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The positron-electron peak puzzle: results from APEX

The APEX Collaboration

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The observation of line structures in the energy spectra of positrons [1-8] and positron-electron pairs [9-12] produced in collisions of very heavy ions has provided a challenging puzzle in nuclear physics for the past fifteen years. In the experiments, carried out at the GSI UNILAC accelerator, lines with similar energies and widths were reported for a number of scattering systems over a range of bombarding energies near the Coulomb barrier. In order to account for the kinematic features of the observed lines, it has been proposed that they may originate from the two-body decay of a hitherto unknown light neutral particle or composite object, which results in near back-to-back, equal energy positron-electron pairs in the laboratory frame. The kinematic characteristics of some of the lines were consistent with the neutral particle decay scenario [9-11], but others were not [11, 12]. The existence of such low-mass neutral states is highly constrained by other experimental and theoretical results [13-20]. In this paper we present results from a new experiment designed to investigate these lines. Data were obtained for the ^{238}U+^{232}Th and ^{238}U+^{181}Ta systems, at energy ranges covering those of previous experiments. No evidence for the previously observed lines was found in our data.

The APEX experiment has been assembled at Argonne National Laboratory. It utilizes CW beams from the ATLAS superconducting linear accelerator [21]. The APEX spectrometer [22] consists of a large symmetric solenoid mounted transverse to the beam direction. A rotating wheel assembly is used to hold up to four targets. The heavy ions are detected in a 24-element array of low-pressure multi-wire proportional counters, which provide position and time-of-flight information. They are placed symmetrically about the beam direction, with respect to which they cover $0^0 - 360^0$ and $20^0 - 68^0$, of the azimuthal and polar angle (θ_{beam}) range respectively. The leptons produced in the heavy-ion collisions follow helical trajectories in the uniform 300 G field, and are detected 1.2-1.5 m from the target by two 198-element pencil-shaped detector arrays placed on the solenoid axis. The Si PIN diode arrays provide energy, position and time-of-flight information, which can be used to calculate the full lepton kinematics. Leptons of 150-1000 keV are accepted in the full azimuthal range, but the efficiency is optimized for leptons of 200-600 keV, which are accepted in the $20^0 < \theta_{beam} < 160^0$ range. Positrons are identified and distinguished from electrons by detecting their characteristic back-to-back annihilation 511 keV γ-rays in two 24-element arrays of position-sensitive NaI(Tl) crystals (55 cm long, 43 cm inner, 49 cm outer diameter). Good positron identification ($< 5\%$ electron contamination) is achieved by correlating the Si and NaI(Tl) information in position and time.

The performance of the apparatus has been extensively tested with radioactive sources placed at the target position. These included ^{203}Hg, ^{113}Sn and ^{85}Sr conversion electron sources for lepton energy calibrations, a ^{68}Ge continuum source for measuring the positron efficiency, and a ^{90}Y source for internal pair conversion (IPC) calibrations. In all cases, the data have been reproduced well by simulations. A

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Table 1. Experimental Parameters; see text for definition

System	E(MeV/u)	N_{e_+}	$N_{e_+e_-}$	ϵ_X	ϵ_{IPC}
^{238}U+^{232}Th	5.78-5.95	246000	126000	1.30	0.44
^{238}U+^{181}Ta	5.79-5.95	59000	17000	0.88	0.30
^{238}U+^{181}Ta	5.94-6.10	84000	25000	0.84	0.27
^{238}U+^{181}Ta	6.13-6.30	70000	16000	0.55	0.18

very stringent test of the apparatus was the in-beam measurement of IPC pairs from the E1 decay of the 1844 keV state in ^{206}Pb, excited in ^{206}Pb +^{206} Pb collisions at 5.90 MeV/u. Using the complete heavy-ion and lepton kinematic information, the lepton energies were Doppler-corrected for emission from either heavy-ion, and a $\approx$ 35 keV wide peak at sum-energy of 822 keV was reconstructed. In addition to its significance for the correct functioning of APEX, this experiment measured an IPC branching ratio of β = $(4.0 \pm 0.7) \times 10^{-4}$[23], in good agreement with the theoretical value of 4.17×10^{-4}[24].

Data on the ^{238}U+^{232}Th and ^{238}U+^{181}Ta systems were collected with ^{238}U beam energies (E) near the Coulomb barrier, and average currents of $\approx 1 - 2$ particle nA. Rolled metal targets were used, with average thickness of $\approx$ 0.7 mg/cm^2, which corresponds to an energy loss of $\approx$ 0.17 MeV/u. The beam energy ranges, and the total numbers of positrons (N_{e_+}) and pairs ($N_{e_+e_-}$) detected in coincidence with two heavy ions are shown in Table 1. The variety of analyses which have been carried out on these data sets have included gating on published parameters, such as the heavy-ion scattering angle and positron-electron difference energy, as well as exploring the kinematically complete information of APEX, such as positron-electron opening angle and positron angle with respect to the beam direction. None of these analyses has produced statistically significant evidence for sharp ($<$ 30 keV wide) sum-energy lines [25]. Two searches for line structure based on proposed physics scenarios are described in the following paragraphs.

The 760 keV [9] and 809 keV [11] sum-energy lines in the ^{238}U+^{232}Th system were reported to have the characteristics associated with the two body decay of an isolated neutral object (X), produced at rest at the center of mass. The measured sum-energy spectrum gated on the positron-electron energy difference and on the solenoidal azimuthal angle-energy correlations expected in such a decay did not show line structure. Using the calculated pair efficiency ϵ_X (shown in Table 1 for a 1.8 MeV/c^2 particle) a limit of $d\sigma/d\Omega_{\mathrm{HI}} < 0.1$ μb/sr was derived [25] (99% c.l.). This is smaller than the value of $d\sigma/d\Omega_{\mathrm{HI}} \approx 5$ μb/sr quoted in [11] and than the smaller values in [26].

Searches were also made for reported lines which do not exhibit all the expected properties of two-body decay. These include lines at 608 keV [11] in ^{238}U+^{232}Th and 625 [11], 634 [12], 748 [11], and 805 keV [11] in ^{238}U+^{181}Ta. The data were analyzed with the lepton energy cuts given in the literature and again no evidence of line structure was seen. Due to the absence of a physical model for the lepton energy and angle distributions, and the emitter velocity distribution, it is not possible to extract an upper limit for the cross sections. Using, however, the efficiency ϵ_{IPC} of APEX for detecting a pair due to an IPC transition in a Z = 92 nucleus at rest (shown in Table 1 for a 1.8 MeV transition), and assuming isotropic decay, we extracted an upper limit of $\sigma < 7$ μb (99% c.l.) for all lines in this system. This is to be compared to the calculated value of ≈ 100 μb based on the published information [11].

For both decay scenarios described above, our limits are 1-2 orders of magnitude lower than the reported values of the cross section. This presents a clear discrepancy, the origin of which may lie in the so far unknown characteristics of the phenomenon. Given the large overlap between the acceptance of APEX with those of the previous experiments, it is implausible that the angle-energy correlations of the lepton pairs are such that they escape detection in our apparatus. In the case that the line phenomenon has a resonance-like dependence on beam energy [11], our upper limits derived from the current data would have to be increased by no more than a factor of 2-3, corresponding to the ratio of target thicknesses in the two cases. The lack of specific decay models for many of the lines, and the conditions under which they are produced makes definitive conclusions hard to draw. Nevertheless, we have ruled out the two scenarios described above. Our results are in disagreement with previous measurements. Similar conclusions have resulted from more recent studies [26, 27].

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