THE POSITRON PEAK PUZZLE - RECENT RESULTS FROM APEX

The APEX Collaboration

I. Ahmad[1], S.M. Austin[2], B.B. Back[1], R.R. Betts[1,3], F.P. Calaprice[4], K.C. Chan[5], A. Chishti[5], P. Chowdhury[5], C. Conner[3], R.W. Dunford[1], J.D. Fox[6], S.J. Freedman[1,7], M. Freer[1,8], S. Gazes[9,10], A.L. Hallin[11], T. Happ[1,12], N. Kaloskamis[5,13], E. Kashy[2], W. Kutschera[1], J. Last[1], C.J. Lister[1,5], M. Li[11], M.R. Maier[2], D.J. Mercer[2], D. Mikolas[2], A. Perera[10], M.D. Rhein[1,12], E. Roa[6], J.P. Schiffer[1,9], T. Trainor[14], P. Wilt[1], J.S. Winfield[2], M. Wolanski[1,8], F.L.H. Wolfs[10], A.H. Wuosmaa[1], A. Young[4], and J.E. Yurkon[2]

[1]*Physics Division, Argonne National Laboratory, Argonne, IL 60439*
[2]*NSCL, Michigan State University, East Lansing, MI 48824*
[3]*Department of Physics, University of Illinois at Chicago, Chicago, IL 60607*
[4]*Physics Department, Princeton University, Princeton, NJ 08544*
[5]*WNSL, Yale University, New Haven, CT 06511*
[6]*Physics Department, Florida State University, Tallahassee, FL 32306*
[7]*Lawrence Berkeley Laboratory, Berkeley, CA 94720*
[8]*Department of Physics, University of Birmingham, Birmingham B15 2TT, UK*
[9]*Department of Physics, University of Chicago, Chicago, IL 60637*
[10]*NSRL, University of Rochester, Rochester, NY 14627*
[11]*Physics Department, Queen's University, Kingston, Ontario, K7L 3N6, Canada*
[12]*GSI, Planckstrasse 1, 64291 Darmstadt, Germany*
[13]*Department of Physics, University of Notre Dame, Notre Dame, IN 46556*
[14]*Nuclear Physics Laboratory, University of Washington, Seattle, WA 98195*

Presented by Russell Betts

Results are presented from a new experiment, APEX, designed to study the previously reported sharp lines in sum-energy spectra of positrons and electrons produced in collisions of very heavy ions. Data have been collected for $^{238}U+^{181}Ta$ and $^{238}U+^{232}Th$. No evidence is found for narrow structures similar to those previously reported. For the specific case of the isolated decay of a neutral particle of mass 1.4-2.1 MeV/c^2, the upper limits on cross sections obtained are significantly less than previously reported. Data are also presented for internal pair conversion in ^{206}Pb. These results are used to set limits for the possible contribution to the pair yield of a 1780 keV transition in ^{238}U observed in heavy-ion gamma-ray coincidence measurements.

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1. Introduction

Reports of line structures of width 50-80 keV in the energy spectra of positrons produced in collisions of very heavy ions [1-8] and, more remarkably, much narrower lines in sum-energy spectra of coincident positrons and electrons [9-12] have provided a persistent experimental and theoretical puzzle. Despite over a decade of effort, no consistent description of the experimental features of the peaks or explanation of their origin has emerged.

In order to account for the widths and other features of the observed lines in the positron spectra and in the sum-energy spectra, it has been proposed that they may originate from the two-body decay of a hitherto unknown light neutral particle or composite object. Such an object must be produced with a relatively narrow velocity distribution in the center-of-mass frame of the colliding heavy ions such that their free pair decay results in near back-to-back, equal energy pairs with consequent, almost exact, cancellation of their Doppler shifts. The existence of such low mass states is highly constrained by other experimental and theoretical results [13-20]. The only other known mechanism to produce sum-energy lines of the observed widths, without the use of the lepton angles for Doppler correction, is internal pair conversion (IPC) of a discrete transition in a nucleus which, however, is required to be nearly at rest. The IPC mechanism has the additional difficulty that it is not expected to give rise to narrow structure in the associated positron spectrum.

Some of the reported sharp sum-energy lines were found [9-11] to have features consistent with the particle scenario, others did not [11,12]. A rather uncertain picture of the phenomenon therefore exists at present. To attempt to resolve the puzzle presented by these observations, three new experiments have recently carried out measurements similar to those reported in the earlier studies. In this paper we present a description of and data from one of these new experiments - APEX - the ATLAS positron experiment. A discussion of the other two experiments EPOS II and the upgraded ORANGE experiment is contained in the following contribution [21]. Some of the APEX results presented here are contained in preliminary form in Ref. 22 and in Ref. 23.

2. The APEX Apparatus

APEX utilizes beams from the ATLAS superconducting linear accelerator at Argonne National Laboratory which has recently been upgraded to provide high intensity CW beams of the heaviest ions [24]. The apparatus, its components and performance are described in detail in Ref. 25, and are therefore only briefly summarized here.

A schematic drawing of APEX is shown in Fig. 1. It consists of a large solenoid mounted

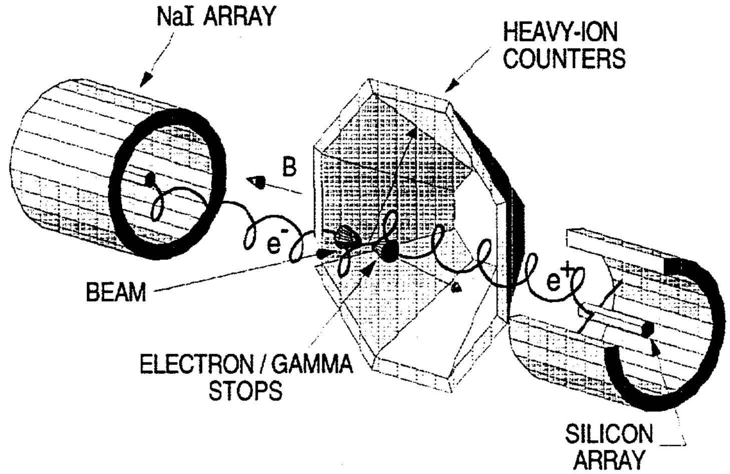

Fig. 1. Schematic drawing of APEX showing the major components.

transverse to the beam direction. The field is produced by eight large coils arranged so as to produce an approximately uniform, 300 Gauss, field along the central axis of the solenoid. The heavy ion beam from the ATLAS accelerator impinges on targets mounted on a target wheel [26] which can rotate at up to 900 rpm so as to allow higher beam intensities than would be possible with static targets. Typical average currents during the measurements reported here were 1-2 pnA with maximum values of up to 4 pnA. Scattered beam particles and recoiling target nuclei are detected in an array of position-sensitive parallel plate gas avalanche counters [27] which cover polar angles from 20 to 68 degrees with respect to the beam axis and have almost complete azimuthal coverage. These detectors allow reconstruction of the kinematics of the heavy ion scattering events leading to positron production. Positrons and electrons produced at the target position are transported with helical trajectories to two highly-segmented, pencil-like arrays of silicon detectors [28,29] each consisting of 198, 1 mm thick detector elements which provide information on the lepton energies and time of flight. Combined with information on the position of the struck detector, the polar and azimuthal angles of emission with respect to the solenoid axis can be reconstructed. Positrons which stop in the silicon detectors are distinguished from electrons through detection of their annihilation radiation in two barrel-shaped arrays [30] of position sensitive NaI(Tl) detectors which surround each silicon array. These detectors are shielded from the intense flux of photons produced at the target by the two, cone-shaped, "electron-gamma" stops positioned close to the target which have the additional function of suppressing the low energy (<115 keV) portion of the electron spectrum. Additional detectors are provided to monitor the beam position, intensity and timing as well as the target condition. Large Ge detectors are used to measure the gamma-ray spectrum in coincidence with scattered ions.

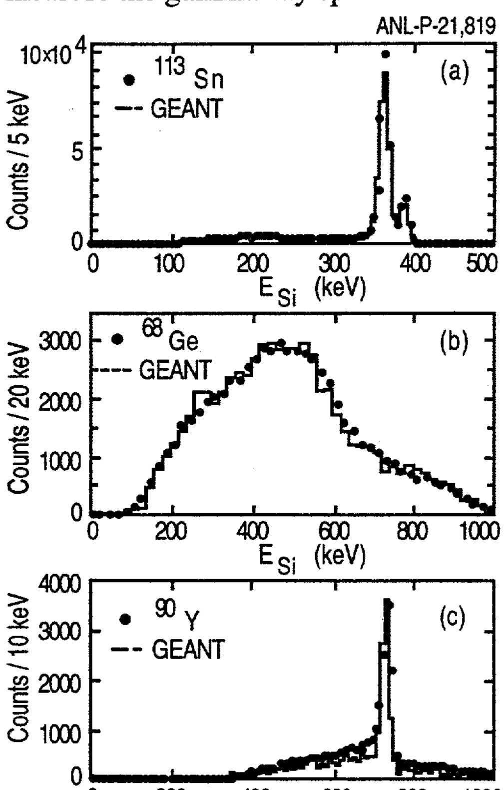

Fig. 2. Comparison between the measured APEX response (solid circles) and calculated response (dashed histograms) for (a) electrons, (b) positrons, and (c) electron-positron pairs.

The performance of the APEX spectrometer has been studied in detail with a variety of source and in-beam measurements. The results of some of the source measurements are shown in comparison with simulations in Fig. 2. The overall performance of the silicon arrays is demonstrated in Fig. 2a which shows the energy spectrum obtained with a ^{113}Sn source placed at the target position. The overall energy resolution is 12 keV (FWHM). The low energy cutoff in the spectrum results from a combination of the cutoff in the solenoid transmission and the threshold in the silicon fast timing electronics, both effects which are included in the simulations. The response and efficiency of APEX for electrons and positrons was determined using conversion electrons from ^{203}Hg, ^{113}Sn and ^{85}Sr, positrons from ^{68}Ge and positron-electron pairs from ^{90}Y, examples of which are shown in Figs. 2b and 2c. The features of these spectra are well reproduced by the results of GEANT simulations which also give excellent agreement with the measured absolute detection efficiencies for positrons and electrons. The precise values of the efficiencies depend on the number of silicon detectors retained in the analysis which varies from experiment to experiment. For example, in the case of the ^{238}U+^{232}Th data set, the absolute peak efficiencies for 363 keV electrons and positrons was determined to be 18% and 4.5% respectively. The efficiency for the ^{90}Y pair decay was determined to be 0.29± 0.01% in good agreement with the calculated value of 0.28±0.02%. In this case, the efficiency for detection of pairs resulting from the isotropic decay of a slowly moving object of mass 1.8 MeV/c^2 was calculated to be 1.3% - the efficiency for an IPC transition of the same energy in ^{238}U at rest is 0.44%.

3. Data for $^{238}U+^{232}Th$

Sharp sum-energy lines which have the characteristics associated with the particle scenario have been reported at 760 keV [9] and 809 keV [11] in the $^{238}U+^{232}Th$ system at bombarding energies between 5.83 and 5.90 MeV/u.

We have made a measurement at 5.95 MeV/u with targets of average thickness 760 μgm/cm^2 corresponding to an energy loss of 0.17 MeV/u. The total integrated luminosity was 7,000 μb^{-1}. The total number of positrons detected in coincidence with two scattered heavy ions was 246,000 and the number of associated pairs, 126,000. These data have been analyzed according to the expectations for a particle produced with a narrow velocity distribution in the heavy-ion center-of-mass frame, the scenario proposed to account for the reported lines. The results of this analysis are shown in Fig 3. The upper spectrum in Fig. 3a is the positron electron sum energy spectrum obtained by selecting near equal positron and electron energies as expected from simulations of the particle decay. This analysis is essentially the same as the "wedge cut" analysis of Ref. 9. The histogram superimposed on the data corresponds to a spectrum of uncorrelated pairs generated by summing positrons and electrons from different events - event mixing. The signal expected from the isotropic decay of an isolated neutral object of mass 1.8 MeV/c^2, produced uniformly through the target with the cross section given in Ref. 11 is shown as a dashed peak superimposed on the event mixed spectrum. These data, further selected on solenoid azimuthal angle-energy correlations expected for two-body decay are shown in the lower portion of Fig. 3a. The superimposed histogram, in this case, corresponds to the appropriate event-mixed spectrum plus a signal one tenth of that quoted in Ref. 11. Neither of these spectra show evidence for structures of width comparable with the previously reported peaks. Upper limits (99% CL) for the cross-sections of peaks of width comparable to our experimental resolution (30 keV FWHM) derived from these analyses are shown in fig. 3b. These upper limits are approximately one and two orders of magnitude smaller, respectively, than the values inferred from the earlier observations [9,11] which are indicated by the shaded area.

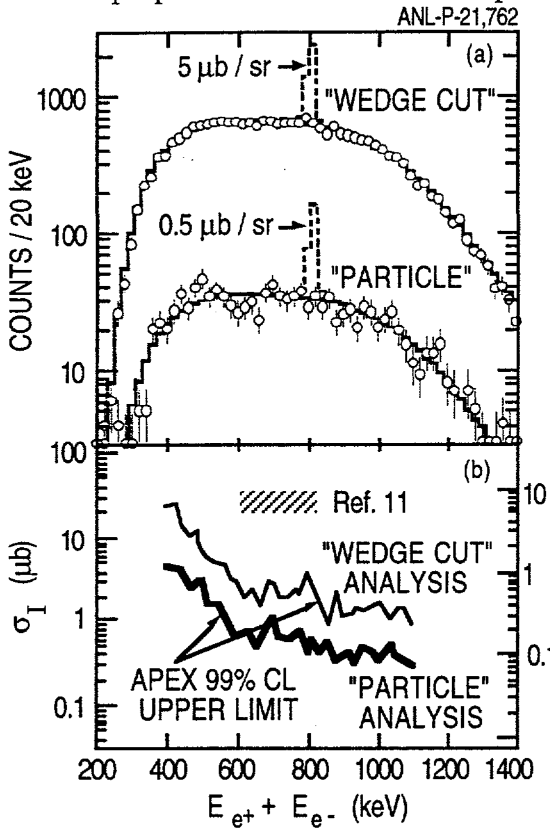

Fig. 3. a) Sum-energy spectra for $^{238}U+^{232}Th$ at 5.95 MeV/u analyzed according to the expectations for the isotropic decay of a particle produced in the center-of-mass (β=0.06), selected on positron and electron energies ("Wedge Cut") and further selected on correlated energies and azimuthal angles ("Particle"). The superimposed curves correspond to event-mixed spectra. The expected additional yields for a 1.8 MeV/c^2 particle produced with cross-sections of 5 and 0.5 μb/sr respectively are shown dashed. b) Upper limits (99% CL) for the cross-section derived from the "Wedge Cut" and "Particle" analyses as a function of sum-energy. The shaded area indicates the energy range of peaks and level of cross-section given in Ref. 11.

4. Data for $^{238}U+^{181}Ta$

Measurements for this system have been made at bombarding energies of 5.95, 6.10 and 6.30 MeV/u using targets of thickness between 650 and 700 μgm/cm^2. The integrated luminosities were 5,800, 11,000 and 8,600 μb^{-1} respectively. In general, the numbers of silicon detectors retained in the analysis of these data were smaller than in the $^{238}U+^{232}Th$ case which is reflected in the smaller detection efficiencies for the particle which are 0.88%, 0,84% and 0.55% at the three bombarding energies respectively. These data have been subject to the analysis based on the particle scenario as was the case for $^{238}U+^{232}Th$. No evidence was found for narrow peaks and the cross-section upper limits were similar - within a factor of two - to those obtained for the ^{232}Th target. Sum-energy lines which do not exhibit all the properties of two-body decay have previously been reported at 625 keV [11], 634 keV [12], 748 keV [11] and 805 keV [11] in the $^{238}U+^{232}Th$ system. We have analyzed our data according to the selection of lepton energies given for these peaks in the literature. Examples of spectra thus obtained are shown in Fig. 4 for the case of the 748 keV line. No evidence is seen for a line near 748 keV or elsewhere in these spectra. In the absence of a model of the lepton energy distributions, lepton angular correlations and emitter velocity distributions, extraction of upper limits to cross sections is impossible. Using, however, the efficiency of our apparatus for IPC from at Z=92 nucleus at rest and assuming uniform production through the target and isotropic decay, we arrive at upper limits for the production cross-sections of 7 μb at all three energies. Similar values are obtained from the analyses carried out for the other lines. According to the information given in Ref. 11, the previously reported peak yields corresponded to production cross sections of approximately 100 μb.

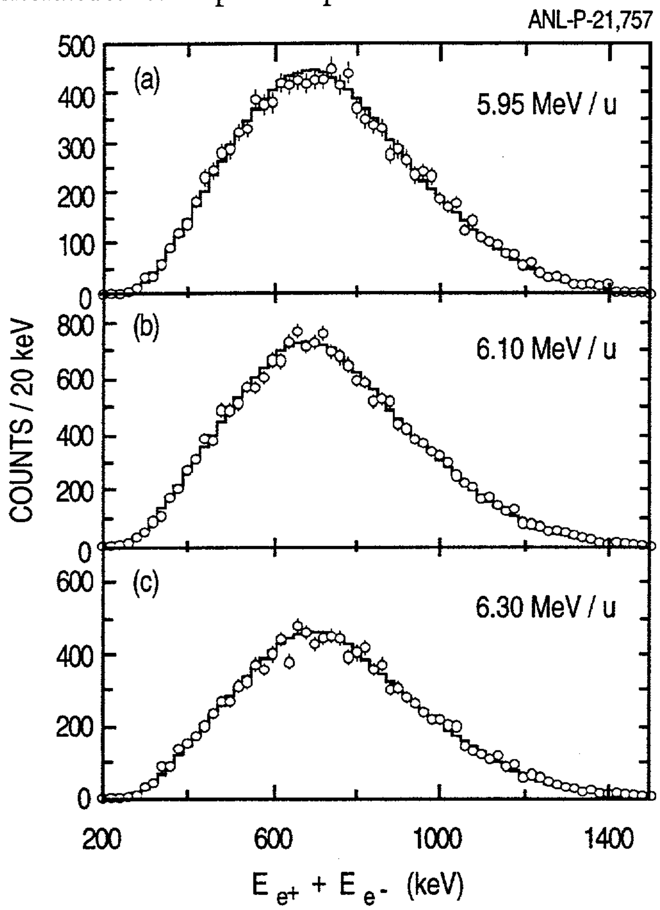

Fig. 4. Sum-energy spectra for $^{238}U+^{181}Ta$ at 5.96, 6.10 and 6.30 MeV/u analyzed according to the selection on lepton energies for the 748 keV line reported in Ref. 11. The superimposed histograms represent spectra obtained by event mixing.

5. Gamma Rays and IPC

The possible role of IPC in the spectra of positron-electron pairs produced in heavy ion collisions has been the subject of a number of discussions [31]. It is well known that IPC of continuum transitions in the scattered nuclei contributes significantly to the overall yield of positrons, particularly in the case of systems with lower total nuclear charge. The possibility that IPC of discrete transitions might somehow produce sharp structure in the pair sum-energy spectra has generally been discounted, as the emission from a moving nucleus, coupled with the broad energy distribution and angular correlation of the pair is expected to result in a severely broadened sum-energy peak in the laboratory sum-energy spectra. The lack of any sharp peaks in the data discussed above would also appear to make such a possibility unnecessary. Nevertheless, in our experiments, we have searched for transitions in the colliding nuclei which might possibly have significant IPC decays in the energy range of interest.

Up to five HpGe detectors were used to measure gamma-rays in coincidence with heavy ions detected in the APEX heavy-ion arrays for the $^{208}Pb+^{238}U$, $^{238}U+^{181}Ta$, $^{208}U+^{232}Th$ and $^{208}Pb+^{232}Th$ systems. Figure 5 shows gamma-ray spectra thus obtained, Doppler corrected for emission from the U-like or Th-like fragment. In addition to the well-known spectrum of low-energy gamma-rays, in the region 1500 to 2000 keV, shown in the insets - corresponding to pair sum energies of 478 to 978 keV - there appears a strong transition at 1780 keV excited in all cases with a cross

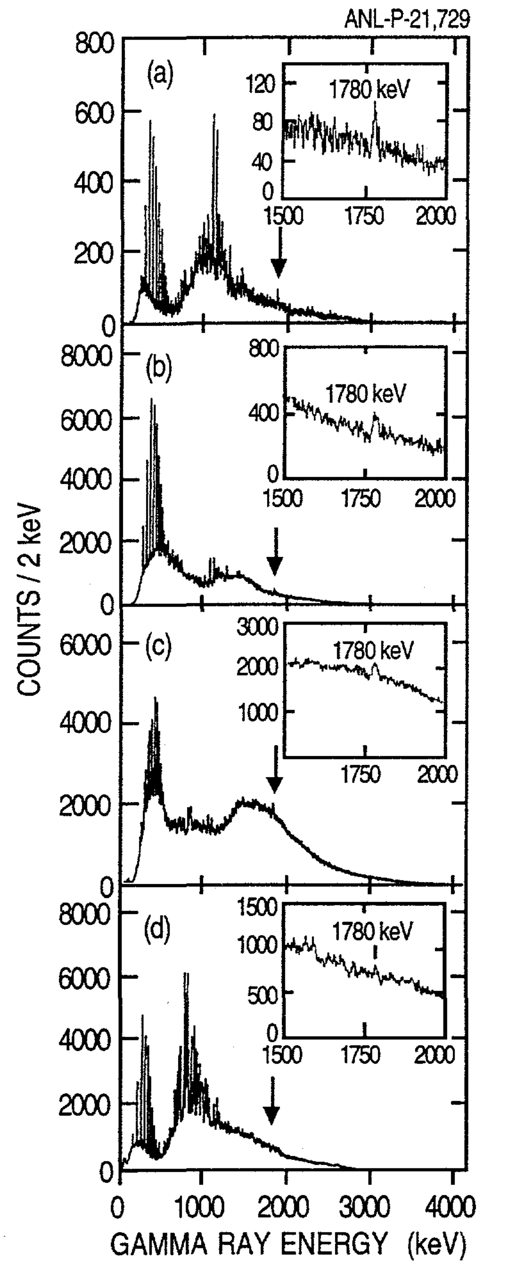

Fig. 5. Gamma-ray spectra Doppler reconstructed from heavy-ion collisions of actinide nuclei. (a) U-like events from $^{208}Pb+^{238}U$ at 5.80 MeV/u, (b) U-like events from $^{238}U+^{181}Ta$ at 5.95 MeV/u, (c) U and Th-like events from $^{238}U+^{232}Th$ at 5.95 MeV/u, and (d) Th-like events from $^{208}Pb+^{232}Th$ at 5.80 MeV/u. All the U-like spectra show a prominent transition at 1780±2 keV.

section of approximately 20 mb. If this is a dipole transition, the theoretical IPC coefficient of 4×10^{-4} leads to an expected pair cross-section of 8 μb at a sum-energy of 758 keV.

As discussed, IPC from a moving heavy ion is not expected to produce sharp lines in the laboratory pair sum-energy spectrum but will only do so when the measured energies are transformed into the rest frame of the emitter - as was the case for the gamma rays. To investigate this, and to test the ability of APEX to reconstruct such a kinematic scenario, we have measured gamma rays and pairs from the $^{206}Pb+^{206}Pb$ system at 5.90 MeV/u. The Doppler corrected gamma ray spectrum resulting from this measurement is shown in Fig. 6. Only two strong transitions are observed corresponding to the decay scheme shown in the inset.

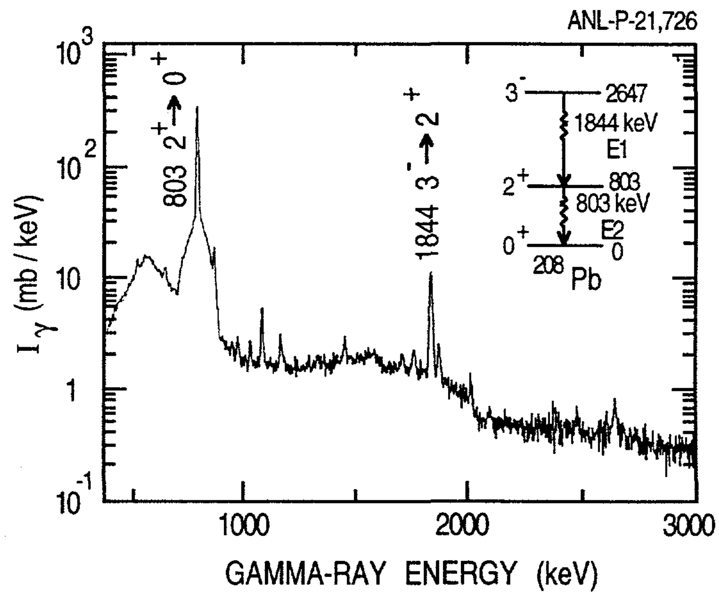

Fig. 6. Doppler corrected γ-ray spectrum from the $^{206}Pb+^{206}Pb$ reaction at 5.90 MeV/u.

The unusual line shape results from the indistinguishability of target and projectile in this symmetric scattering system. For the purposes of our investigation of IPC, the E1 transition at 1844 keV is the one of interest, its population cross-section of 122 mb leading to an expected pair cross section of 51 μb. The pair sum energy spectra from this measurement are shown in Fig. 7. The upper portion shows the uncorrected sum-energy spectrum which appears quite smooth within statistics despite the presence of a known strong IPC signal at an unshifted sum energy of 822 keV. These same events, now corrected for the motion of the source are shown in the middle section, clearly showing the expected peak at 822 keV. The lower

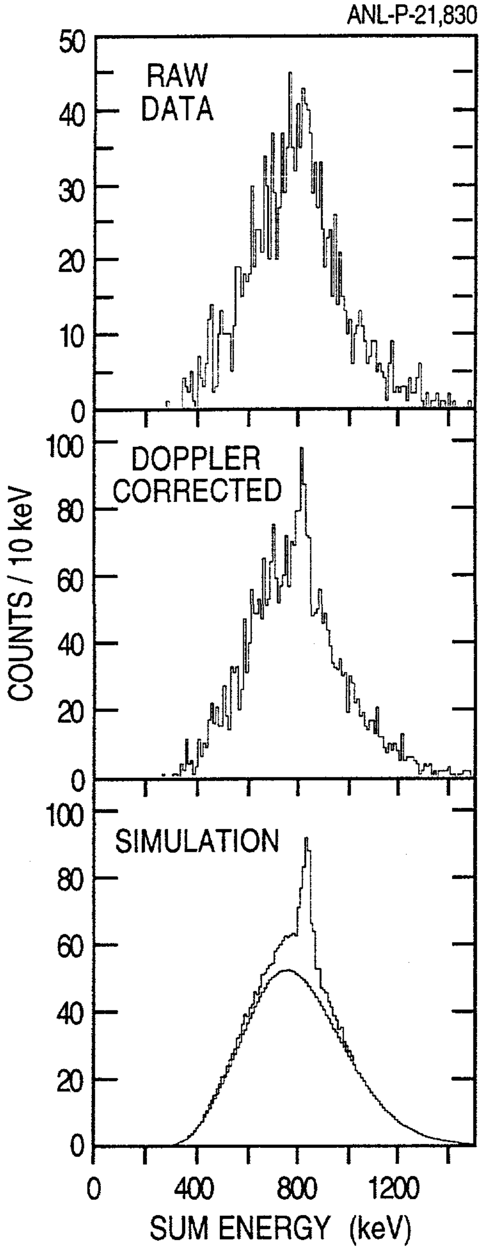

Fig. 7. Pair sum-energy spectra for $^{206}Pb+^{206}Pb$ a) Uncorrected, b) Doppler corrected for emission from ^{206}Pb, and c) Simulated, based on expected yield superimposed on event mixed background.

portion shows a simulation of this spectrum where the IPC signal has been added to an appropriately normalized background generated by event mixing as discussed before. Note again, as was the case for the Doppler correction of the gamma rays, the unusual line shape that results from the indistinguishability of target and projectile.

Based on this demonstrated understanding of the IPC kinematics and yield, we are now in a position to address the extent to which the 1780 keV U transition might appear in the associated pair data. Figure 8 shows the Doppler corrected pair spectrum for $^{238}U+^{232}Th$. The measured cross-section for the 1780 keV gamma ray together with the assumption of a dipole character of the transition leads to an expected intensity of 80 counts of width 40 keV in the pair spectrum which corresponds to a 1σ effect on top of the observed background. We therefore conclude that IPC is not a viable source of the reported peaks, even when the data are corrected for emission from a moving source.

6. Summary and Conclusion

Our measurements have to date shown no evidence for lines with the characteristics of those previously reported and the cross section limits derived from our data are considerably lower than those implied by the previous results. The origin of this apparent discrepancy may lie in so far unknown characteristics of the phenomenon. Although the overlap of the acceptance of APEX with that of previous experiments is large, it is nevertheless conceivable that the energy and angle correlations of the lepton pairs are such that they escape detection in our apparatus. However, quite extreme situations are required for this to occur. There is some evidence [11] that the cross section for the line phenomenon is dependent on beam energy. Our measurements, particularly for $^{238}U+^{181}Ta$, have covered a wide range of energies encompassing the region of previous line observations, and it is unlikely that the energy calibrations of ATLAS and the UNILAC are so far in error that there is no overlap between the current and previous measurements. Even if the line production cross section does show a sharp resonance-like energy dependence, the increase of our cross section upper limits would only be by the ratio of the target thicknesses in the different measurements and would, at most, be a factor two. The lack of specific models for the lines and the conditions under which they are produced, makes definitive conclusions hard to draw. For the specific scenarios of the particle and IPC we are able to make definite statements and we believe therefore, that the present results represent a real and significant disagreement with the previous work.

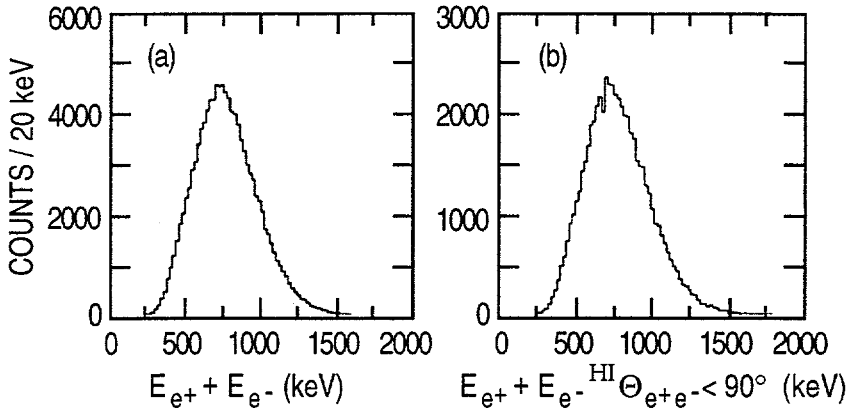

Fig. 8. Doppler reconstructed electron-positron sum-energy spectrum from $^{238}U+^{232}Th$ at 5.95 MeV/u. (a) Total data and (b) events with an electron-positron opening angle of less than 90°, a selection which enhances E1 1PC.

7. Acknowledgments

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