UCY–PHY–99/04

Positron spectra from internal pair conversion observed in ^{238}U + ^{181}Ta collisions

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(Revised version, August 23, 2000)

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Abstract. We present new results from measurements and simulations of positron spectra, originating from ^{238}U + ^{181}Ta collisions at beam energies close to the Coulomb barrier. The measurements were performed using an improved experimental setup at the double-Orange spectrometer of GSI. Particular emphasis is put on the signature of positrons from Internal-Pair-Conversion (IPC) processes in the measured e^+–energy spectra, following the de-excitation of electromagnetic transitions in the moving Ta–like nucleus. It is shown by Monte Carlo simulations that, for the chosen current sweeping procedure used in the present experiments, positron emission from discrete IPC transitions can lead to rather narrow line structures in the measured energy spectra. The measured positron spectra do not show evidence for line structures within the statistical accuracy achieved, although expected from the intensities of the observed γ–transitions ($E_\gamma \sim 1250-1600$ keV) and theoretical conversion coefficients. This is due to the reduced detection efficiency for IPC positrons, caused by the limited spatial and momentum acceptance of the spectrometer. A comparison with previous results, in which lines have been observed, is presented and the implications are discussed.

PACS. 14.60.Cd Electrons and positrons – 23.20.Ra Internal pair production – 25.70.Bc Elastic and quasielastic scattering – 25.70.De Coulomb excitation – 25.70.Hi Transfer reactions – 29.30.Aj Charged particle spectrometers: electric and magnetic

1 Introduction

Previous measurements performed at GSI in Darmstadt by the EPOS and the Orange groups have shown the appearance of narrow (FWHM $\simeq 30 - 80$ keV), and unexpected, e^+–lines at energies in the range 250–400 keV in the positron spectra, obtained from heavy-ion collisions near the Coulomb barrier [1–3]. The lines were superimposed on continuous spectral distributions from quasi-atomic positron emission and from nuclear positron background, which has been determined from measured low resolution γ-spectra and theoretical IPC conversion coefficients [4, 5]. No viable explanation could be found to account for these results. Initially, the measurements were performed to investigate the decay of the neutral vacuum of QED predicted by theory [6], a phenomenon which can lead to the emission of monoenergetic positrons in *supercritical* collisions [6]. But it was clear that the width of the reported e^+–lines was too narrow as to be attributed to this effect and, particularly, the occurrence of similar e^+–lines in the so-called *subcritical* collision systems [6] have excluded an interpretation of the lines in the frame work of spontaneous positron emission [3].

In follow-up extended e^+e^--coincidence experiments electrons were measured in coincidence with positrons, and the measured e^+e^-–sum-energy spectra revealed even narrower lines [7–10]. First attempts were made to interpret these lines in the context of the e^+e^-–decay of a previously unknown neutral particle with a mass around 1.8 MeV/c^2 [7]. But soon this hypothesis was definitively ruled out by subsequent Bhabha-scattering experiments [11].

Only in recent experimental [12–15] and theoretical [16] studies, extended investigations of Internal Pair Conversion (IPC) as potential source of the observed e^+e^-–sum-energy lines in very heavy collision systems at the Coulomb barrier have been carried out. To be more specific, the IPC scenario has been systematically addressed in our investigations by studying the collision systems ^{238}U + ^{206}Pb and ^{238}U + ^{181}Ta . It could be shown that electromagnetic transitions in one of the colliding nuclei which de-excites by emission of IPC e^+e^-–pairs can lead to in principle observable narrow lines in the corresponding Doppler-shift corrected e^+e^-–sum-energy spectra and in back-to-back e^+e^-–coincidence spectra, as observed with the double-Orange spectrometer [12]. The cross sections of the observed γ–lines are typically of the order of some mb up to several 10 mb leading to weak e^+e^-–sum-energy lines with cross sections of 0.1 μb to several μb. The experimental sensitivity for the detection of e^+e^-–lines was limited to cross sections of this order. Based on this new experience, we could show moreover that the general features of most of the previously reported weak e^+e^-–sum-energy lines resemble conspicuously to the IPC process.

In the context of the investigation of IPC processes also the energy distributions for positrons emitted after IPC was reconsidered. Our focus was particularly on positron spectra from several γ–transitions with energies between 1250 keV and 1600 keV observed with high resolution γ–spectroscopy in the Ta–like nucleus [12]. The motivation of the present work was to find out if e^+–emission from discrete nuclear transitions could give rise to lines in the e^+–energy spectra with characteristics similar to previously reported e^+–lines. In these former experiments line structures with differential cross sections of the order of 0.2 μb/sr up to about 1 μb/sr in Doppler-shift uncorrected e^+–energy spectra were reported in several collision systems [3]. Particularly in the system ^{238}U + ^{181}Ta , two very weak e^+–lines at energies of ~230 keV and of ~310 keV have been observed at a beam energy of 5.9×A MeV with production probabilities of $(3.2 \pm 0.8) \times 10^{-7}$/collision [$(0.40 \pm 0.10)\mu$b/sr] and of $(1.5 \pm 0.5) \times 10^{-7}$/collision [$(0.23 \pm 0.06)\mu$b/sr], respectively. The FWHM of the lines was (35 ± 11) keV and (13 ± 4) keV, respectively. Both lines appeared in coincidence with heavy ions scattered into a rather broad angular range ($15^\circ \leq \theta_{ion} \leq 50^\circ$) [3].

The recent systematic investigations allowed to study the response and sensitivity of our experimental setup to e^+–spectra from IPC processes. Additionally, extensive Monte Carlo simulations, which take into account the progress made in the theoretical treatment of IPC in very heavy nuclei during the last few years [16], were performed to support our understanding of the IPC process. In these simulations we consider the complete kinematics of the collision system ^{238}U + ^{181}Ta at a beam energy of 6.3×A MeV, as also studied in our experiments. Lepton pairs from an IPC transition are generated in the rest frame of the emitting ion with energy distributions taken from theoretical calculations. The energies of the leptons are transformed into the laboratory system and the simulated events are then analyzed with the same analysis program used to analyze the experimental data. The experimental acceptance of the setup is also considered in the simulation program. In a second step, the laboratory energies of the leptons are corrected event by event by taking into account the angular resolution of our setup by a Monte Carlo procedure.

The experiments were performed at the UNILAC accelerator of GSI, using an improved experimental setup at the double-Orange spectrometer. The experimental setup, the methods used as well as the Doppler-shift technique exploited have been described in details in our previous publications (see e.g. in [10, 12, 13]). In particular, the recent investigations of the collision system ^{238}U + ^{181}Ta were first presented and discussed extensively in [12], with emphasis on the appearance of weak e^+e^-–sum-energy lines due to IPC processes. Here we report the results from a complementary analysis of this collision system with the objective to search for corresponding line structures in the measured e^+–spectra.

2 Experimental and simulation results

The collision system ^{238}U + ^{181}Ta was investigated using beams of ^{238}U with an energy of 6.3×A MeV and 1000 μg/cm^2 thick ^{181}Ta targets. The γ-ray spectrum, measured with a Ge(i) detector at 90° to the beam direction and obtained after an event-by-event Doppler-shift correction to the Ta–like recoiling ions, is shown in Fig. 1a for R_{min} values between 21.4 and 24 fm. As can be seen, several electromagnetic transitions are excited with energies between 1300 keV and 1600 keV. Their total excitation cross sections have values between a few mb and some 10 mb. These γ–transitions are obviously hitherto unknown in the ^{181}Ta–nucleus [17], but they were also measured by the EPOS [14] and APEX [15] collaborations as well as by Ditzel et. al. [18]. The excitation probability, $P_\gamma(R_{min})$, was determined as a function of the distance of closest approach, R_{min}, by normalizing the γ–yield in certain R_{min} intervals with the corresponding number of elastically scattered ions. R_{min} was derived from the measured scattering angle $\theta_{ion,CM}$ assuming Rutherford trajectories.

Figure 1b shows the excitation probability $P_\gamma(R_{min})$ as a function of R_{min} for the strongest γ–transition at E_γ = (1380 ±2) keV, which is representative for all γ–lines observed between 1300 keV and 1600 keV. The dependence of the excitation probability on R_{min} is nearly constant in the R_{min} range between 20 and 25 fm. Hence it is significantly different from the corresponding behaviour of the well known low-energy γ–transitions in ^{181}Ta due to Coulomb excitation, as demonstrated by Fig. 1c for the case of the 718 keV E2 transition. This indicates a different excitation mechanism of the high-energy γ–lines.

All transitions shown in Fig. 1a are accompanied by e^+e^-–pair-emission after IPC with total cross sections expected between some 0.1 μb and several μb, assuming transitions with multipolarities $l > 0$ and IPC coefficients of the order of 10^{-4}. The energy partition between the positron and the electron of an IPC pair is determined by the final state interaction with the Coulomb field of the emitting nucleus. The emission probability for an IPC positron with a definite kinetic energy is described by the energy-differential pair conversion coefficient $d\beta/dE_{e^+}$ which is a function of the nuclear charge number, the energy and the multipolarity of the transition. Figure 2a shows a Monte Carlo simulation of the expected emission probabilities for an IPC positron and the partner electron as a function of the e^+–energy for the strong 1380 keV transition in the Ta–like nucleus which is the best candidate for an observation in our experiments. The results in Fig. 2a are given in the rest frame of the emitting nucleus taking into account the latest theoretical calculations on IPC assuming E1 multipolarity [16]. Due to the final state interaction the positron of an IPC pair is preferentially emitted with the highest available kinetic energy of $E_{e^+} = E_\gamma - 2m_ec^2 = 358$ keV (solid curve), while for the partner electron the energy is complementary and given by $E_{e^-} = E_\gamma - 2m_ec^2 - E_{e^+}$ (dotted curve).

After transformation of the e^+–energies into the laboratory system we obtain the distribution shown in Fig. 2b for $R_{min} = 21.4 - 24$ fm. If we now take into account the acceptance of the Orange e^+–spectrometer at the chosen current settings, the distribution of Fig. 2b is reduced to the broad (FWHM ∼80 keV) line structure at ∼280 keV shown in Fig. 2c. The e^+–spectrum was scanned by ramping the spectrometer current up and down within a preselected current interval in the same manner as it was done in the experiment. The current settings for the present experiment were such chosen that the IPC positrons with energies >∼280 keV were detected with maximum efficiency, whereas those with laboratory energies larger than the maximum possible center-of-mass (CM) e^+–energy of

358 keV cannot be detected. This is due to the fact that positrons are only detected in the backward hemisphere with emission angles between 110° and 140° relative to the beam direction (see e.g. in [12]). The shape of Fig. 2c at energies below 280 keV is affected by the significantly reduced efficiency of the spectrometer in this region and by the low–energy cut–off at 200 keV. It should be underlined here that the present experiment was optimized for the detection of narrow e^+e^-–lines with sum energies around 630 keV, and not for the measurement of single positron spectra.

An event-by-event Doppler shift correction to the events of Fig. 2c leads to the CM distribution shown in Fig. 2d. The correction was performed by taking into account the finite angular resolution of the positron and heavy-ion detectors. Particularly, the positron emission angle was set to a constant value of 125° as also used in the analysis of the real data (for details see Ref [12]). In this case we obtain a line with a FWHM of ∼60 keV, whose maximum is now shifted to an energy of ∼320 keV relative to the uncorrected distribution.

According to these simulation results the IPC positrons from the 1380 keV transition should give rise to a rather narrow peak-like contribution in the measured e^+–spectra with a FWHM of 60 to 80 keV and energies of ∼320 keV and ∼280 keV, for the CM and laboratory e^+–energies, respectively. The CM distribution can be reconstructed by means of an event-by-event Doppler-shift correction [12].

To simulate the total contribution of IPC positrons from the Ta–like ion to the measured e^+–spectra we have still to take into account the remaining γ–transitions observed between 1300 keV and 1600 keV, for which pure E1 multipolarity is assumed. Additionally we consider for the weak γ-transitions around 1500 keV a possible admixture of an E0 contribution to an E2 transition. This possibility was discussed in [12] where a line structure in the e^+e^-–sum-energy spectra, obtained in ^{238}U + ^{181}Ta collisions, was found after Doppler-shift correction to the Ta–like ions. It exhibits the characteristics of close-lying IPC lines originating from the electromagnetic transitions between 1500 and 1550 keV and appears 8 times stronger than expected from the corresponding γ–spectrum by assuming E2 IPC coefficients of the order of 10^{-4}. It should be made clear that this empirical assumption does not influence the final results at all, and has been considered here only for a consistent treatment with our previous results [12].

Including these considerations we obtain from our simulations the IPC e^+–energy distributions shown in Fig. 3. Figure 3a shows the expected e^+–spectrum when an event-by-event Doppler-shift correction to the Ta–like recoils is applied, whereas Fig. 3b shows the corresponding e^+–spectrum in the laboratory system. As can be seen, in the Doppler-shift corrected spectrum (Fig. 3a) the 60 keV broad line-structure at ∼320 keV, resulting from the 1380 keV transition, is still clearly distinguishable. Without Doppler-shift correction both distributions are shifted and smeared out, such that only two low intensity narrow structures near 300 keV and 400 keV are still visible (Fig. 3b).

The measured e^+–energy spectra together with the calculated IPC e^+–energy distributions from the above discussed electromagnetic transitions are presented in Fig. 4. These spectra are shown in coincidence with only one ion (Ta–like), scattered in the R_{min} range 21.4 to 24 fm, but without requiring a coincidence with an electron. The underlying R_{min} range was chosen in order to optimize the signal-to-background ratio for the IPC positrons. The solid line in Fig. 4a shows the measured Doppler-shift corrected e^+–energy distribution while the dotted line represents the expected distribution of the IPC positrons from the observed γ–transitions in the Ta–like nucleus(cf. Fig. 3a) scaled up by a factor of 10.

The expected narrow structure from the 1380 keV transition around 320 keV cannot be observed in the measured spectrum. The IPC production probability from this transition is $(2.1 \pm 0.5) \times 10^{-7}$ per elastically scattered ion for R_{min} = 21.4–24 fm, as calculated from the corresponding measured γ–transition probability and an IPC coefficient of 10^{-4}. Note here that the expected e^+–line energy and its production probability are very close to the values, measured for an e^+–line with an energy of ∼310 keV in the previous experiments [3].

For our latest measurements the statistical detection limit for IPC positrons from the 1380 keV transition is 2.6×10^{-7}/collision. It is extracted from the measured continuous spectra assuming a superimposed IPC e^+–line with 60 keV FWHM and two standard deviations statistical significance. In this case the IPC production probability is lower than the statistical detection limit and thus consistent with the non-observation of the expected IPC line. The production probability of the continuous e^+–distribution itself amounts to $(4.20 \pm 0.03) \times 10^{-6}$ per collision for e^+–energies between 290 and 350 keV.

It originates from unresolved γ–transitions and collision induced atomic positrons [4].

In the Doppler-shift uncorrected spectra (Fig. 4b) the possibility to observe lines from IPC positrons is even worse. The expected IPC e^+–distribution represented by the dotted line in Fig. 4b (also scaled up by a factor of 10) shows only two slight structures around 300 keV and 400 keV which are too weak as to be detected in the measured spectra. They are dominated by the continuous positron distribution.

It is worth mentioning at this point that the γ-ray spectra, obtained after Doppler-shift correction to the Ta–like ion, show another pronounced structure composed of three rather close lying γ–lines at energies of $\sim$ 1240 keV, $\sim$ 1260 keV and $\sim$ 1275 keV (not shown in Fig 1a). The positron production probability expected from these transitions is $\sim 1.5 \times 10^{-7}$/ collision using an IPC coefficient of 0.5×10^{-4}. In the present experiment one could expect from these transitions a $\sim$ 50 keV broad e^+–line structure centered around 235 keV in the laboratory energy spectra, very close to the previously reported e^+–line at $\sim$230 keV [3]. But due to the very low spectrometer efficiency ($\epsilon \sim 2 \times 10^{-3}$) for low positron energies in this experiment the expected signature of a 235 keV line is far below the detection limit.

Figure 5a shows the γ-ray spectrum corrected for Doppler shifts, assuming an emission from the U–like ions, scattered in the R_{min} range 19–29 fm. Only some very weak γ–lines with energies between 1300 keV and 1500 keV can be observed in the above R_{min} range. For instance, one can mark two lines at (1364 $\pm$ 7) keV and (1402 $\pm$ 7) keV with differential cross sections close to 1 mb/sr. The corresponding IPC contribution from these two transitions to the e^+–energy spectrum is very small, i.e. $\sim 6 \times 10^{-9}$/collision for an IPC coefficient of 0.5×10^{-4}. It is obvious that this weak IPC contribution is undetectable in the measured spectra. The latter are shown in Figs. 5b and Fig. 5c, without and after a Doppler-shift correction, respectively. The spectra were obtained in coincidence with only one scattered ion (U–like) for the R_{min} range from 19 to 29 fm. From these spectra a detection limit of 2.4×10^{-7}/collision (2σ) is derived for an IPC line.

3 Summary and Conclusions

We studied positron emission after IPC processes of several high–lying γ–transitions in Ta– and U–like nuclei excited in ^{238}U + ^{181}Ta collisions at a bombarding energy of 6.3×A MeV. Several γ–lines have been observed in the measured γ–spectra, taken after an event-by-event Doppler-shift correction to the Ta–like or U–like ions, with transition energies between 1300 keV and 1600 keV. These transitions can de-excite via the IPC branch with IPC coefficients of the order of 10^{-4}.

The goal of our investigations was to gain information about the shape and intensity of the IPC positron distributions, originating from the above discussed γ–transitions, which can be expected in the measured Doppler–shift corrected and uncorrected positron energy spectra. To accomplish it, extensive Monte Carlo simulations were in addition carried out, particularly for the strongest γ–transition at 1380 keV in the Ta–like nucleus. They revealed that, due to the angular and momentum acceptance of the Orange e^+–spectrometer as used in this experiment, IPC from these transitions can lead to rather narrow peak-like contributions to the e^+–energy spectra. The line-structures are expected at e^+–energies between 280 and 350 keV and have widths of ∼60 keV up to ∼80 keV (FWHM), in the Doppler-shift corrected and uncorrected energy spectra, respectively. Only some γ–transitions in the Ta–like nuclei appear with sufficient strength to give rise to IPC positron lines with production probabilities close to the detection limit. While in the U–like nucleus no transition was found which could give rise to any detectable positron line.

The observations discussed above are of particular interest with respect to the appearance of weak positron lines in our previous experiments. More specifically, in the collision system ^{238}U + ^{181}Ta , measured at a somewhat lower bombarding energy of 5.9×A MeV, two lines at ∼230 keV and ∼310 keV with production probabilities of $\sim 3.2\times10^{-7}$/collision and $\sim 1.5\times10^{-7}$/collision, respectively, were reported from the Doppler-shift uncorrected spectra [3]. From the present findings, an IPC origin of these e^+–lines cannot be excluded. Indeed, as shown above, the measured γ-transitions in the Ta-like nucleus would lead to IPC e^+–lines with production probabilities ($\sim 10^{-7}$/coll.) and energies (∼230 keV and ∼320 keV) which are consistent with Monte Carlo Simulation results based on these

IPC transitions. This does not apply, however, to the very first e^+–lines found in the collision system U+U with rather high production probabilities ($\sim 10^{-5}$/coll.) [2] which are not consistent with the intensities expected from the γ-transitions measured in this experiment.

It should be noted again that a direct comparison between the previous and the present experiment is problematic due to the following facts: First in the present experiment, the spectrometer current settings were different and optimized for an electron-positron coincidence experiment. As mentioned above, in this case energies below 200 keV were completely suppressed and the detection efficiency for positrons with energies between 200 keV and 300 keV was reduced considerably in comparison to the former experiments. Second no high-resolution γ-ray spectra were available in the old experiments to reveal weak discrete IPC transitions, having probably underestimated their role at that time.

Our recent investigations of e^+–emission with the Orange setup, equipped with a high-resolution γ-ray detector, revealed that discrete nuclear transitions, populated via Coulomb excitation or in nuclear transfer reactions, can indeed appear in the outgoing moving nuclei with energies above 1 MeV. IPC processes from these transitions can lead to rather weak and narrow line-like structures in the measured positron energy spectra. Due to the dominating continuous e^+-spectral distributions appearing in heavy-ion collisions, the detection of these IPC e^+–lines is rather difficult and depends strongly on the special features of the setup used as well as on the experimental sensitivity and techniques exploited.

Although the IPC scenario studied in the present experiment provides evidence for a rather simple explanation for some of our previously reported weak e^+–lines, it is clear that a definite proof of this scenario as an overall explanation of all the previously reported e^+- and e^+e^--lines would require new dedicated experiments, which to our knowledge are not planned neither at GSI nor elsewhere.

Acknowledgement: *We would like to thank all the people of the UNILAC accelerator operating crew for their efforts in delivering stable ^{238}U beams with high intensities.*

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Figure Captions

Fig. 1. a) Doppler-shift corrected γ–ray spectrum observed in the collision system ^{238}U + ^{181}Ta at a beam energy of 6.3×A MeV. Ta–like recoiling ions for rather peripheral collisions (R_{min} = 21.4 – 24 fm) are assumed to be the emitter. Several lines appear at energies below 1600 keV (see also Fig.8 of Ref. [12]).

b) Excitation probability of the strongest γ–line at ∼1380 keV as a function of R_{min}. These data were first presented in Ref. [12].

c) Excitation probability for a well known E2 γ–transition at 718 keV in a lower-lying rotational band in ^{181}Ta (not shown in 1a) as a function of R_{min}.

Fig. 2. Monte Carlo simulation results for energy distributions expected for e^+ and e^- emission after IPC in a nucleus with a charge number of Z=73 and an electromagnetic transition with an energy of E_γ = 1380 keV and E1 multipolarity.

a) Original e^+ (*solid line*) and e^- (*dotted line*) energy distributions expected in the rest frame of the emitting nucleus at the emission time. The sum of their kinetic energies has always a constant value which is given by the energy of the γ–transition.

b) The original e^+–energy distribution after transformation into the laboratory system to account for the Doppler shift due to the motion of the emitting ion.

c) The corresponding e^+–energy distribution in the laboratory system by taking into account the chosen momentum acceptance of the spectrometer.

d) The same events as in 2c, but after an event-by-event Doppler-shift correction has been applied utilizing the angular resolution of the setup.

Fig. 3. Monte Carlo simulation of the e^+–energy distribution expected from several IPC transitions in Ta (Z=73) with energies between 1250 keV and 1600 keV, as suggested by the γ-ray spectrum shown in Fig. 1a. All the γ–transitions are assumed to be of pure E1 multipolarity, with the exception of the small contribution of those appearing between 1500 keV and 1600 keV for which an admixture of E2 and E0 with a mixing ratio of 1:8 [12] is taken into account.

a)The e^+–energies are corrected for Doppler shifts, assuming an emission from the Ta–like ions.

b) The corresponding e^+–energy distribution expected in the laboratory system is shown.

Fig. 4. a) Measured e^+–energy spectrum from ^{238}U + ^{181}Ta collisions at a beam energy of 6.3×A MeV. The *dotted-line histogram* indicates the e^+–contribution, multiplied by 10, which can be expected from IPC of excited states in the Ta–like nucleus (cf. Fig. 3a). Both spectra are corrected for Doppler shifts, assuming an emission from the Ta–like recoils scattered in the R_{min} range between 21.4 and 24 fm.

b) The corresponding spectra obtained in the laboratory system are shown.

Fig. 5. a) Measured γ-ray spectrum, corrected for Doppler shifts, assuming an emission from the U–like ions scattered in the R_{min} range from 19 to 29 fm.

b) Measured e^+–energy spectrum in the laboratory system for the above R_{min} range.

c) The same as in Fig. 5b, but after Doppler-shift correction to the U–like scattered ions.

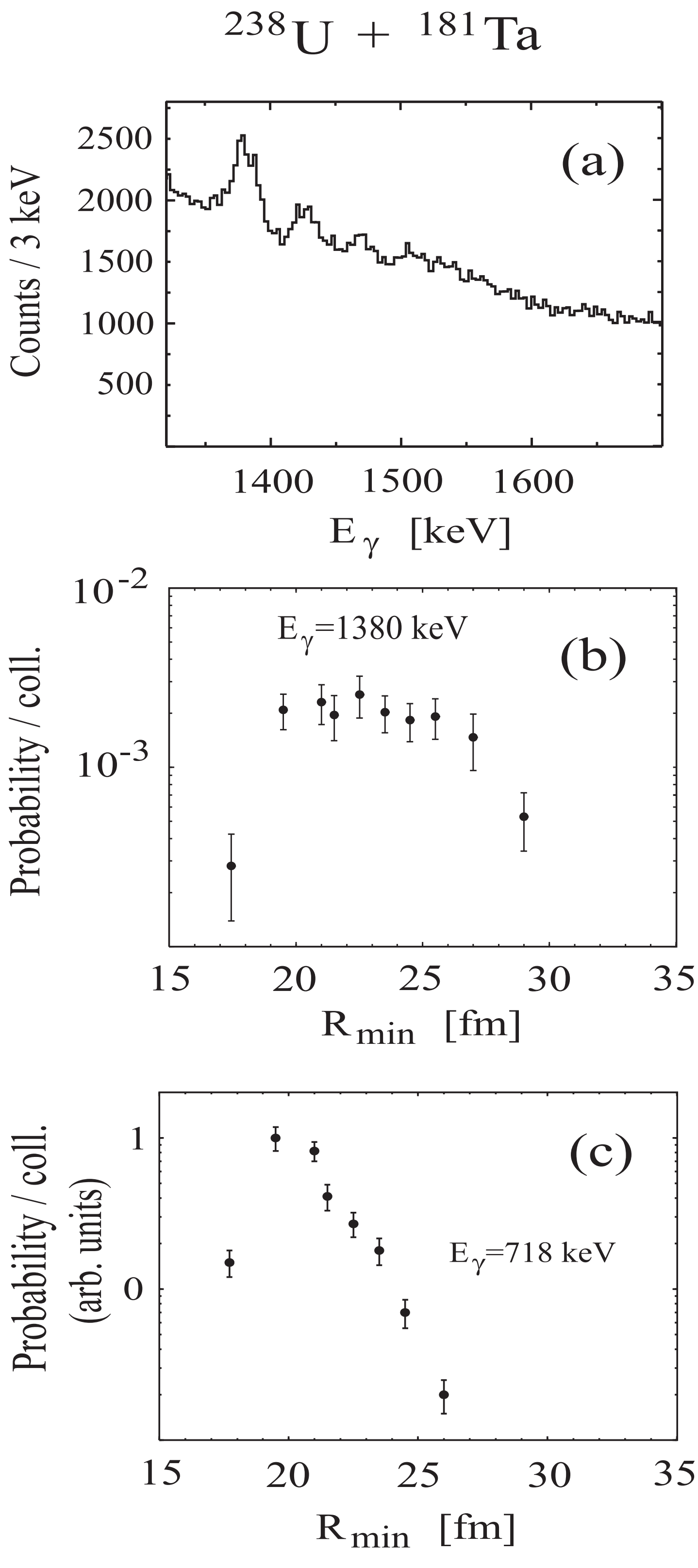

Figure 1

(S. Heinz *et al.*, EPJ A)

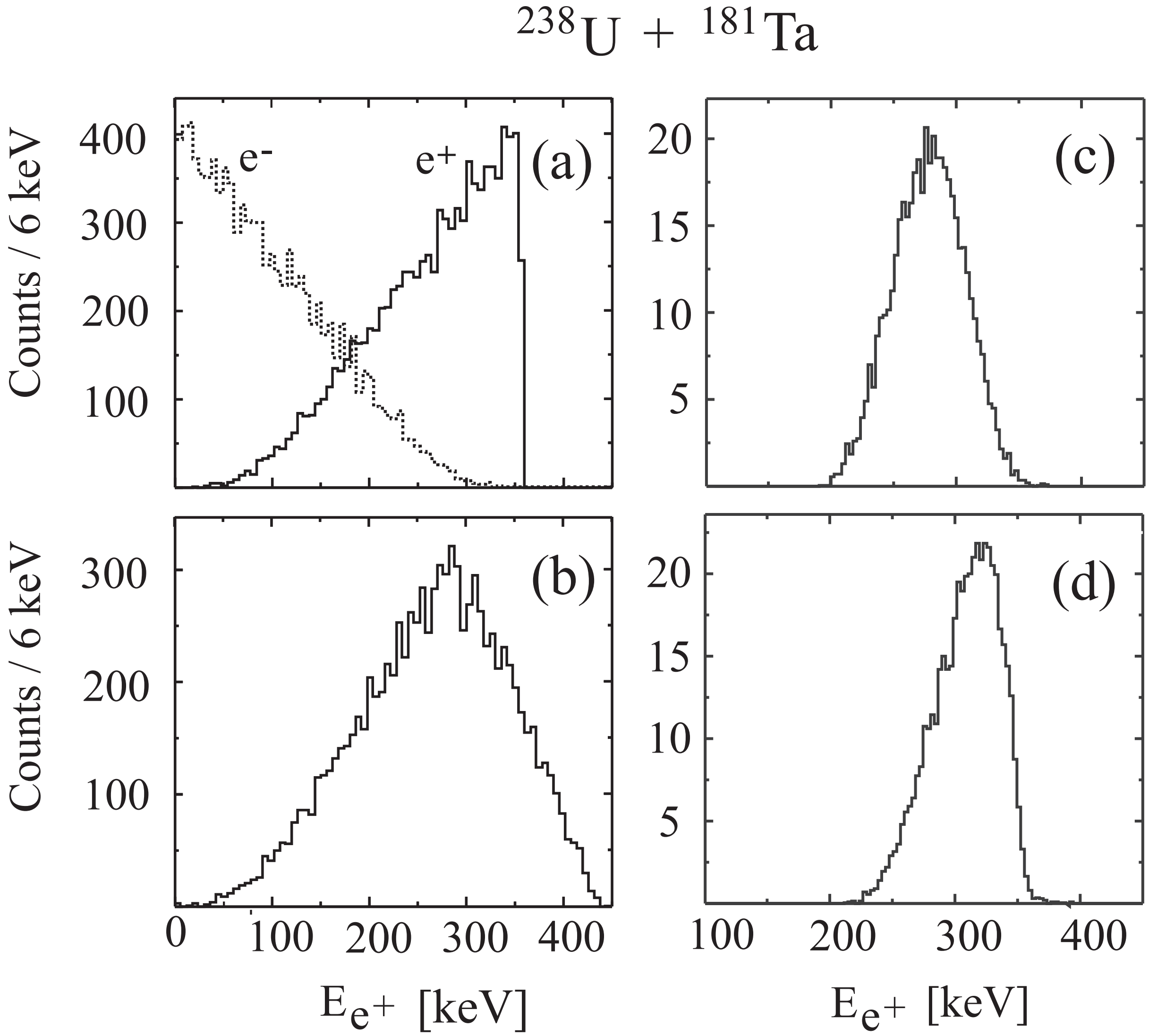

Figure 2

(S. Heinz *et al.*, EPJ A)

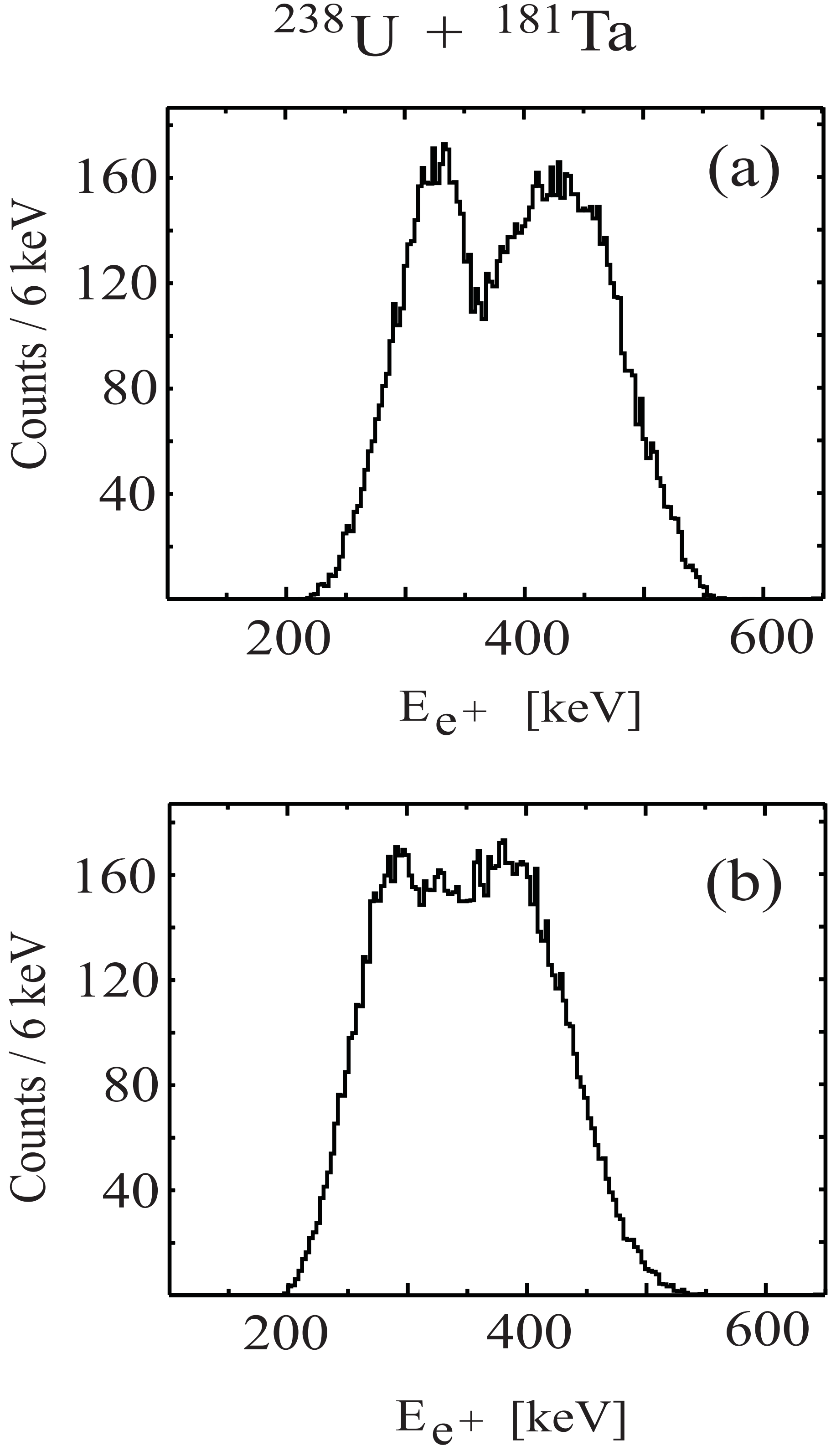

Figure 3

(S. Heinz *et al.*, EPJ A)

$^{238}U + ^{181}Ta$

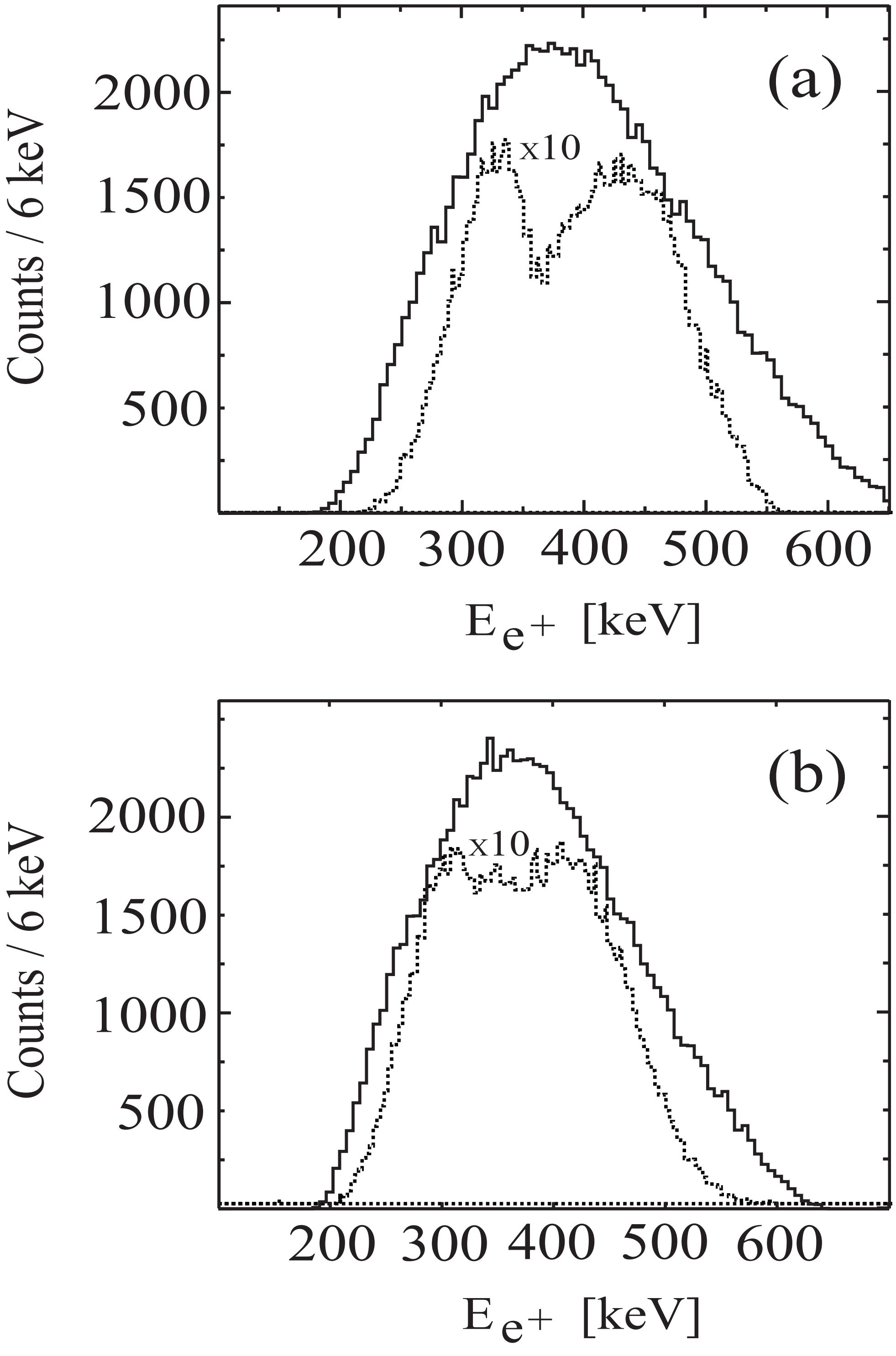

Figure 4

(S. Heinz *et al.*, EPJ A)

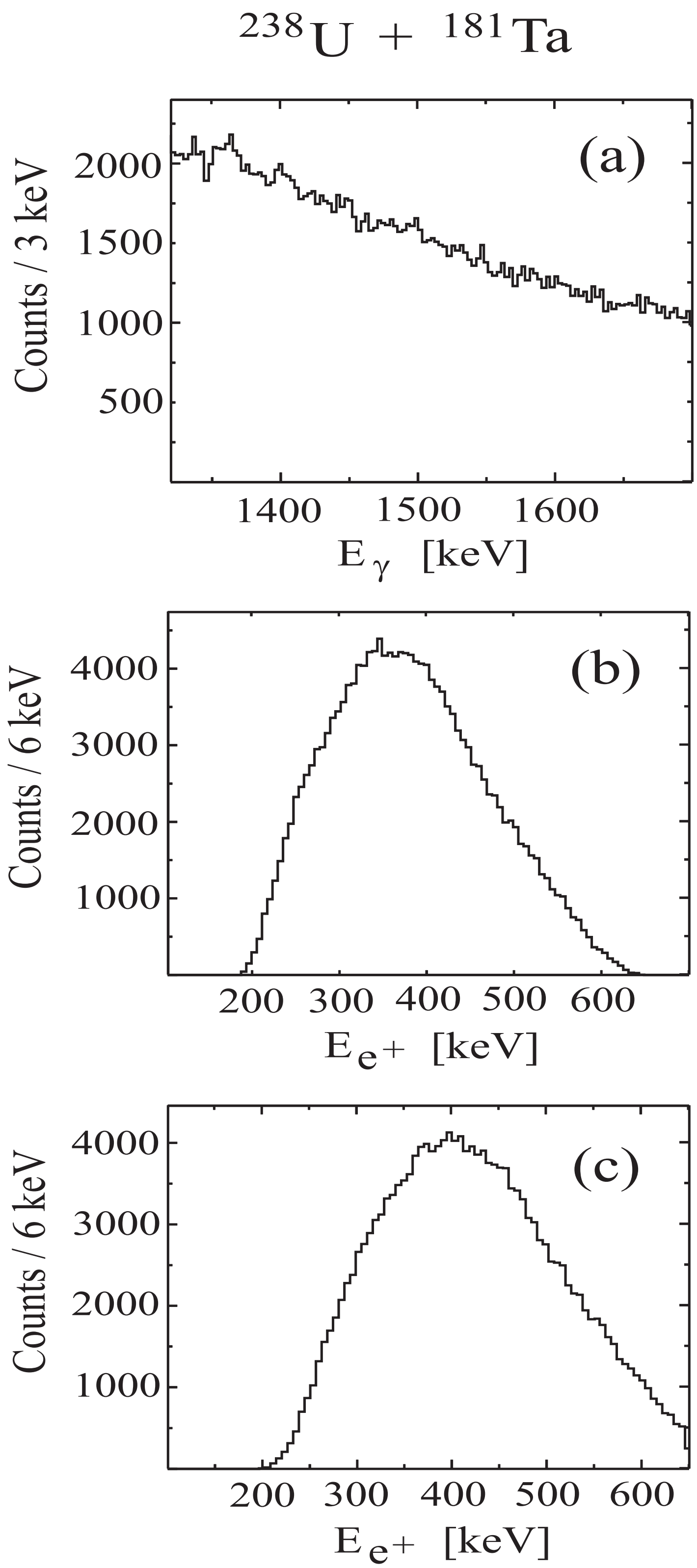

Figure 5

(S. Heinz *et al.*, EPJ A)