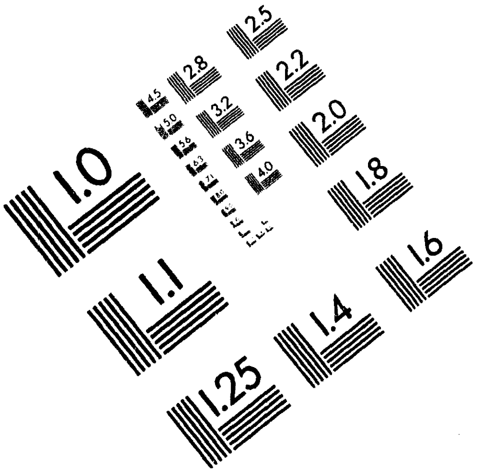

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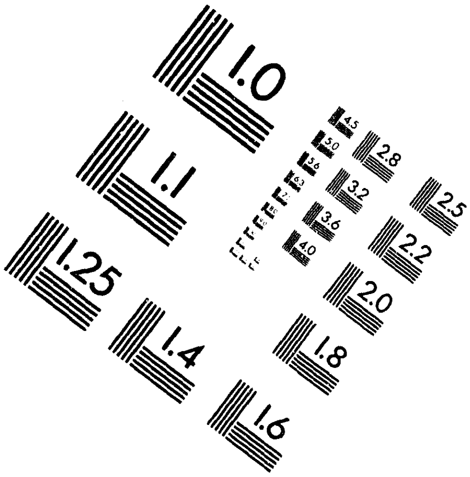

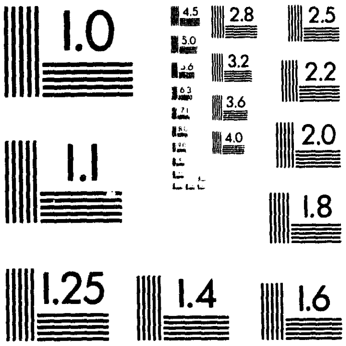

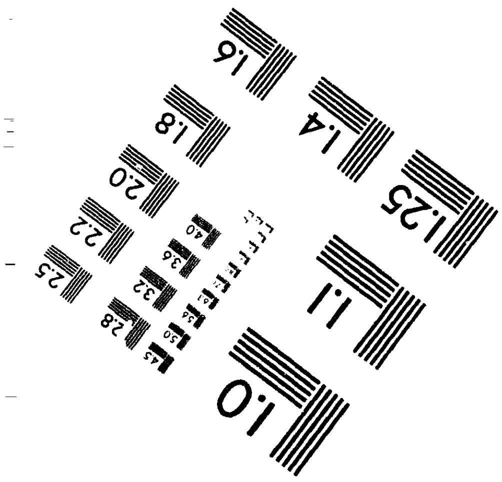

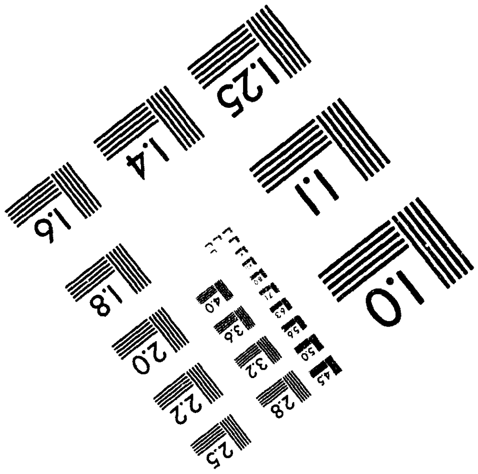

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Positron Production in Heavy Ion Collisions: Current Status of the Problem - II

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Presented by R. R. Betts

1. INTRODUCTION

Narrow peaks have been observed at GSI Darmstadt in the energy spectra of positrons and sum-energy spectra of positron-electron pairs, produced in collisions of very heavy ions [1-12]. To date, there is no satisfactory explanation of the origin of these lines although many differing models have been proposed. The current status of the experimental studies of the phenomenon as carried out at GSI has been summarized in the preceding paper [13]. In this contribution, we describe the features of a new experiment aimed at the study of the line phenomenon and present the results of our first experiments. The specific goals of our experiment are to clarify the experimental situation regarding the lines through high-resolution, high-statistics data and, by direct measurement of the vector momenta of the peak pairs, to determine their kinematics.

2. APEX

The ATLAS Positron Experiment (APEX) is a second-generation experiment, designed to measure positrons and coincident electrons produced in collisions of very heavy ions. The experiment uses beams of U and other ions produced by the recently upgraded ATLAS superconducting linac at Argonne National Laboratory.

The conceptual design of APEX is shown in Fig. 1 which displays the main components

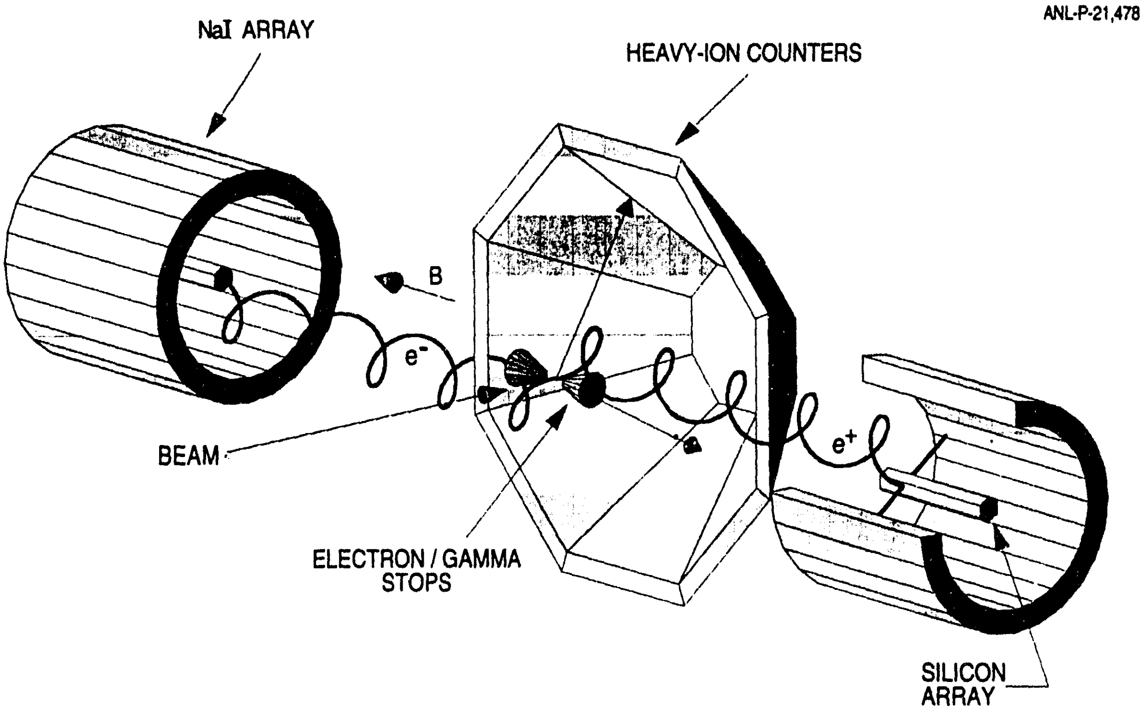

Fig. 1. Schematic drawing of APEX showing the major components.

of the experiment. These components are located in a uniform solenoidal magnetic field of 300 Gauss, oriented perpendicular to the beam direction. A rotating target wheel at the center of the device is designed to allow the use of targets such as U and Th with minimum deterioration due to heating and to reduce the effects of sputtering. Scattered ions and the recoiling target nuclei are detected in an array of twenty-four position-sensitive gas counters which allow the reconstruction of the kinematics of the heavy-ion scattering associated with positron production. Situated close to the target and on either side, on the solenoid axis, are two cone-shaped pieces of heavymet which are coated with low-Z material to suppress positron production on their surface. These serve the dual purpose of shielding the annihilation radiation detectors from gamma and x-rays produced at the target as well as providing a geometrical suppression of the intense flux of low-energy electrons. The geometry of these electron/gamma stops is such that they intercept the trajectories of all electrons and positrons with energies less than approximately 120 keV. Leptons which pass into the outer regions of the field, travel in helical trajectories until they strike one of the two silicon arrays, positioned on the magnetic axis of the solenoid. Each of these arrays consists of 216, individually read out, 1-mm thick PIN diodes which provide energy, timing, and position information for the positrons and electrons which strike them. Positron identification is accomplished by detection of the characteristic annihilation radiation in two twenty-four element arrays of position-sensitive NaI detectors which also provide the basic trigger for the experiment. The trigger is generated when two back-to-back ($165° \leq \Delta\phi_{\gamma\gamma} \leq 180°$) photons are detected. The information provided by the NaI arrays is used to calculate the position of the source of these back-to-back photons and thus the location of the positron annihilation on the silicon array. This provides clean and unambiguous identification of positrons in the presence of a much higher rate of electrons.

APEX allows a direct measurement of the angles of emission of the positrons and electrons, a feature not directly provided by the GSI experiments. In the experiments carried out so far, the invariant mass resolution of 30 keV (FWHM) for a hypothetical 2-MeV neutral object is limited by the time resolution of the silicon detectors of $\Delta t = 3.5$ ns (FWHM). An invariant mass resolution of 25 keV for a hypothetical 2-MeV neutral object can be achieved. The ultimate limitation to this resolution is the multiple scattering of the leptons in the target material.

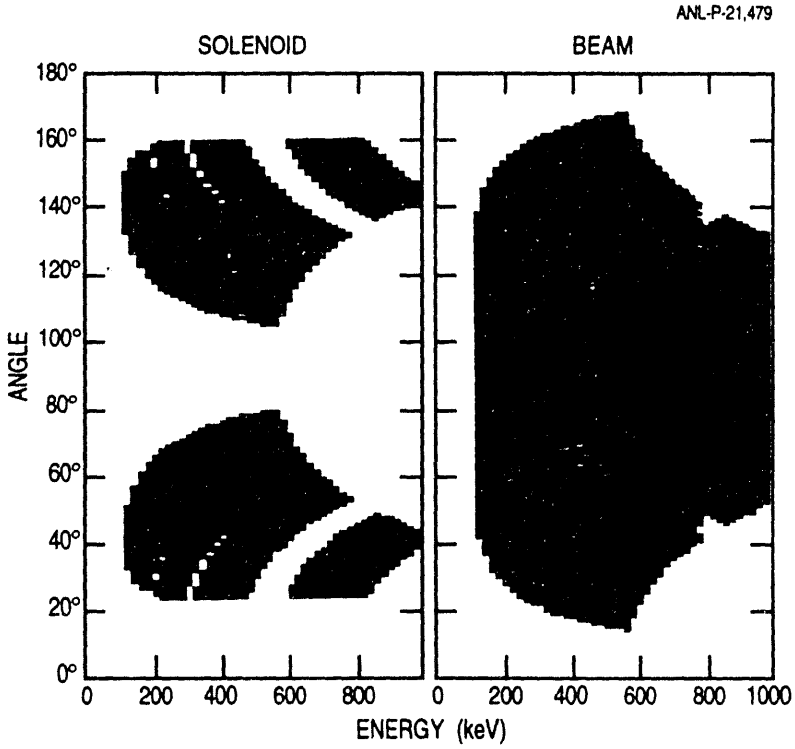

Fig. 2. Geometrical acceptance of APEX as a function of lepton energy shown in the solenoid (left) and beam (right) coordinate systems.

The geometrical acceptance of APEX is shown in Fig. 2 in both the solenoid and beam coordinate systems. In the energy range 200-600 keV, APEX accepts positrons and electrons over the angle range $20° < \theta_{BEAM} < 160°$ where θ_{BEAM} is the angle of emission with respect to the beam direction. This corresponds to good, but not perfect, overlap with the geometrical acceptance of the GSI experiments. Including the transport efficiency, lepton detection efficiency and positron reconstruction efficiency we calculate a full sum-energy pair detection efficiency of 3% assuming back-to-back emission of the pair. For experiments to date, due to a significantly reduced number of silicon channels with resolution better than 20 keV, this number falls to approximately 1%. More detailed descriptions of several of the components of APEX are given in Refs. 14-18. The apparatus was completed in summer 1993 and the first experiments were carried out over the past six months, using ^{238}U beams with intensities up to 5 pnA at energies up to 6.3 MeV/u.

3. EXPERIMENTAL RESULTS

The first beam induced positrons were detected in March 1993 using the partially instrumented apparatus and a number of test runs were carried out later in the year. The first run with the completed apparatus took place in November 1993 and a subsequent run followed in March 1994. For these initial experiments the ^{238}U + ^{181}Ta system was chosen for study. Several narrow sum-energy lines have been reported for this system under different experimental conditions [10,12] and the ^{181}Ta targets are well able to withstand bombardment with intense ^{238}U beams without the need for target rotation. The target thickness of 1 mg/cm^2 was chosen so that the energy loss of the beam in this thickness (0.2 MeV/u) approximately matches the width of the energy dependence of the yield of the 748 keV sum-energy line reported in Ref. 10. Data were taken at bombarding energies of 5.95, 6.10, and 6.30 MeV/u. The beam energies were determined by a time-of-flight technique and are believed accurate to ±0.01 MeV/u. The total integrated luminosities for the three energies were 5,000, 11,000, and 9,000 μb^{-1} at 5.95, 6.10, and 6.30 MeV/u respectively.

The key to the identification of positrons in APEX is the position correlation between the source of the annihilation radiation detected in the position-sensitive NaI arrays and the location of the leptons detected with the Si arrays. This is illustrated in Fig. 3, where the difference in the on-axis position determined from these two detectors is displayed for events in which a lepton is detected in prompt time coincidence with annihilation photons. The two curves show this correlation for both beam induced events and positrons from a ^{68}Ge source placed at the target position. Within the limits of 0 ± 5 cm, the two curves are almost identical. The differences for large values of the position difference stem in part from the high end-point energy of the ^{68}Ge source which results in a different illumination of the silicon arrays than is the case for the beam induced positrons. Nevertheless, the beam induced positrons are cleanly and unambiguously identified. It is estimated that at most 5% of the positrons are misidentified electrons.

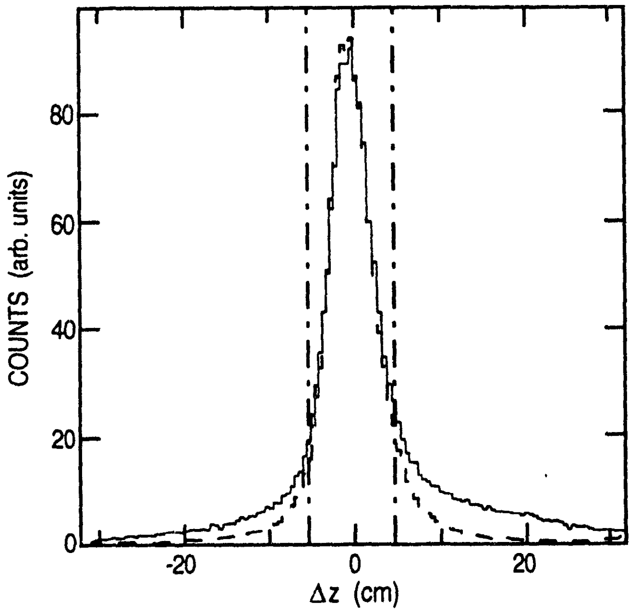

Fig. 3. Difference in the on-axis positions for beam-induced positron events (solid) and ^{68}Ge source positrons (dashed). The vertical lines show the window (±5 cm) for accepted events.

The ability of APEX to observe positron-electron pair events in the presence of an intense background of electrons can be tested with an ^{90}Y source. ^{90}Y decays largely by e^- emission to the ground state of ^{90}Zr but has a weak (0.011%) branch to the 1761 keV 0^+ state which subsequently decays by pair emission to the ground state. The sum energy of the pair is 739 keV. Figure 4 shows the sum-energy spectrum of positron electron pairs from such a

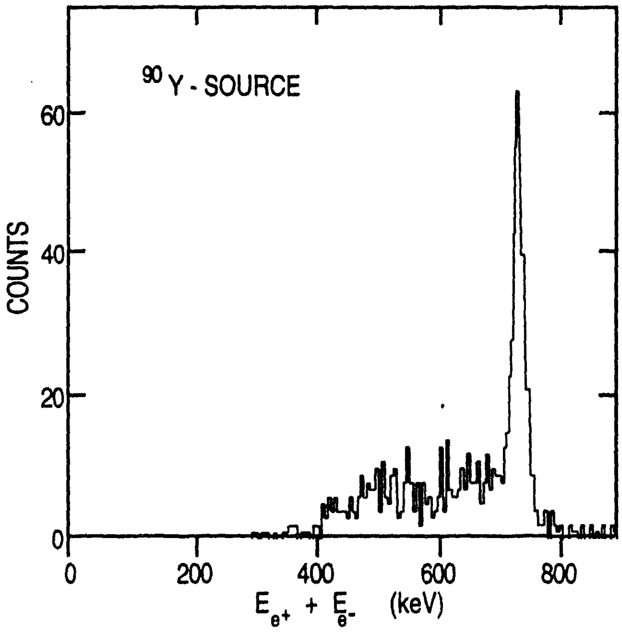

Fig. 4. Sum-energy spectrum for positron-electron pairs in ^{90}Y decay.

measurement. The sum-energy peak is observed with a width of approximately 27 keV. The background below the peak results from out-scattered positrons and electrons which do not deposit their full energy in the silicon. These data were taken with a 30 μCi source which gives 10^6 electrons per sec, comparable to the number produced during in-beam measurements.

The acceptance of APEX has been studied using various source measurements. A comparison between the measured response for a ^{68}Ge source and the results of simulations is shown in Fig. 5. It is important to note that the simulations include the effects of missing detectors excluded from the in-beam analysis due to poor resolution. This comparison demonstrates that we are able to reproduce the response of APEX for positrons in both shape and absolute magnitude.

An important aspect of APEX is the variety of monitor detectors used for absolute normalization and evaluation of target condition, thickness, etc. One of these, a 70% Ge detector, was used to take heavy-ion gamma-ray coincidence data during the positron measurements. From the observed transitions resulting from Coulomb excitation of the projectile and target we can deduce the expected electron-conversion lines which should appear in electron heavy-ion coincidences also taken during the positron measurements and thus directly test the energy resolution and angle measurements under in-beam conditions. The Doppler-corrected electron-singles spectrum thus obtained during the ^{238}U + ^{181}Ta measurements assuming emission from the U-like fragment is shown in Fig. 6. This spectrum does indeed show the expected conversion lines. The measured width of these lines is about 20 keV, consistent with expectations based on the intrinsic energy resolution and the uncertainty in the angle measurements due to the 3.5 ns silicon time resolution.

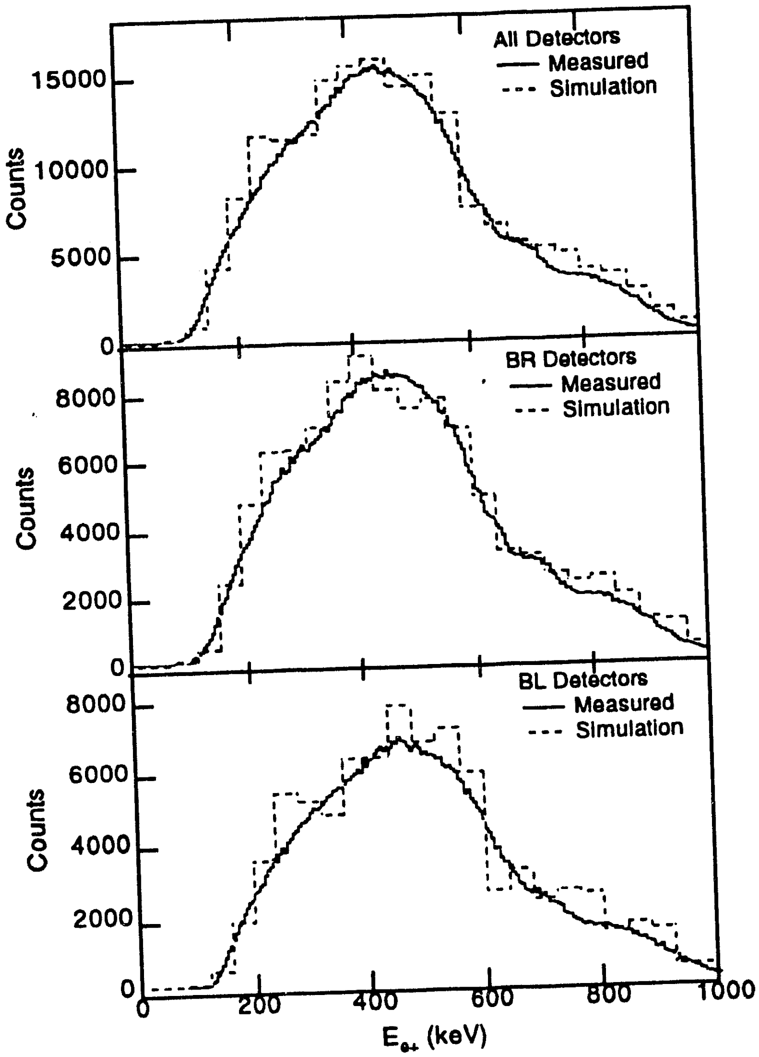

Fig. 5. Comparison between measured and simulated ^{68}Ge spectra. The simulated yield is normalized to the measured source strength.

The portion of the gamma-ray spectrum above 1022 keV may, after suitable unfolding, be combined with theoretical internal pair conversion coefficients to calculate the positron yields resulting from pair conversion of excited nuclear states and which then can be compared with the measured positron yields. This is shown in Fig. 7 where a measured positron spectrum obtained at 6.1 MeV/u is compared with the expected yield based on the sum of the pair-conversion positrons (IPC) plus a contribution from dynamically produced positrons. The overall agreement in shape and absolute magnitude confirms our understanding of the acceptance of APEX plus the absolute normalization of the data.

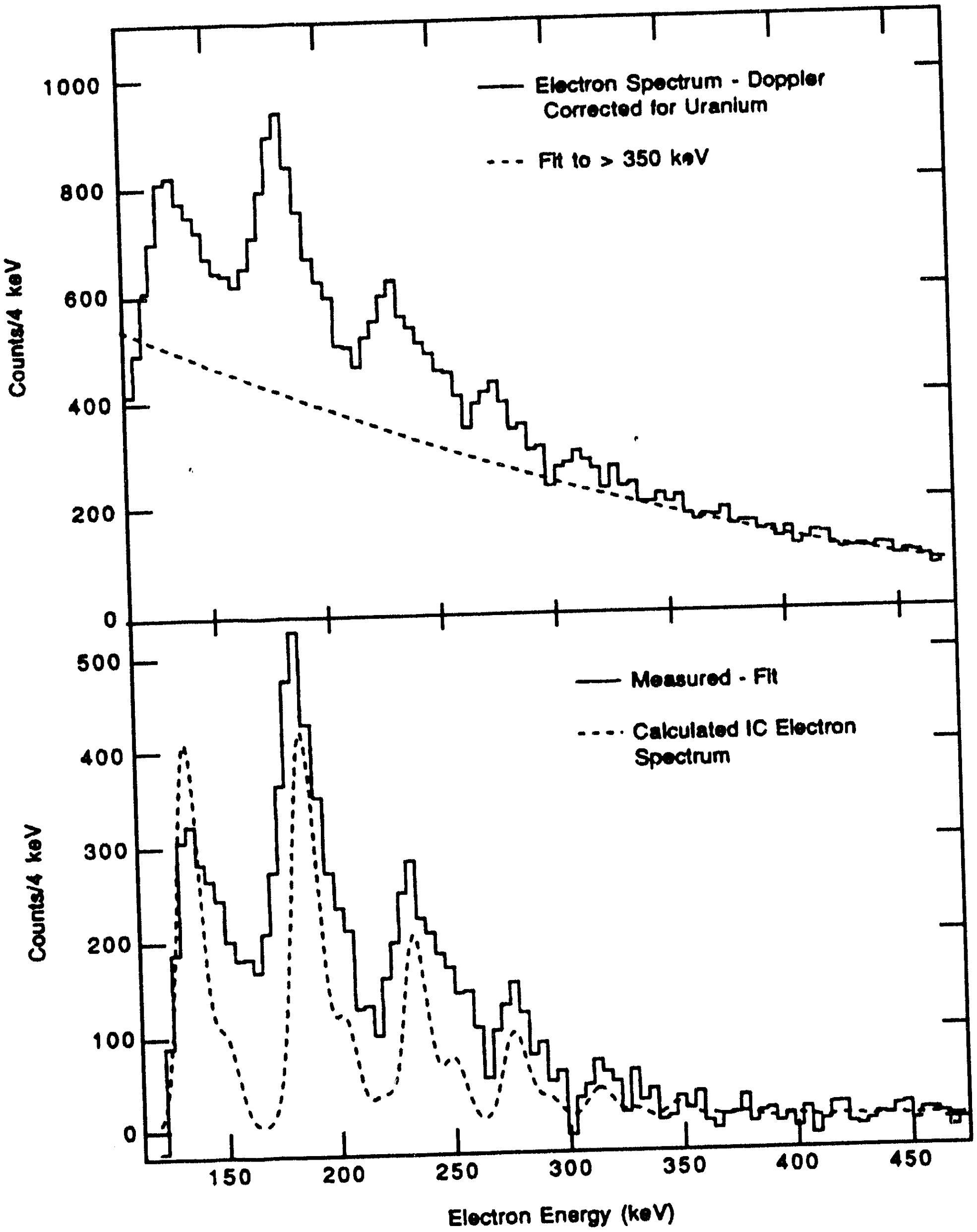

Fig. 6. Electron singles spectra from $^{238}U + ^{181}Ta$ at 6.1 MeV/u which have been Doppler corrected assuming emission from the U-like fragment. The relative normalization of the peaks in the calculated spectrum is abitrary and the comparison to the data is only qualitative.

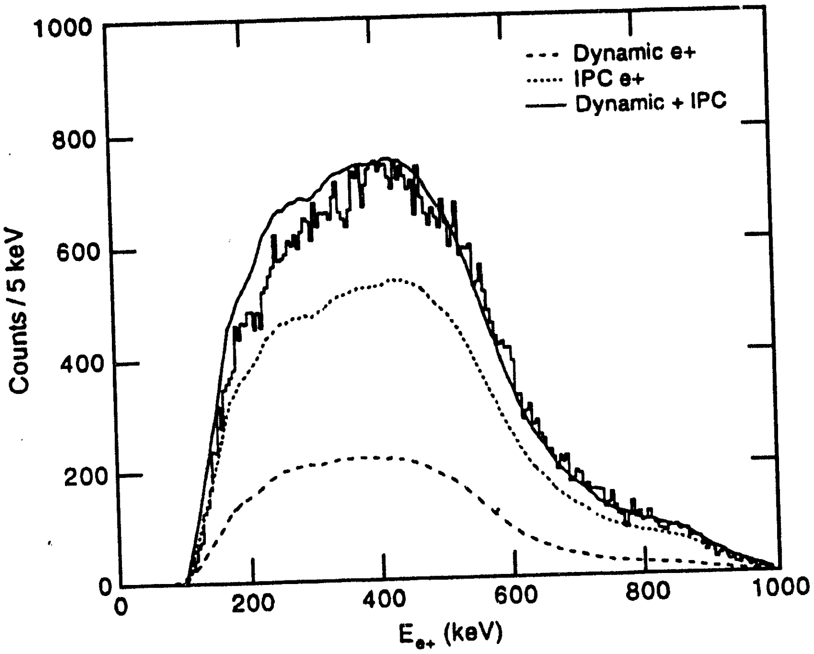

Fig. 7. Positron singles spectrum from ^{238}U + ^{181}Ta at 6.1 MeV/u compared to the expected yields from internal pair conversion and dynamic positron production.

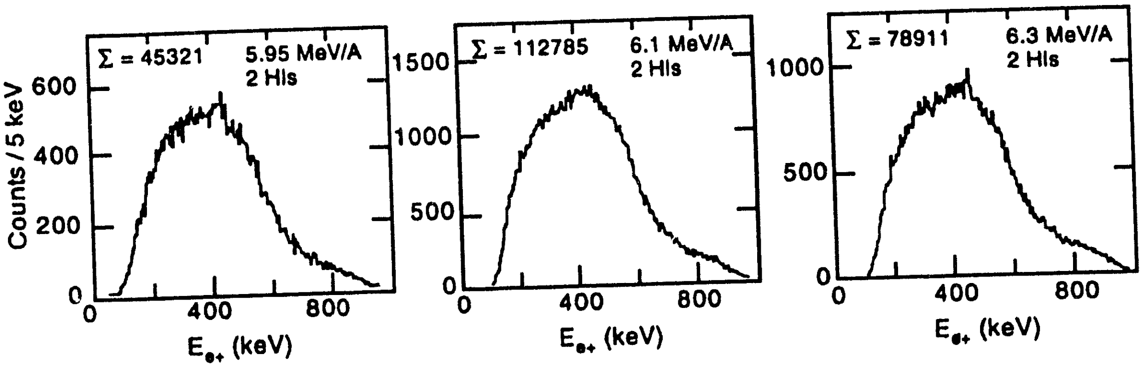

Fig. 8. Energy spectra of positrons produced in the ^{238}U + ^{181}Ta reaction at E_{lab} = 5.95, 6.1 and 6.3 MeV/u .

Positron singles spectra measured at 5.95, 6.1 and 6.3 MeV/u are shown in Fig. 8. These spectra were obtained under the condition of two quasi-elastically scattered ($\bar{Q} = 0$, $\Delta Q = 40$ MeV) heavy ions detected in the angle range $20^\circ \leq \theta_{HI}^{LAB} \leq 68^\circ$. The spectra are smooth within statistics. For those events with an electron detected in prompt time coincidence, positron-electron sum-energy spectra are shown in Fig. 9 under the same conditions as those of Fig. 8. These are also smooth showing no statistically significant deviations. A wide variety of analyses of these data have been carried out, selecting on heavy-ion scattering, lepton energies, etc. In all of these no statistically significant evidence has been found for sharp sum-energy lines.

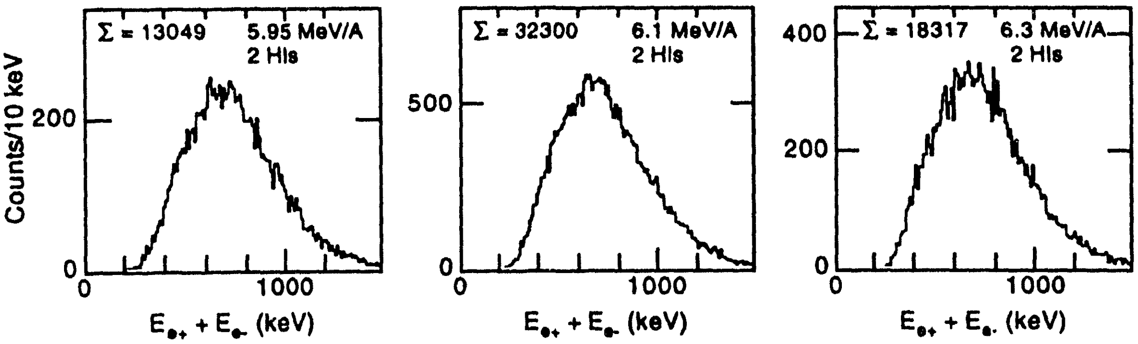

Fig. 9. Sum-energy spectra of electrons and positrons produced in the ^{238}U + ^{181}Ta reaction at E_{lab} = 5.95, 6.1 and 6.3 MeV/u.

Monte-Carlo simulations of various pair-production scenarios have been carried out. For the decay of a particle at rest, sharp lines result from equal-energy, back-to-back pairs. It is assumed that they are emitted isotropically in the laboratory frame and produced uniformly through the target, in coincidence with heavy ions detected in the APEX geometry. For this scenario, we estimate a sensitivity at 6.1 MeV/u of approximately 1 μb for a sum energy of 750 keV. Simulations in which the particle is moving with velocities up to the beam velocity do not lead to significantly smaller sensitivity. At 5.95 MeV/u and 6.3 MeV/u the sensitivity is somewhat smaller, proportional to the reduced integrated luminosity. For pairs produced with a sharp sum-energy, but uncorrelated in angle with positron and electron energy spectra characteristic of internal pair production, again emitted isotropically in the laboratory frame, the corresponding sensitivity at 6.1 MeV/u is approximately 10 μb. The same reduction in sensitivity applies to the 5.95 and 6.3 MeV/u data.

A number of sharp lines have been previously reported for the ^{238}U + ^{181}Ta system. Singles positron peaks have been observed [6] at energies of 230 keV and 310 keV at a bombarding energy of 5.9 MeV/u with a 1000 μgm/cm^2 thick target. Sum-energy lines are observed at 634 keV (6.3 MeV/u, 1000 μgm/cm^2) [12], 625 keV and 805 keV (6.24-6.38 MeV/u, 600 μgm/cm^2) [10] and 748 keV (5.93-6.13 MeV/u, 600 μgm/cm^2) [10] where the numbers in parenthesis refer to the range of bombarding energies for which the peak was observed and target thickness respectively. No evidence is observed for these lines in our data at the present stage of analysis.

A direct comparison with these peaks is difficult as the deduced cross sections depend crucially on the details of their (largely unknown) kinematics, angular distributions and angular correlations, which strongly influence the acceptances of the experimental apparatus. There also appear to be inconsistencies between the different sets of published data which may also reflect features of the phenomenon such as a strong bombarding energy dependence of the cross section and strong angular distribution and angular correlation effects. Taken at face value, using scenarios which approximate the observed features of the data and assuming isotropic positron production uniformly through the entire target thickness, the expected yields range from 200 to 2000 counts in the sum-energy peak. Although it should be noted that the different angular acceptances of the various experiments may mean that the cancellation of the Doppler effects on the positrons and electrons is different from case to case and that the expected yield may not therefore all appear in a sharp sum-energy peak.

It is possible that some of the discrepancy arises from the incomplete overlap of the acceptances for the different experiments which for the case of the sharp lines reported for ^{238}U + ^{181}Ta may have a substantial effect. For example, the assumption of isotropic positron emission may not be valid and significantly forward-backward peaked emission would lead to substantially reduced sensitivity in APEX due to missing silicon channels in critical regions of acceptance. It is possible that the line cross sections have sharper energy dependence than suggested by the original data, making any new experiment susceptible to uncertainties in the absolute beam energy and also sensitive to the choice of target thickness and therefore energy averaging interval of the beam. Further, the sharp lines reported in ^{238}U + ^{181}Ta [10] have quite asymmetric energy differences between the positrons and electrons which makes the results sensitive to the precise values of the thresholds in detection of the lowest energy electrons. Much further work is therefore needed before definitive conclusions can be drawn.

4. SUMMARY

A new generation experiment designed to study positron production in collisions of very heavy ions is now complete and in operation. An understanding of the acceptance and response of the apparatus has been demonstrated and the ability of APEX to cleanly identify positrons has been shown.

The first results for ^{238}U + ^{181}Ta at three bombarding energies do not show evidence for sharp peaks in the electron-positron sum-energy spectra and considerable effort is going into understanding this apparent discrepancy with the earlier results. Currently, the experiment is being improved, mainly by increasing the number of silicon channels with resolution better than 20 keV which, if successful, will lead to a factor of three increase in efficiency for equal-energy back-to-back pairs.

Future experiments are planned for a number of systems including ^{238}U + ^{232}Th for which the most striking evidence for back-to-back, equal energy pairs has been reported. This system, although requiring more difficult targets, is optimally suited for the APEX acceptance and the peaks also appear in a region of acceptance with maximum overlap with the EPOS experiment at GSI.

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