Search for peak structure in $e^+ +$ Th collisions

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The interaction of positrons emitted by a ^{68}Ga radioactive source with a thorium target was studied. Positron and electron energy spectra were measured in coincidence by using mini-orange spectrometers and high-resolution Si(Li) detectors. Peak structure which could be related to a new phenomenon has not been found in the spectra. All of the lines observed are explained in terms of well-known nuclear or atomic mechanisms.

I. INTRODUCTION

The discovery of narrow peaks in the energy spectra of positrons emitted from very-heavy ion collisions at bombarding energies close to the Coulomb barrier[1-6] presents an interesting problem since the properties of the observed lines appear to be unexplainable in terms of established mechanisms. To date, positron lines were found in collision systems ranging from Th + Th up to U + Cm ($Z_1+Z_2=180-188$), and recently also in the lighter systems Th + Ta (Ref. 7) and U + Ta (Ref. 8) ($Z=163$ and 165). The energy of the positron peak, as reported in Refs. 1, 3, and 5, varies between 320 and 360 keV. Somewhat lower energies (~ 280 keV) were found in Refs. 2 and 4, while a very recent study of U-U collisions by the same authors[6] now reveals multiple peak structure having a centroid energy which is in better agreement with the energy values reported in Refs. 1, 3, and 5. A particularly important result has been obtained from electron-positron coincidence experiments[5] which give evidence for correlated emission of monoenergetic electrons and positrons.

A number of attempts have been made to explain the occurrence of the narrow positron peak and its properties theoretically. As yet, none of the interpretations offered is fully satisfactory. One possible reason for the emission of monoenergetic positrons has been seen in the vacuum decay in supercritical fields of long-lived giant nuclear systems[9,10] with a combined nuclear charge of $Z>137$. More recent discussions, particularly in connection with the results of Ref. 5, focus on the production of a previously unobserved light neutral particle and its subsequent decay into an electron-positron pair.[11,12] Other models presently proposed involve the decay of compound configurations, such as polyelectron complexes[13] or positronium droplets.[14]

To date, all experimental studies concerned with the emission of monochromatic positrons were carried out at heavy-ion accelerators. Very recently, however, an alternative approach was taken[15] by studying the interaction of positrons emitted from a radioactive source with thin thorium and tantalum targets. Electron and positron energy spectra were measured in coincidence, and evidence for narrow peak structures was found in both the positron and electron spectrum at ~ 340 keV. It should be noted, however, that the identification of a small line at this energy is complicated by background due to annihilation gamma rays which produce a Compton edge in the spectrum at 340 keV. For an unambiguous confirmation of the reported peaks additional experiments appear to be necessary, in particular measurements with better suppression of the background. In this paper we report on such an experiment.

II. EXPERIMENTAL METHOD AND RESULTS

The experimental setup used for the present investigation is shown in Fig. 1. The apparatus is very similar to that employed by Erb *et al.*,[15] with modifications made with respect to the positron source and the magnetic spectrometers used for the detection of electrons and positrons. The efficient reduction of the above-mentioned Compton-scattering background has been an important aspect in this study, and efforts were also made to improve the time and energy resolution of the particle detectors. The experiments were performed using a ^{68}Ga positron source which was prepared via the ^{68}Zn(p,n)^{68}Ga reaction by exposing a ^{nat}Zn target to a collimated (2 mm in diameter) beam of 5.5 MeV protons. The irradiation took 1–3 h, depending on the source activity required. The beam energy chosen ensured that only the isotope ^{68}Ga was produced with measurable strength since the ^{64,66}Zn(p,n)^{64,66}Ga reactions, which also produce positron activity, are prohibited by large negative Q values of -7.95 MeV and -5.96 MeV, respectively.[16] The half-life of ^{68}Ga is 68 min, and the maximum kinetic energy of the emitted positrons is 1.89 MeV. After irradiation, a 58 mg/cm^2 Th target was placed in front of the source, with a lead collimator, 8 mm in diameter, used to keep source and target 3 mm apart. For data taking this source-target assemblage was subsequently transferred to a separate scattering chamber which contained the spectrometers. Data were accumulated for 60–90 min. After completion of this cycle the Zn foil was irradiated again.

Positrons and electrons leaving the target foil were distinguished by two mini-orange spectrometers made of $SmCo_5$ permanent magnets, one of which served as a filter for electrons, the other for positrons. The spectrometers were placed at $\pm 45°$ with respect to the symmetry axis of the source-target arrangement. Si(Li) detectors, 3 mm

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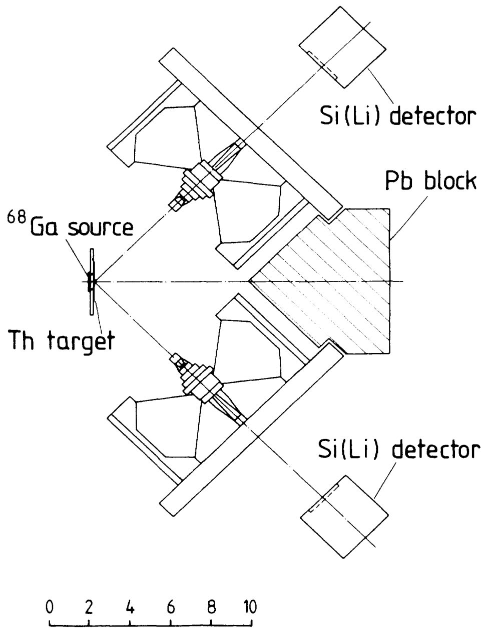

FIG. 1. Experimental setup used for the present study. The apparatus included two mini-orange spectrometers, one of which served as a filter for positrons, the other for electrons.

thick and operated at liquid-nitrogen temperature, served to detect positrons and electrons. The sensitive area of the e^+ and e^- detector was 300 mm^2 and 200 mm^2, respectively. The energy resolution was typically 2 keV, which does not include broadening due to straggling in the source or target. The time resolution achieved in this experiment was 10 nsec (FWHM). The distance from the Th target to either detector was 16 cm, which is long enough to permit efficient shielding of the detectors. An unfavorable consequence of this geometry, however, is the low spectrometer transmission. The transmission window was determined from a measurement of conversion-electron yields of a ^{152}Eu source with and without the spectrometers. A maximum intensity gain of 6 was obtained for the positrons at 360 keV, and 4 for the electrons at 550 keV.

A serious contribution to the background is caused by annihilation photons which escape from the e^+ detector and then enter the e^- detector. These photons produce prompt coincidences with the detected positrons and result in a Compton edge at 340 keV in the coincident e^- spectrum. To minimize the number of these events, a lead shield was placed in the wedge-shaped area between the spectrometer-detector arrangements, which was 6 cm thick in the line of sight (see Fig. 1). Another source of coincident background originates from annihilation gamma rays which are Compton scattered by spectrometer material and cause structure at ≤ 340 keV in the e^+, as well as the e^- spectrum. To reduce this contribution, magnet configurations consisting of only three thin magnets were chosen. In addition, lead baffles placed in the center of the orange spectrometers blocked photons, electrons, and positrons on the line of sight between target and the detectors. The baffles employed were to some extent transparent to photons having energies exceeding ~ 800 keV. Coincidences involving these higher-energy gamma rays are easily identified in the spectra, however, as will be discussed below.

Positron and electron spectra which were measured in coincidence are shown in Fig. 2. These spectra contain both true and random coincidences. To emphasize the structure due to random coincidences, no window was set in the time spectrum. Two major sources of background are seen. In both spectra a Compton edge is found at 340 keV, which results from detection of 511 keV annihilation photons in the respective Si(Li) detector. In the electron spectrum additional structure is seen at 401 and 492 keV. These lines are interpreted as being due to random coincidences between positrons or photons seen by the e^+ detector and *K*- or *L*-shell photoelectrons from thorium atoms exposed to the high flux of annihilation gamma rays next to the source.

By subtracting random coincidences, the spectra shown in Fig. 3 are obtained. No structure, which is statistically significant, remains in the positron spectrum. It is noted that the Compton edge at 340 keV has completely disappeared. In the electron spectrum, however, structure is seen at 340 keV and possibly at 871 keV. The origin of these lines is readily explained by the decay properties of

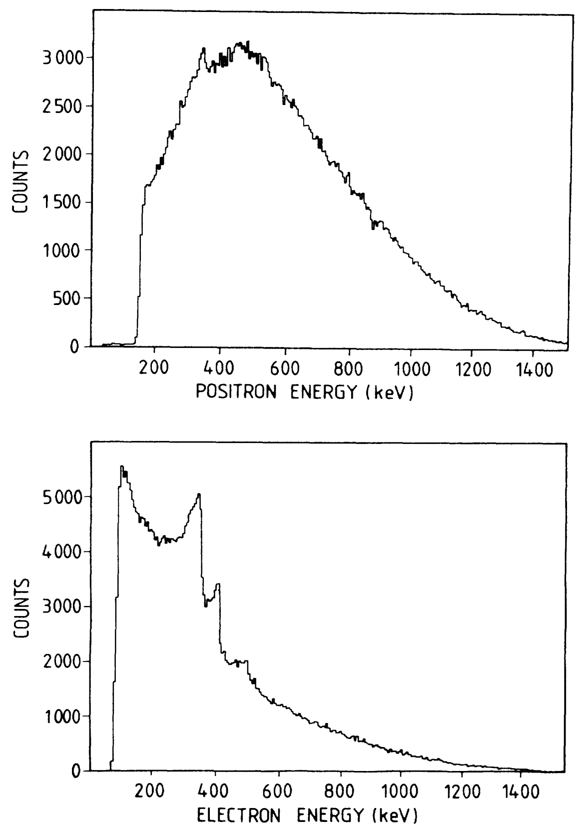

FIG. 2. Kinetic-energy spectra of positrons (upper display) and electrons (lower display) obtained from $e^+ + Th$ collisions and measured in coincidence. The spectra shown contain both true and random coincidences to demonstrate sources of background (see the text).

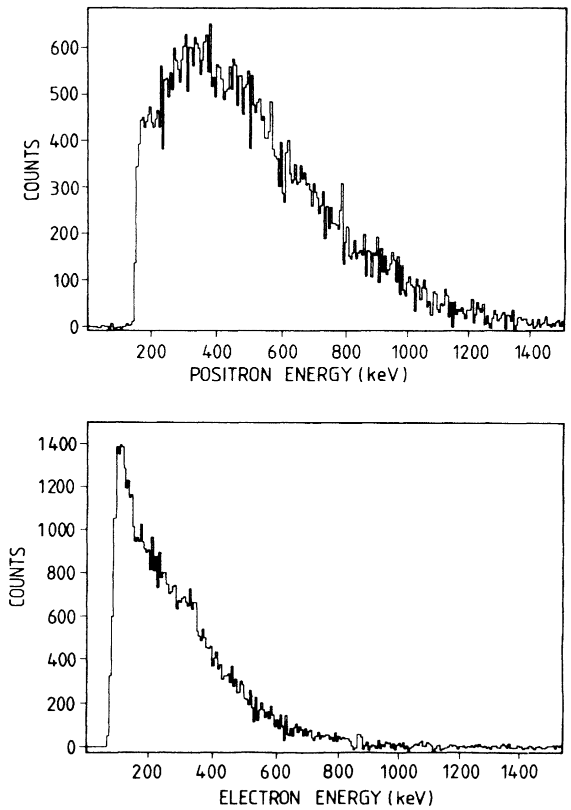

FIG. 3. Kinetic-energy spectra of positrons (upper display) and electrons (lower display) measured in coincidence after subtraction of random coincidences.

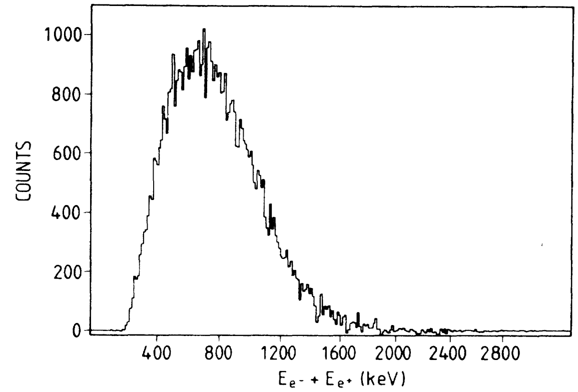

FIG. 4. Intensity distribution of e^+e^- coincidences plotted versus the summed positron and electron energies.

the ^{68}Ga source. A fraction of $\sim 2\%$ of the positrons emitted by ^{68}Ga leaves the ^{68}Zn daughter nucleus in the first excited state at 1078 keV, which subsequently decays via $E2$ gamma emission. To photons of this energy, the lead baffles in the orange spectrometers are to some extent transparent, as was pointed out above. Hence, gamma rays emerging from the source are seen by both the e^+ and e^- detectors. The Compton edge at 340 keV is believed to result from coincidences between 1078-keV photons seen by the e^+ detector and 511-keV gamma rays detected by the e^- detector. The latter photons result from the annihilation of the decay positrons which probably occurs anywhere between the target and the e^- detector. The structure at 871 keV is assumed to be due to coincidences between positrons detected by the e^+ detector and 1078-keV photons seen by the e^- detector. Both events involve positrons having a maximum kinetic energy of 820 keV. The scenarios just outlined are easily verified by setting appropriate gates on the positron spectrum. By selecting events that have an energy >820 keV, i.e., gating on positrons that lead to the ground state of ^{68}Zn, the structure of 871 keV is completely removed from the electron spectrum. By cutting off all events that have an energy <871 keV in the e^+ spectrum, coincidences with 1078-keV photons, detected via the Compton effect, are eliminated, and the edge at 340 keV is removed from the e^- spectrum. Hence, no significant structure remains unexplained in the electron spectrum.

In the coincidence experiments of Ref. 5, peak structure was found not only in the positron spectrum, but also in the simultaneous emission of electrons. The energies of the e^+ and e^- peaks were found to agree to approximately 380 keV within the experimental errors. Moreover, peaks were also observed in the spectrum of summed positron and electron energies ($E_{e^+}+E_{e^-}$) at ~ 760 keV, as well as in the spectrum of subtracted positron and electron energies ($E_{e^+}-E_{e^-}$) at ~ 0 keV. This result has led to speculations that a new and previously unobserved particle, which decays into an electron-positron pair, might have been discovered in these heavy-ion collisions.[11,12] In the work of Ref. 15, evidence was presented for a line at the somewhat lower energy of 670 keV in the summed-energy spectrum, and it was suggested that this line and the peaks found in the heavy-ion experiments[5] might have a common origin. The sum spectrum obtained from the present data, as shown in Fig. 4, reveals no statistically significant structure at this energy. On the basis of the results obtained from this study, it is suggested that the 670-keV line in the sum spectrum, as well as the 340-keV peaks in the positron and electron spectra of Ref. 15, are due to coincidence mechanisms involving annihilation gamma rays. The analysis of the present experiment has shown that such coincidences can be strongly suppressed by efficient shielding of the detectors.

In summary, we conclude that our search for peak structure in the positron and electron spectra resulting from the interaction of positrons with a thorium target did not produce significant evidence for the existence of such peaks. The results of our experiment suggest that the lines reported in Ref. 15 are caused by coincidences with annihilation photons. Hence, it appears that up to now only heavy-ion collisions provide the mechanism that produces correlated positron and electron lines.

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