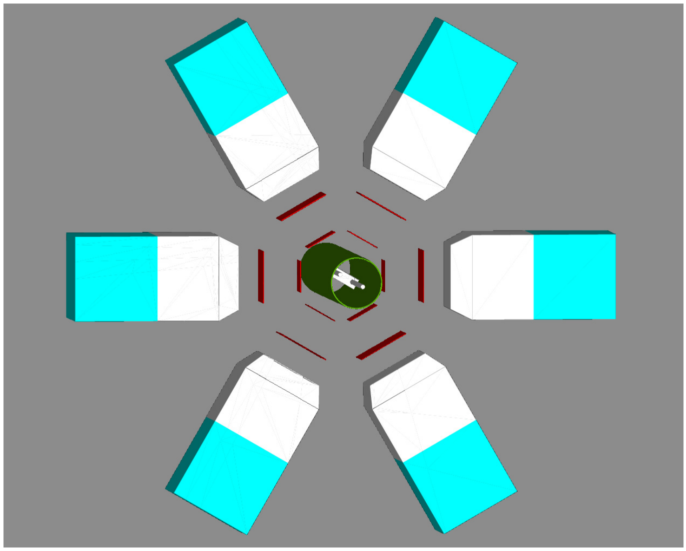

Fig. 1. Schematic view of the 6-folded detector array as implemented in the Geant4 simulations.

The timing information from the plastic detectors was recorded using the CFD (CAEN V812) discriminators and CAEN V775 TDC units, while the energy signals were processed by CAEN V792 QDC units. The trigger of the DAQ included mainly two-fold coincidence events and some downscaled single events to monitor the plastic detectors.

The DSSSD detectors of the outer ring have 32 $\times$ 32 strips, while the smaller detectors of the inner ring have 24 $\times$ 24 strips. Each DSSSD detector is paired with two Mesytec MUX-32 preamplifier units, each providing 32 signal channels. The MUX-32 units combine preamplification, shaping, and discrimination in a single, compact module, offering excellent energy and time resolution. The MUX-32 can also process the signals of two channels simultaneously transmitting two energy signals and two position signals through a shared bus. This feature allows for a precise energy calibration of each scintillator that was not possible with the previous spectrometer (see later). Each strip of the DSSSD detectors generates signals, which is proportional to the position of the strip at a sensitivity of 22.2 mV increment per bin. 460 mV fixed offset, the address coder gives an additional offset of 355 mV $\times$ address. The analog signals are then sent to analog-to-digital conversion units for digitization (CAEN V785).

3. Test experiment

In order to evaluate the upgraded spectrometer, internal e^+e^- pairs were generated by the resonant proton capture reaction ^{7}Li$(p,\gamma)^8$Be at a proton beam energy of $E_p = 450$ keV with a beam current of 1 μA. The experiment was conducted at the 2 MV accelerator of ATOMKI's Tandetron facility in Debrecen. A LiF target with a thickness of 30 μg/cm^2 and with a 0.1 mm Al foil backing, which was installed in a vacuum chamber made of a carbon fiber tube with a diameter of 5 cm and a wall thickness of 1 mm. The excited ^{8}Be decays to the ground state and to the broad, particle-unstable first excited state with a 17.64 MeV ($\Gamma = 11$ keV) and with a 14.74 MeV ($\Gamma = 1.5$ MeV) isovector M1 transitions, respectively. Figure 2 shows the distribution of the total kinetic energy of the e^+e^- pairs measured for the ^{7}Li$(p,\gamma)^8$Be reaction. e^+e^- pairs from an E0 transition ($E = 6.05$ MeV), as contamination, are also present as a result of the ^{19}F$(p,\alpha)^{16}$O reaction.

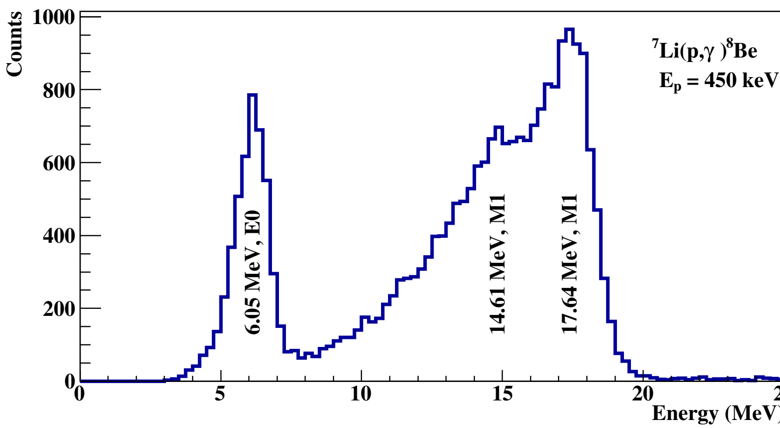

Fig. 2. Energy sum spectrum of the e^+e^- pairs from the ^{7}Li$(p,\gamma)^8$Be (M1 transitions) and ^{19}F$(p,\alpha)^{16}$O (E0 transition) reactions. The histogram bin width is 250 keV.

The calibration of the scintillators was performed with the peak energies of the above γ transitions ($E = 6.05$, 17.64, and 14.74 MeV). Since the e^- (and the corresponding e^+) energy spectrum detected by a plastic scintillator is continuous, we required double-multiplicity events from the DSSSD detectors, which means that both particles of the e^+e^- pairs are detected in the same scintillator. As a result, the energies of the e^+e^- pair are summed in the same plastic scintillator producing lines corresponding to the energy of the 6.05, 17.64, and 14.74 MeV transitions. The test measurement time was 55 hours. The event rate for the plastic detectors ranged between 50 and 200 Hz, while for the small and large DSSSD detectors were 200 and

500 Hz, respectively. The DAQ operated at 20 Hz which included mostly 2 fold coincidence events and some of the single events (1/32). Accordingly, the dead-time of the data acquisition system is negligible.

4. Geant4 simulations of detector response

Monte Carlo (MC) simulations were performed using the Geant4 code (version 11.2.1) [5] with the standard QBBC physics list to validate the response function of the multi-array detector system. For the generation of the e^+e^- pairs from IPC, the energy and angular distributions were calculated following the theory of Rose [6, 7] and implemented as custom event generators in PrimaryGeneratorAction.cc as described in more detail in Ref. [3]. The trajectories of the primary electrons and positrons were tracked until a cutoff energy was reached, and both the kinetic energy, deposited within the scintillator material, and the hit positions in the DSSSD units were stored. Considering the limitations on computational power, we omitted the simulation of the scintillation process and the related optical photon transport; therefore, the scintillator signal was idealized in the first approximation to be equal to the total energy loss of the particles. To estimate the real signal, the energy loss was convoluted by the experimentally determined energy uncertainty, which then represents both the internal resolution of the scintillator material and the electronic noise. Passive elements of the experimental setup, such as the target, the target holder rods, and the carbon vacuum tube, were also implemented in the simulations. For the reduction of the simulated data, we applied the same procedure as for the measured data, so a comparison of a few simulated and measured reference decays can validate the reliability and efficiency of our new detector array.

To identify potential background signals, we also simulated the response of the array to secondary electrons induced by high-energy γ radiation within the target material (external pair creation) or in any active and passive components of the detector system. In addition, background processes such as $\gamma\gamma$-coincidences, single high-energy γ events, and signals induced by traversing cosmic muons were also simulated. Ultimately, weight factors were assigned to each simulated background contribution and added to the simulated e^+e^- event distributions of the reference reactions to describe the kinetic energy and angular distribution of the e^+e^- pairs measured for each specific reaction.

The acceptance of the detector array was experimentally deduced using uncorrelated e^+e^- pairs of different single-electron events (Fig. 3). For comparison, the MC-simulated isotropic distribution is also presented. The minor deviations observed between the simulated and experimentally determined acceptance might be associated with edge effects within the DSSSD detectors, and the variation of the beam spot position during the experi-

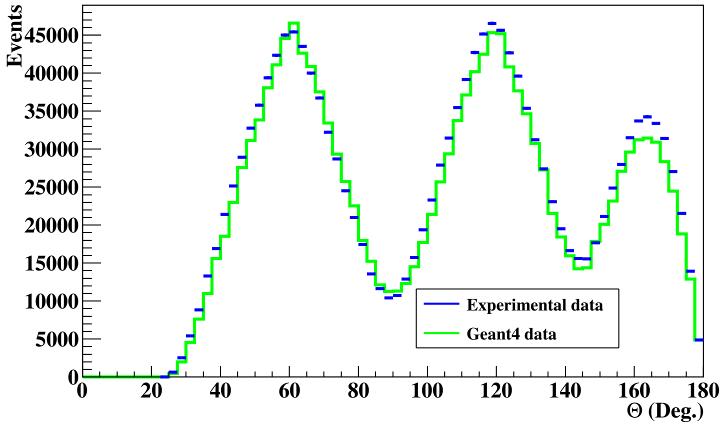

Fig. 3. (Color online) Angular distribution of uncorrelated e^+e^- pairs from subsequent single-electron events (blue/black histogram with error bars) and the MC-simulated isotropic distribution (green/light gray histogram). These distributions represent the acceptance of the detector array.

ment, although other possible sources need further investigation. However, by employing experimental acceptance for normalizing the experimental angular correlations and using the simulated response solely to normalize the simulated angular correlations, all of these effects can be eliminated.

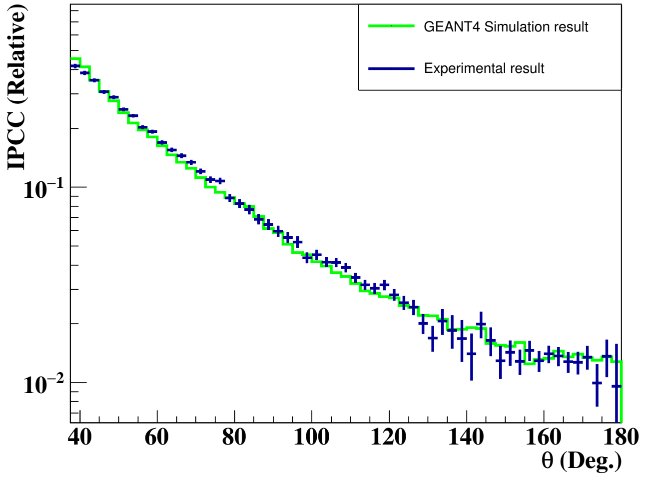

Fig. 4. (Color online) Experimental angular distribution of internal e^+e^- pairs from the resonant proton capture reaction ^{7}Li$(p,\gamma)^8$Be (blue/black histogram with error bars) and the angular correlation of the e^+e^- pairs simulated by Geant4 for the M1 transition of ^{8}Be with a transition energy of $E = 17.6$ MeV (green/light gray histogram).

The measured and simulated angular correlations of the e^+e^- pairs are compared in Fig. 4. Both distributions were normalized with the spectrometer response to the isotropic emission of e^+e^- pairs. As shown in the figure, a very good agreement was obtained between the experimental and simulated curves, which confirms the reliability of our experimental setup.

5. Summary

A new electron–positron pair spectrometer has been designed and constructed for the simultaneous measurement of the energy and angular correlations of e^+e^- pairs from IPC based on the design of our earlier spectrometer. Experimental results are obtained over a wide angular range for high-energy transitions in ^{8}Be. Comparison with Geant4 simulations demonstrates that the angular correlations of e^+e^- pairs can be determined with sufficient resolution and efficiency between 40° and 180° in the e^+e^- energy sum range of 6–18 MeV.

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