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The ATLAS Positron Experiment - APEX

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ABSTRACT

APEX - the ATLAS Positron Experiment - is designed to measure electrons and positrons emitted in heavy-ion collisions. Its scientific goal is to gain insight into the pussling positron-line phenomena observed at the GSI Darmstadt. It is in operation at the ATLAS accelerator at Argonne National Laboratory. The assembly of the apparatus is finished and beginning 1993 the first positrons produced in heavy-ion collisions were observed. The first full scale experiment was carried out in December 1993, and the data are currently being analysed. In this paper, the principles of operation are explained and a status report on the experiment is given.

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1. Introduction

Extremely strong electromagnetic fields are produced in close collisions of high-Z atoms at energies close to the Coulomb barrier. This situation has been predicted to give rise to qualitatively new phenomena associated with the over-critical binding of the inner electron orbits, such as the spontaneous emission of positrons [1].
Experiments, originally motivated by these ideas and carried out at the GSI Darmstadt over the past decade, have produced some remarkable and unusual results, i.e. the observation of peak structures both in the positron spectra [2-5] and in the sum-energy spectra of coincident electrons and positrons [6-10]. If confirmed, these results would seem to signal the appearance of, certainly interesting and possible fundamental, new physics.
A number of different scenarios have been proposed to account for the observation of sharp lines, none of which is wholly consistent with the data or constraints imposed by other known physics. The most pressing questions then relate to a clarification of the experimental situation and, in particular, a precise determination of the kinematics of the coincident electron-positron pairs which give rise to the sharp sum-energy lines.

2. Experimental apparatus

The vast experience in positron spectroscopy gained by the GSI groups over the past decade and the numerous questions which arise with the observation of the peak structures helps to define the specific tasks a second generation experiment should fullfill [11,12]. Briefly, these are: (i) clear identification and measurement of positrons emitted in heavy-ion collisions, (ii) high detection efficiency for electrons and positrons in the energy range from 150 keV $\leq$ E $\leq$ 600 keV, (iii) effective suppression of electrons with energies below 150 keV, (iv) ability to determine the emission angle of the leptons to perform a Doppler correction of the measured energies and to determine the opening angle between the lepton pairs, (vi) detection of the scattered heavy ions to determine the collision kinematics and the reaction Q-value. (v) high granularity of the detection devices to reduce the chance for multiple hits in one counter. The latter point is of major importance because high beam intensities have to be used to obtain statistically significant data sets within reasonable beam times.

Figure 1 shows a schematic view of the APEX apparatus and its major detector systems. It consists of a solenoid mounted transverse to the beam direction. Electrons and positrons produced at the target position spiral along the field lines of a homogeneous magnetic field (B = 0.03 T) and are transported to two silicon detector arrays mounted on the solenoid axis. These arrays each consist of 216 3×0.5 cm^2, 1 mm thick PIN diodes [13] arranged on a surface of a hexagonal cylinder 36 cm long with 1.5 cm sides. The detectors provide information on the energy, position and time of flight of each lepton, thus allowing a reconstruction of their vector momenta.

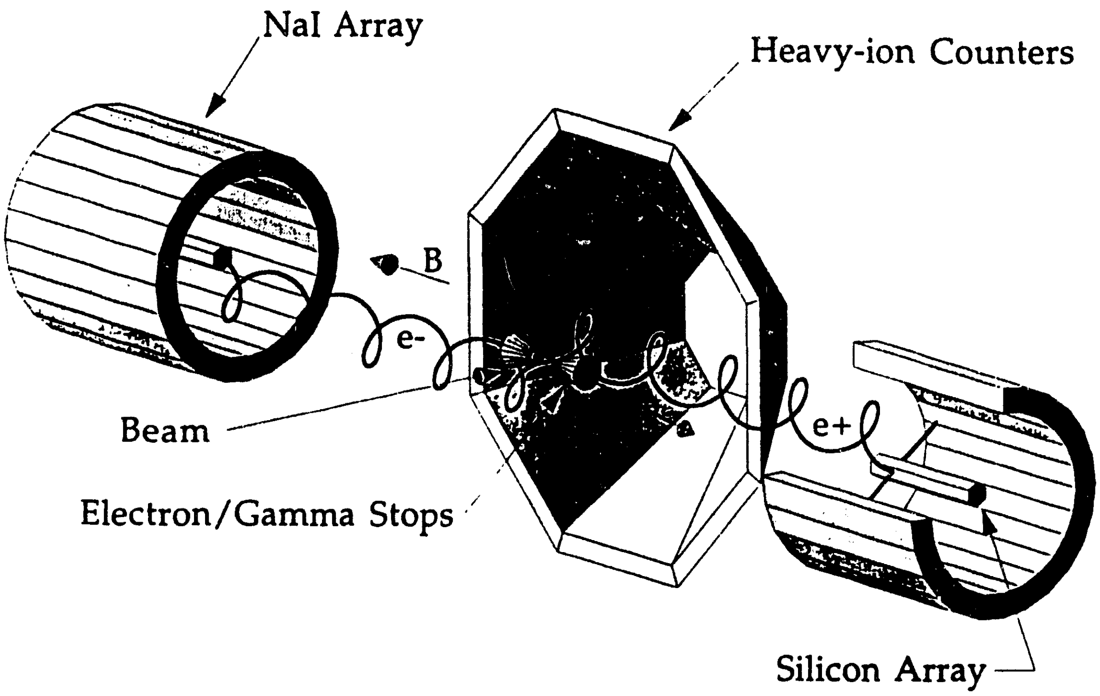


Fig. 1: Schematic drawing of the APEX setup and its major detectors.

The angle with respect to the solenoid is given by

$$\cos\Theta = p_z/p, \quad p_z = mz/t,$$

where p_z, the component of momentum along the solenoid axis, is determined from the time of flight and the detection position. The total momentum is calculated from the measured energy. An important feature of this device is that the spiral orbits always have close to a complete number of turns and the time of flight is then an integer multiple of the cyclotron period

$$t = nT_{cyc} = n\frac{2\pi m}{eB}.$$

Providing the time resolution is sufficient to determine the number of turns a lepton has undergone, the time of flight can be determined to the precision of the energy measurement.

The energy calibration of the silicon detectors is obtained using radioactive electron conversion sources providing monoenergetic electrons with energies of 193.7 keV and 263.9 keV (^{203}Hg), 363.3 keV (^{113}Sn) and 481.7 keV (^{207}Bi). Figure 2 shows the energy spectrum obtained with the Sn and the Hg sources, exhibiting an energy resolution of 13.2 keV and 9.8 keV (FWHM) for 193 keV and 363 keV electrons, respectively.

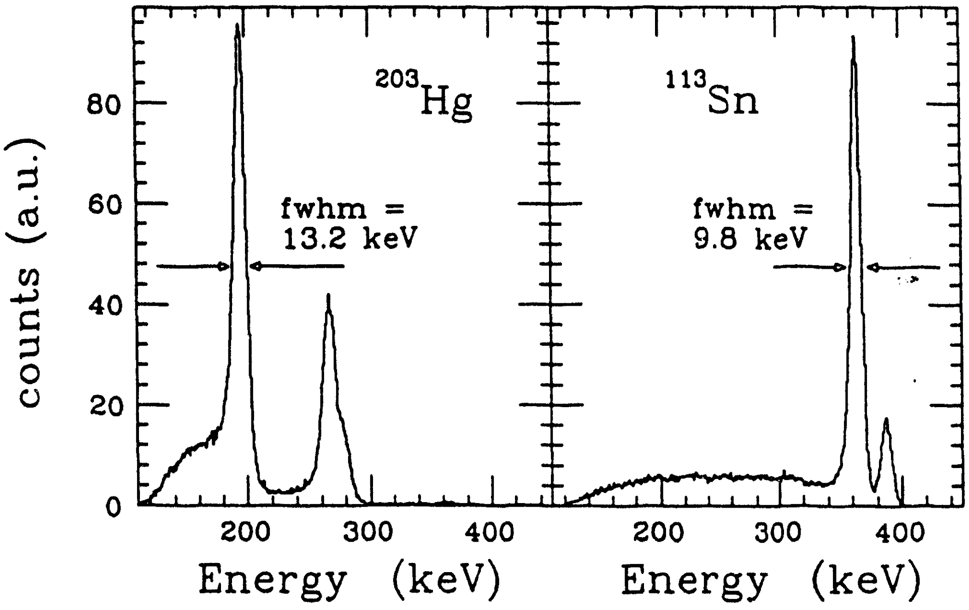


Fig. 2: Energy spectra obtained with the conversion electron sources ^{203}Hg (left part) and ^{113}Sn (right part).

An unique feature of APEX is the fact that both electrons and positrons are transported to the same detectors which results in a high degree of symmetry in their detection efficiencies. Positrons are distinguished from electrons by their annihilation radiation detected in two large position-sensitive NaI barrels surrounding the Si arrays [14]. Each barrel consists of 24 NaI bars with a thickness of 6 cm and a length of 55 cm. These crystals are specially made with a short attenuation length such that the pulse height information from both ends of the crystal can be used to determine the position of the annihilation photon. When both photons are detected the position on the silicon array where the annihilation took place thus can be reconstructed. The on-axis position resolution is $\Delta Z = 3$ cm (FWHM) and an energy resolution of 13% (FWHM) at 511 keV is achieved.

The crystals are equipped with *Hamamatsu H2611* phototube assemblies which work in the magnetic field without further shielding. Both barrels are enclosed in a cylindrical, Pb shielded cradle which protects the scintillators from ambient room background and γ-rays from the beam-dump. Near the target position, conical electron/gamma-stops (Fig.1) prevent direct radiation from the target hitting the inside of the array. For each barrel the outputs of the 96 photomultipliers are connected to a trigger processor which generates a trigger signal when a preloaded trigger pattern occurs. In normal operation two opposite NaI bars (or the neighbouring ones) are required to be hit to yield a trigger signal. Further conditions have to be satisfied

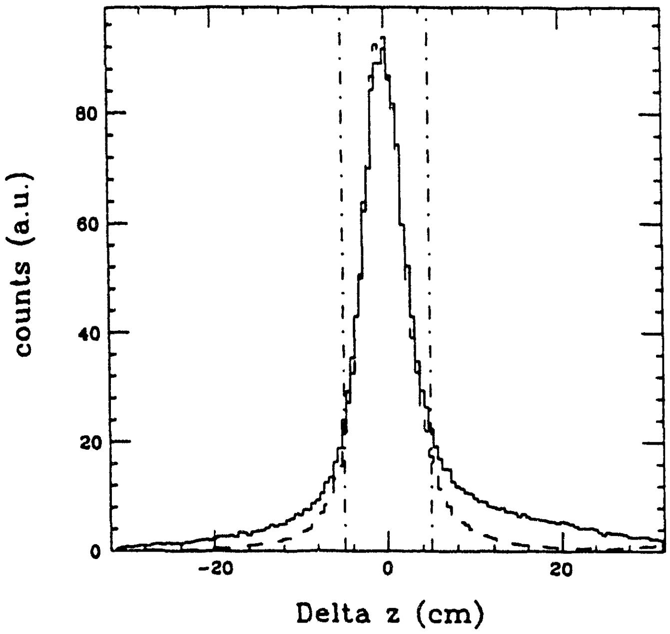


Fig. 3: Difference of the reconstructed on-axis position and the position where the positron was detected (solid line: beam data, dashed line: positron source measurement). The dashed-dotted lines give the window limits for positron identification.

in the analysis to identify a hit on the silicon detector as a positron: (i) the two γ-rays detected in opposite NaI bars must be in prompt time coincidence (Δt = 10 ns), (ii) there should be prompt time coincidence between the γ-ray, the event in the silicon detector and the beam pulse (Δt = 25 ns), (iii) the energy deposited in at least one of the two NaI bars must be within the 511 keV full-energy peak region (ΔE=200 keV), (iv) the reconstructed on axis position of the annihilation γ-rays (z_{NaI}) must correspond to the z-position of the silicon detector which fired ($\Delta z = z_{NaI} - z_{Si} \leq 5$ cm), (v) no second hit on the silicon array within the Δz window.

The spectra displayed in Fig. 3 show the difference in the on-axis position as obtained from the reconstructed position where the annihilation took place and the z position of the silicon detector which detected a lepton in prompt time coincidence. The spectrum obtained from beam induced events is compared with the spectrum obtained from positrons emitted from a ^{68}Ge β^+-source. The similar shapes of the two spectra demonstrates that in beam positron events are well defined through the Δz condition (the gate is shown in Fig. 4, too).

During beam measurements the ratio of positrons to electrons produced is only of the order of about 10^{-4}. A source test was used to verify the ability to detect coincident electron-positron pairs above a huge background of electrons. For this test a ^{90}Y source was mounted in the target position. A small percentage of decays (0.011%)

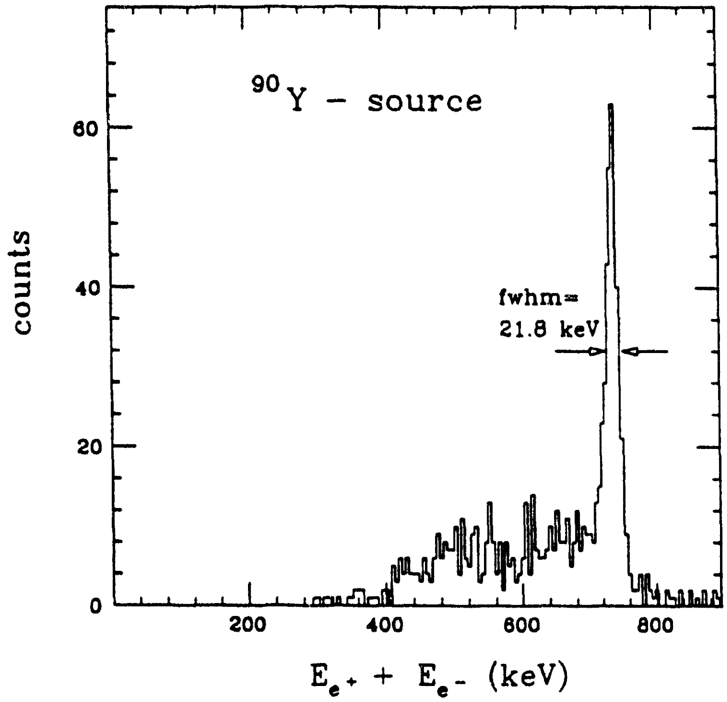


Fig. 4: Sum energy spectra of coincident positron-electron pairs originating from the E0 transition in ^{90}Zr.

populate the first excited 0^+ state in ^{90}Zr. This state can decay only by electron or pair conversion processes. When pair conversion takes place an electron-positron pair with a combined energy of $E_{e^-} + E_{e^+} = 739$ keV is emitted. The ratio of positrons to electrons emitted is $3.5 \cdot 10^{-5}$ per ^{90}Y decay. The background of electrons originating from decays to the ground state extends up to 2.28 MeV. Figure 4 shows the sum-energy spectrum of electron-positron pairs detected in coincidence. The sum energy can be reconstructed within 21.8 keV (FWHM). The tail originates from backscattered electrons.

An large solid-angle array of 24 Low Pressure Multi-Wire Proportional Counters serves to detect the scattered ions [15]. Eight three-element trapezoidal counters provide 360° coverage in the azimuth angle and 20° - 68° coverage in the polar angle. They are operated at a pressure of 5 Torr Isobutane and a typical anode voltage of 500 V. A plane of anode wires with 1 mm wire spacing yields the time-of-flight information. The scattering angle information is provided by a transmission-line delay cathode. The time-of-flight resolution is 1.1 ns (FWHM) which includes a 0.5 ns time resolution from the beam. The angular resolution is about 0.25° (FWHM) with systematic errors up to one degree. For asymmetric collision systems the projectile and the target like particles can be identified by their time of flight and scattering angle information. Figure 5 shows a two dimensional plot of these quantities for the system U + Ta at 6.1 MeV/nucleon. The U and the Ta branches are clearly separated. Thus a Doppler

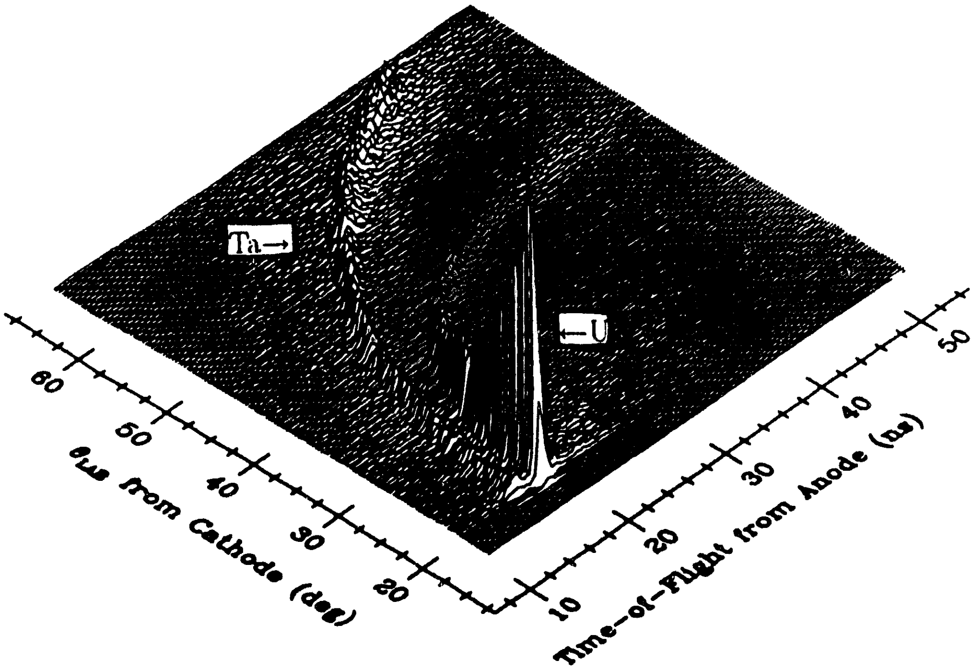


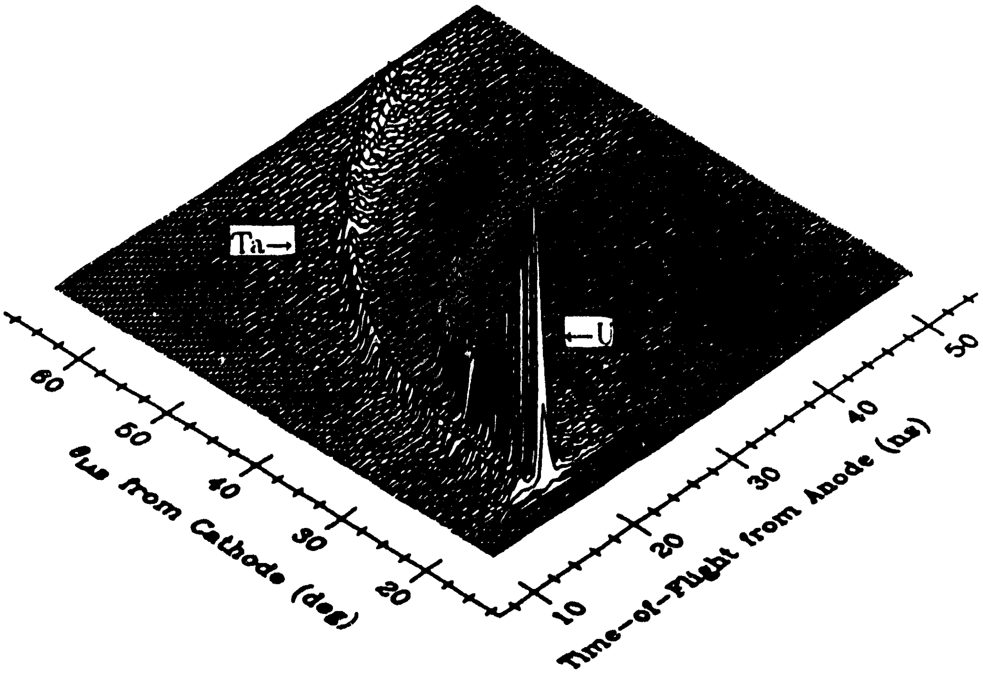
Fig. 5: Two dimensional representation of the time of flight versus the scattering angles as obtained from the heavy-ion arrays in U + Ta collisions at 6.1 MeV/nucleon.

correction for the leptons detected in coincidence to heavy ions can be performed.

3. Summary

The APEX spectrometer has recently been completed and, over the past year, has progressed from the testing phase to full operation. Initial experience has shown that, in essentially all respects, the apparatus performs as conceived and designed. Beams of ^{238}U of intensity up to 5 pnA from ATLAS have been used to bombard 1 mg/cm^2 ^{181}Ta targets and beam induced positrons have been measured with high resolution and extremly low background. The measured acceptance of the device is close to specifications.

In the first physics production run, which took place in December 1993, a total of over 600,000 positrons were measured with over 250,000 positron-electron coincidences. These data are currently being analyzed. The analysis of these data and of future experiments over the next several years should certainly lead to new insight into the origin of the line phenomenon.



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