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The Miracle of the Electron-Positron Pair Production Threshold

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Pair production was first observed in 1932, which led to two early Nobel prizes in physics, to Carl Anderson for the discovery of positrons (1936) and to Paul Dirac for the theory of anti particles (1933). Science textbooks state that the production of electron-positron pairs is possible at photon energies above 1.022 MeV, which is the sum of the rest masses of the particles involved. Measurements at the threshold require a selectable photon energy in the range above 1 MeV, high-energy resolution to scan the onset, and high intensities. Due to the need of simultaneous energy and momentum conservation, pair production needs a recoiling particle, and thus it can be observed most easily in solid matter. More exactly, the minimum energy required for pair production is given by the relation $E_\gamma \geq 2\, m_e c^2(1 + m_e/m_r)$, where m_r is the mass of the recoiling particle [1]. With the particle rest energy of $m_e = 511$ keV/c^2, in heavy atoms we get $m_r >> m_e$, and thus in a good approximation photon energies $E_\gamma \geq 2 \cdot m_e c^2 = 1.022$ keV allow the creation of electron-positron pairs. However, for a proton as recoil particle the calculated threshold energy is increased by 557 eV, for a copper target by 9 eV, and even for the very heavy element $_{111}$Roentgenium by about 2.1 eV. Thus pair production cannot take place at *exactly* $2 \cdot m_e c^2$.

The pair production cross-section σ is approximately proportional to Z^2, i.e. the square of the charge of the nucleus, and thus heavy elements are favorable samples. Extremely unfortunate is the fact that the cross-section has a logarithmic dependence on the photon energy, and is thus strongly decreasing close to the threshold. This is one reason why the closest energy to threshold investigated so far [2] was at 1.057 MeV, still 35 keV above – quite far away for such a fundamental phenomenon! So far mainly discrete emission γ-lines of radioactive sources were used to investigate the production of electron-positron pairs by γ-rays. But if a particular photon energy is needed, it becomes more and more difficult to find an appropriate isotope, which emits γ-rays of the desired energy. In addition, the choice will be limited to weak transitions, and the moderate γ-ray intensities are emitted isotropically, making experiments even more difficult. In the publication just mentioned, Compton scattered γ-rays from a ^{60}Co source were used to change the energy and to get closer to the threshold; however, with an energy resolution of the order of 100 keV. It is obvious that reliable, high-precision cross-sections in the threshold region are nearly impossible to obtain. However, the cross-section measurements performed so far show significant deviations from theoretical predictions. The measured values are mostly larger than theory and show resonance-like features, which qualitatively might be understood as the final state Coulomb interaction between electron and positron [3]. However, the results just represent an approximate explanation – and thus have to be investigated in more detail. Regarding these difficulties it is not too astonishing that the most recent experimental results about pair production close to threshold were published in 1992 [3].

The fast decrease in the pair production cross-sections when approaching the threshold from higher energies is the most hindering fact to measure σ. For Germanium σ decreases from 0.197 [barns/atom] at 2.0 MeV photon energy over $6.94 \cdot 10^{-4}$ [b/atom] at 1.1 MeV to mere $1.9 \cdot 10^{-9}$ [b/atom] at 1.023 MeV (see Figure 1).

For first feasibility tests γ-rays were created by direct transitions after neutron capture in the high flux reactor at the Institute Laue-Langevin (ILL) in Grenoble (France). Different targets allow using a

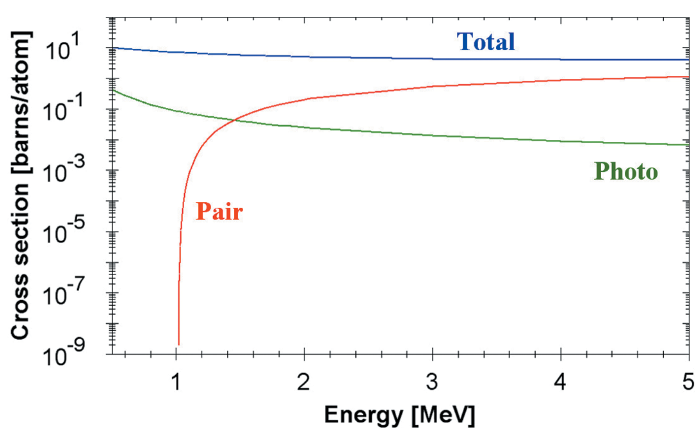

Figure 1: Pair production, photoelectric absorption, and total cross-sections for Germanium, calculated using the program XCOM 3.1 [4].

much larger variety of γ-energies than possible with radioactive sources. The double crystal γ-ray spectrometer GAMS4 [5,6] at the ILL allows one to select a suitable energy of the prompt gamma rays up to 10 MeV. Two Si or Ge crystals in Laue configuration can be used as monochromator. If the second one is switched between the non-dispersive and the dispersive reflection geometry, the measurement of the difference angle yields twice the Bragg angle θ and thus accurate absolute energy values. The performance of the monochromator in the MeV range is exciting: the achieved experimental resolution at 1 MeV amounts to 2.5 eV only, using Si(660) reflections [7]. Thus very high resolutions in the eV range can be realized at wavelengths of about 0.01 Å. However, it was found that a single reflection of a Cu(111) monochromator crystal or its harmonics yielded sufficient energy discrimination for initial experiments while providing much more intensity.

The setup of the experiment and the detector system used for investigating pair production are shown in Figures 2 and 3, respectively. This setup consists of four NaI scintillation detectors, which surround the central, high-purity Germanium detector, which also acts as sample. The detection of pair production is performed by detecting the annihilation of the created positrons with electrons of the sample, which results in the emission of two photons of 511 keV energy in opposite directions. The scintillation counters were used in two opposite pairs in coincidence to gate the readout of the HPGe detector after detection of the annihilation photons. Thus the energy of the γ-photon, having created an electron-positron pair, could be measured with the HPGe detector as a double escape peak, and the spectrum of the primary beam was collected by switching off the coincidence gating.

However, the achievable intensities are moderate. At 1108 keV energy (86 keV above threshold) about 50 cts/s were collected in the largest peak of the primary spectrum in one channel of the multichannel analyzer; this number drops to about 10^{-4} cts/s, i.e. less than 1 ct/h, in the coincidence signal. Those numbers clearly illustrate the difficulties in approaching the threshold even closer, which corresponds to a further reduction of the cross-section by another five orders of magnitude if one wants to reach 1 keV above threshold. However, the experiment verified the cross-section enhancement near threshold discussed above (see [8] for details).

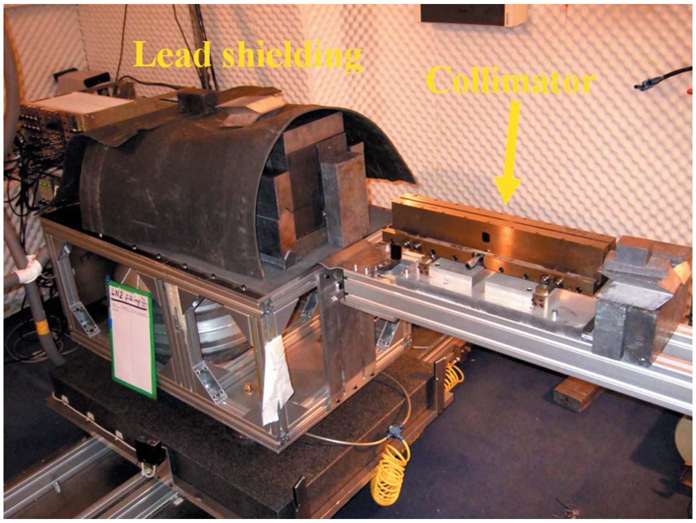

Figure 2: Setup of the experiment. The γ-ray beam enters the radiation protection hutch from the right. The lead shielding covers the detector system.

In the following we want to evaluate the current possibilities of synchrotron radiation sources for investigation of the pair production process near and above threshold in the energy range between 1 and 2 MeV photon energy. As a simple example we consider the synchrotron radiation spectrum emitted from a bending magnet of field B installed in a storage ring operated with electrons or positrons of energy E_s. A wiggler would increase the intensity by a factor given by the number of poles. The critical energy E_c, i.e. the energy at which the same amount of power is emitted below and above, is given in practical units by E_c [keV] = 0.665 · B[T] · E_s[GeV]^2. This relation enables us to judge the possibility of creating high energy photons. For example, a 10 T magnet in the 8 GeV storage ring SPring-8 (Hyogo, Japan) yields E_c = 0.43 MeV [9,10]. In the case of the ESRF (Grenoble, France), the lower ring energy of E_s = 6 GeV resulted in E_c = 0.24 MeV and thus significantly reduced intensities around 1 MeV due to the steep intensity decrease above E_c. The APS (Chicago, USA), with 7 GeV, is between the two others mentioned. The only storage ring that could be operated for synchrotron radiation at even higher energies of 12 GeV (up to 13 GeV at reduced current), PETRA II (Hamburg, Germany), is now rebuilt to the 6 GeV source PETRA III. Thus the chance has been lost to use the good spectral flux of the installed undulator or of superconducting bending magnets with moderate field for γ-ray measurements.

For high field insertion devices (8-12 T) at SPring-8 (8 GeV, 100 mA), photon fluxes of about $5 \cdot 10^{12}$ photons/(s·mrad·0.1% bandwidth) at 1 MeV are calculated [9]. A superconducting three-pole device capable of 10.3 T magnetic field was already tested at low ring currents and a field of up to 9.7 T, and a first rough photon spectrum up to 2 MeV was recorded using a NaI detector. More details about the setup are given by Utsunomiya et al. [11].

Important for a detailed investigation of pair production processes are the special properties of synchrotron sources, which make them unique and allow experiments never attempted before. Synchrotron radiation has an extremely intense *continuous* spectrum, is highly collimated, and has well-defined linear/circular polarization properties. This allows us to measure the dependence of the angular distribution of the particles created from polarized γ-rays and to compare it with theory. The intensities should be high enough to make even higher resolution determination of the energy of the annihilation radiation feasible. In addition, the possibility to create standing wave fields allowing the shift of the electromagnetic field with respect to the atomic cores might allow modulating the pair conversion probability. It is challenging to note that anomalies in pair production cross-sections could be associated with new light particles [12].

The technical premises for measuring cross-sections at threshold with high energy resolution are given with respect to sources and monochromators. Detection systems for the detection of pair production are well developed. The setup at GAMS4 can be improved further by about two to three orders of magnitude in efficiency by an improved geometry, new detectors, and electronics. This would be a milestone towards the use of synchrotron radiation, when it becomes available at suitable gamma ray energies for such experiments. Also, deviations from the Z^2 dependence of the cross-section could be investigated in detail. However,

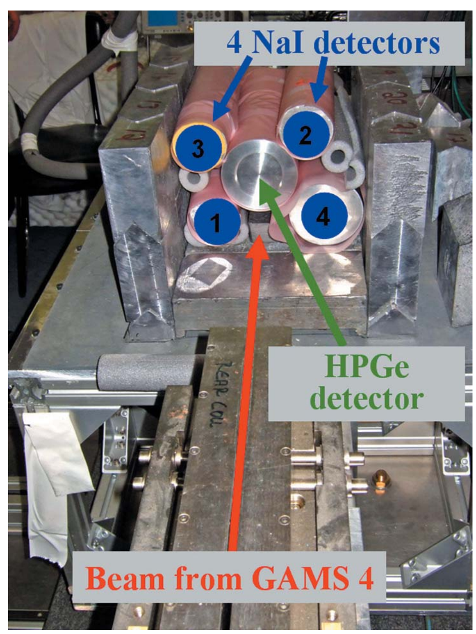

Figure 3: Detector system. The central HPGe detector is surrounded by four NaI detectors.

how close one can get to the threshold must be exploited, considering the strongly decreasing pair production probability, and whether even stronger specialized sources are needed to really observe the threshold directly. However, resonances due to generation of bound states of the electron might cause a significant increase of the cross-sections, and also crystal structure and other environmental factors can suppress or enhance pair production [13]. The electron/positron pair production by photons is one of the most basic processes that should be studied in more detail. This could give additional insight into the creation of matter from photons.

In conclusion, it is obvious that the ubiquitous textbook statement "pair production of electron-positron pairs is possible above the threshold of 1022 keV" still has to be confirmed for the threshold region. Synchrotron radiation, with its continuous spectrum, could be used to solve the elementary riddles associated with this process. Such experiments will lead to an improved theoretical understanding of pair production, particularly in solids at the threshold.

Acknowledgments

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