arXiv:nucl-ex/9706009v2 23 Oct 1997

Weak e^+e^- lines from internal pair conversion observed in collisions of ^{238}U with heavy nuclei

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Abstract

We present the results of a Doppler-shift correction to the measured e^+e^-–sum-energy spectra obtained from e^+e^-–coincidence measurements in ^{238}U + ^{206}Pb and ^{238}U + ^{181}Ta collisions at beam energies close to the Coulomb barrier, using an improved experimental setup at the double-Orange spectrometer of GSI. Internal-Pair-Conversion (IPC) e^+e^- pairs from discrete nuclear transitions of a moving emitter have been observed following Coulomb excitation of the 1.844 MeV (E1) transition in ^{206}Pb and neutron transfer to the 1.770 MeV (M1) transition in ^{207}Pb . In the collision system ^{238}U + ^{181}Ta , IPC transitions were observed from the Ta-like as well as from the U-like nuclei. In all systems the Doppler-shift corrected e^+e^-–sum-energy spectra show weak lines at the energies expected from the corresponding γ–ray spectra with cross sections being consistent with the measured excitation cross sections of the γ lines and the theoretically predicted IPC coefficients. No other than IPC e^+e^-–sum-energy lines were found in the measured spectra. The transfer cross sections show a strong dependence on the distance of closest approach (R_{min}), thus signaling also a strong dependence on the bombarding energy close to the Coulomb barrier.

PACS numbers: 14.60.Cd; 23.20.Ra; 25.70.Bc; 25.70.De; 25.70.Hi; 29.30.Aj

1 Introduction

Previous results of the EPOS and ORANGE collaborations at the UNILAC accelerator of GSI have revealed unexpected lines in the e^+e^-–sum-energy spectra obtained in heavy-ion collisions at bombarding energies near the Coulomb barrier [1, 2]. No viable explanation could be found for these experimental results. At the beginning it was tempting to interpret these lines as being due to the e^+e^- decay of a previously unknown neutral particle with a mass around 1.8 MeV/c^2, a conjecture which was ruled out by subsequent conclusive Bhabha-scattering experiments [3]. After this time it became clear that Internal Pair Conversion (IPC) from excited nuclear transitions, which can in principle lead to narrow lines in the e^+e^-–sum-energy spectra, was not sufficiently investigated and also theoretically less well understood, such that some of the reported weak lines might be due to this process. Only very recently, combined experimental and theoretical efforts have provided a better understanding of this fundamental decay channel of excited nuclear transitions in heavy nuclei at rest [4], and the method of how to observe weak lines from a moving emitter was developed systematically.

The motivation of the present work was indeed a search for discrete IPC transitions, excited in heavy-ion collisions at energies close to the Coulomb barrier, as possible candidates for previously observed weak e^+e^--sum-energy lines with cross sections of the order of a few μb for the ^{238}U + ^{181}Ta system and some tenth of μb for ^{238}U + ^{208}Pb collisions [2]. Particularly for the last system, two e^+e^-–sum-energy lines at (575 ± 6) keV and at (787 ± 8) keV have been observed at a beam energy of 5.9 MeV/u [2]. The 787 keV line appeared in both quasielastic central ($R_{min} < 20$ fm) and rather peripheral ($R_{min} =$ 20–26 fm) collisions, whereas the 575 keV line occurred only in coincidence with central collisions. Both lines were seen without a Doppler-shift correction and only in the opening-angle region $\theta_{e^+e^-} = 155° - 177°$, for which Doppler broadening is expected to be small for similar energies of both leptons. The underlying e^+e^-–energy-difference range was -100 keV $\leq \Delta E = E_{e^+} - E_{e^-} \leq +34$ keV, which also reflects the sweeping procedure of the Orange spectrometers. It is centered around $\Delta E = -40$ keV for the above observations.

In order to test the response and sensitivity of our experimental setup to IPC pairs from a moving emitter and to learn the observation methods for weak lines we investigated first a known transition in ^{206}Pb populated via Coulomb excitation, using a ^{238}U beam and a ^{206}Pb target. On the other hand, since the number of combined nuclear charge (Z_u =174) is the same for the collision systems ^{238}U + ^{206}Pb and ^{238}U + ^{208}Pb , the e^+e^- lines seen previously in the latter system [2] should also appear in the present experiment, if their origin is closely connected with the strong electromagnetic fields available in the collision. In addition, the ^{238}U + ^{181}Ta collision system was investigated with the objective to search for IPC sum-energy lines.

Here we report the first results from these improved investigations, being performed at the UNILAC accelerator of GSI. A dedicated Doppler-shift technique is exploited at the double-Orange setup [5, 6, 7], which allows to reveal narrow lines in the corrected e^+e^-–sum-energy and γ-ray spectra from a moving emitter in an environment being dominated by continuous spectral distributions. In addition 180° observation scenarios and data analysis were also exploited for the observation of narrow e^+e^-–lines.

It should be underlined here that the investigations and data analysis of this work are more far reaching with respect to Internal Pair Conversion as possible source of e^+e^-–lines than the experimental results reported most recently by the APEX collaboration [8] at ANL and the EPOS II [9] and ORANGE [10] collaborations at GSI, who have presented e^+e^-–sum-energy spectra without a Doppler-shift correction, and have all failed to observe previously reported narrow lines.

2 Experimental setup

As shown in Fig. 1, leptons emitted from a target placed between two toroidal magnetic field spectrometers with their axis parallel to the beam direction were momentum analyzed by the toroidal magnetic field and detected with two arrays of high-resolution Si detectors. The toroidal ($\frac{1}{r}$)-field is generated by 60 iron-free coils. Electrons with emission angles $\theta_{e^-} = 38° - 70°$ and positrons with $\theta_{e^+} = 110° - 145°$ relative to the beam axis are accepted by the spectrometers. The lepton detectors consist each of 72 Si PIN diodes (chips) of trapezoidal shape (base: 24 mm, top: 16 mm, height: 16 mm, thickness: 1 mm) arranged in a Pagoda-like form [5]. Each chip is subdivided into three segments. A

Pagoda roof consists of six PIN diodes, i.e. 18 segments. One detector array is composed of 12 such roofs. Thus, we get a position sensitive detector with 216 segments read out in a matrix mode. At a given field setting only particles with a certain sign of charge are focused onto the corresponding detector arrays. Thus, a very clean separation of electrons and positrons is achieved.

For further lepton identification the lepton energy and momentum is determined simultaneously. The deposited energy is measured by the PIN diodes, and the lepton momentum is calculated from the deflection and the field setting. Only events for which the energy-momentum relation is fulfilled are accepted, with the result that the remaining e^+ misidentification is small and can be determined reliably. This is demonstrated in Fig. 2 for the case of the positron identification. As can be seen a clear signature for the focussed positrons is achieved. In such a spectrum background processes like scattered electrons and γ rays as well as positrons backscattered from the detectors result in a broad continuous distribution which can be determined quantitatively. In the case of the electron identification due to the higher electron production probabilities the corresponding spectrum is practically background-free (see also Ref. [5]).

The spectrometer accepts lepton pairs with opening angles, $\theta_{e^+e^-}$, from 40° to 180° in the laboratory system. This range can be subdivided into 10 bins of width $\approx \pm 10°$. For reconstruction of the reaction kinematics both scattered heavy ions are detected by 19 Parallel Plate Avalanche Counters (PPACs) which accept ions scattered under polar angles of $\theta_{ion} = 12.5° - 35°$ and $\theta_{ion} = 40° - 70°$ with a resolution of 1.0° and 0.5°, respectively. The azimuthal-angle resolution of all (ion and lepton) detectors is $\Delta\phi = 20°$.
For the detection of γ rays we used a high resolution 70%-Ge(i) detector placed at $\theta_\gamma = 86°$ relative to the beam axis at a distance of 40 cm from the target. An ionization chamber installed at $\theta = 40°$ (not shown in Fig. 1) measures the energy of scattered particles and thus controls the effective target thickness. It is also used for current normalization.

Extensive measurements carried out with radioactive ^{90}Sr and ^{207}Bi sources proved that our setup is capable of detecting IPC pairs and of determining their opening-angle distribution from an emitter at rest [4, 5]. The measured FWHM of these sum-energy lines is ~16 keV, consistent with the sum-energy resolution of the lepton detectors.

3 Doppler-shift correction

In the case that the leptons are emitted from a moving source, i.e. from an outgoing ion which moves with a reduced velocity $\beta_{ion} = (\upsilon_{ion}/c)$, their energy measured in the laboratory is affected by a Doppler shift. The kinetic energy of the leptons in the rest frame of the ion E_{cm} and their corresponding energy E_{lab} in the laboratory system are connected by a Lorentz transformation

$$E_{cm} = \gamma_{ion} \left(E_{tot} - \sqrt{E_{tot}^2 - m_0^2 c^4} \times \beta_{ion} \cos\alpha \right) - m_0 c^2, \tag{1}$$

where $E_{tot} = E_{lab} + m_0 c^2$, and α being the relative angle between the lepton and the emitting ion which depends on their polar and azimuthal angles as follows [1].

$$\cos\alpha = \sin\theta_{lepton} \sin\theta_{ion} \cos(\phi_{ion} - \phi_{lepton}) + \cos\theta_{lepton} \cos\theta_{ion}. \tag{2}$$

The reduced velocities of the outgoing ions after the collision are given below:

$$\beta_{ion}^{p} = \frac{\sqrt{A_p^2 + A_t^2 + 2A_p A_t \cos\theta_{cm}}}{(A_p + A_t)} \beta_p \tag{3}$$

$$\beta_{ion}^{t} = \frac{2A_p \sin(\theta_{cm}/2)}{(A_p + A_t)} \beta_p, \tag{4}$$

where A_p and A_t are the mass numbers of the projectile and target ion, respectively, θ_{cm} is the heavy-ion scattering angle in the c.m. system, and $\beta_p = \sqrt{2(E_p/A_p)/931.5}$ is the reduced velocity of the incident ion, with (E_p/A_p) being the bombarding energy per nucleon in units [MeV/u].

From the above relations it is obvious that the correction of the energy (Doppler shift) (Eq. (1)) and its uncertainty (Doppler broadening) depends mainly on the experimental polar and azimuthal angular determination and resolution of the detected leptons and heavy ions. In our setup, the dominant contribution to the Doppler broadening is due to the lepton polar angles which cannot be determined within the angular range accepted by the spectrometers, and only weighted mean values of $\overline{\theta}_{lepton}$ =55° and $\overline{\theta}_{lepton}$ =125° are used, for the forward and backward spectrometer, respectively.

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[1] The angles refer to the laboratory system, unless explicitly stated otherwise

The response and sensitivity of our setup to reveal narrow lines emitted from a moving ion after applying an event-by-event Doppler-shift correction to the measured energies has been carefully investigated by Monte Carlo simulations. In such calculations lepton pairs from an IPC transition are generated in the rest frame of the emitting ion with energy distributions taken from theoretical calculations [11] and assuming an isotropic e^+e^-–opening-angle distribution. The energies of the leptons are transformed into the laboratory system using the inverse transformation of Eq. (1). The simulated events are then analyzed with the same analysis program used to analyze the experimental data. In a second step, the laboratory energies of the leptons are corrected event by event using Eq. (1) and taking into account the angular resolution of our setup by a Monte Carlo procedure.

An illustrative example of such calculations is shown in Fig. 3 for the 822 keV IPC (E1) transition in ^{206}Pb, populated by Coulomb excitation in ^{238}U + ^{206}Pb collisions at a beam energy of 5.93 MeV/u. The solid broad distribution shows the e^+e^-–sum-energy spectrum expected in the laboratory system if an emitter velocity of $v_{ion} \approx 0.04c - 0.08c$ is considered, as it is the case for peripheral collisions with $\theta_{ion,cm} = 50^\circ - 70^\circ$. It is centered around 815 keV and has a FWHM of about 90 keV. The dashed narrow peak represents the same events after an event-by-event Doppler-shift correction is applied to the laboratory energies. The peak is centered at the expected position (∼822 keV) and has a FWHM of ∼16 keV. The latter is mainly due to the uncertainty of the lepton polar angles, discussed above. For central collisions, a velocity of $v_{ion} \approx 0.1c$ for the recoiling ion is expected which leads to sum-energy distributions with widths of about 100 keV in the laboratory system and of nearly 40 keV after Doppler-shift correction.

It should be pointed out here that the detection of IPC e^+e^-–sum-energy lines in the real experiment is rather difficult because they are produced with weak intensities, superimposed on a continuous spectral distribution (see below) mainly caused by pair creation in the time-changing high Coulomb field of the high-Z collision partners (dynamic e^+e^- creation). It is particularly difficult to detect IPC lines from projectile-like nuclei in grazing collisions, because the Doppler shifts and their resulting corrections are rather large. In such cases the sensitivity can be improved by restricting the analysis to events with e^+e^-–opening angles of about 180° or by eliminating the most peripheral scattering events with $R_{min} \geq 25$ fm.

4 Experiment and results

4.1 The collision system ^{238}U + ^{206}Pb

Data were taken for the collision system ^{238}U + ^{206}Pb using ^{238}U beams and 800 μg/cm^2 thick ^{206}Pb targets mounted on a rotating target wheel. The projectile energy (5.93 MeV/u) is slightly below the Coulomb barrier (6.06 MeV/u). The 3^--level at 2.65 MeV in ^{206}Pb is populated via Coulomb excitation and deexcites for the most part into the lower lying 2^+-level with a γ-transition energy of 1844 keV [12]. Following an event-by-event Doppler-shift correction to the Pb-like recoiling ion, a pronounced γ line with a total excitation cross section of σ_γ =(55 ± 5) mb appears at (1844 ± 1) keV in the measured energy spectrum (Fig. 4a). Its FWHM is 22 keV, mainly caused by uncertainties in the Doppler-shift correction introduced by the finite angular resolution of the heavy-ion detectors.

The excitation probability, $P_\gamma(R_{min})$, was determined as a function of 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 determined from the measured scattering angle $\theta_{ion,cm}$ assuming Rutherford trajectories. At large R_{min} values, P_γ shows an exponential decrease, whereas at small R_{min} values P_γ is cut off abruptly at $R_{min} \sim 17$ fm, where the nuclei come into contact. Such a behaviour is typical for Coulomb excitation (Fig. 4b). The results are in accordance with measurements of the EPOS collaboration who investigated the same collision system at a bombarding energy of 5.82 MeV/u and ∼400 μg/cm^2 thick targets. They reported recently a measured cross section of σ_γ = (44 ± 7) mb [13].

From the 1844 keV transition we expect IPC pairs with a sum energy of 822 keV. Multiplying the measured γ cross section with the theoretically predicted IPC coefficient of $\beta = 4.0 \times 10^{-4}$, for an electromagnetic transition with multipolarity E1, Z=82 and 1850 keV energy [14], we expect a total cross section for IPC of σ_{IPC} =(22 ± 2) μb. In order to optimize the peak-to-continuum ratio in the e^+e^--sum-energy spectra, we eliminated large positive energy differences $\Delta E = E_{e^+} - E_{e^-} > 175$ keV, and accepted only rather peripheral collisions with $R_{min} \geq 23$ fm. Thus, we could reduce the contribution of the continuum pairs produced by the large time-changing Coulomb field and combinatorial background from coincidences of δ electrons emitted in the same collision with positrons. Particularly, negative energy differences ($E_{e^+} - E_{e^-}$) select the combination of low e^+ energies and high e^- energies, thus reducing significantly the contribution of the exponentially increasing δ-electron rate at low energies. The event-by-event Doppler-shift corrected e^+e^-–sum-energy spectrum obtained under these conditions is shown in Fig. 4c. The spectrum is integrated over the whole range of lepton opening angles covered experimentally. As shown, the continuous part of the measured spectrum is well reproduced by a reference distribution (smooth solid curve), being gained by an event-mixing procedure.

From the IPC cross section quoted above, a total of about 35 IPC pairs is then expected in the spectrum shown in Fig. 4c, using an IPC detection efficiency of $\epsilon_{IPC} = (1.6 \pm 0.2) \times 10^{-3}$. They should result in a line at an energy of $\sim$820 keV with a FWHM of $\sim$ 20 keV, superimposed on the e^+e^- continuum. The IPC detection efficiency has been obtained by a Monte Carlo simulation, which assumes isotropically emitted e^+e^- pairs and theoretically-calculated lepton energy distributions for $Z = 82$ and E1 multipolarity [11]. It should be noted here that in this case the assumption of isotropically emitted e^+e^- pairs is a good approximation, as shown by the analysis of the measured IPC line. The sweep for these measurements was performed such that lepton pairs with rather positive energy differences $E_{e^+} - E_{e^-} \approx 200$ keV were detected with a maximum efficiency. The total IPC pair detection efficiency was $(2.9 \pm 0.4) \times 10^{-3}$ for this sweep mode. The elimination of pairs with energy differences $\Delta E > 175$ keV leads to the reduced detection efficiency quoted above. Note also here that previous measurements were differently performed, such that pairs with $E_{e^+} - E_{e^-} \approx -40$ keV were detected with the maximum efficiency, resulting in a total detection efficiency of 3×10^{-3} and a better signal to continuum ratio for the detection of IPC lines. The width of the Doppler-shift corrected line depends on the emitter velocity and on the angular resolution of the detectors. As pointed out in sect. 3, for the case of a rather slow emitter (i.e., $v_{ion} \approx 0.05c$), as obtained from peripheral collisions and looking at the target-like excited nucleus, we expect line widths near the limit given by the detector sum-energy resolution, i.e., FWHM $\sim$ 16 keV [5]. Figure 4c shows an excess, relative to the continuous distribution determined by event mixing, of (40 $\pm$ 12) counts in the energy window 805 keV to 825 keV and (57 $\pm$ 14) counts in the energy window between 805 keV and 835 keV. This corresponds to differential cross sections of $(\mathrm{d}\sigma/\mathrm{d}\Omega_{cm}) = (3.1 \pm 1.0)\ \mu\mathrm{b/sr}$ and $(\mathrm{d}\sigma/\mathrm{d}\Omega_{cm}) = (4.4 \pm 1.1)\ \mu\mathrm{b/sr}$, respectively, for $\theta_{ion,cm} = 40^\circ - 70^\circ$ ($\mathrm{R}_{min} = 23 - 32$ fm).

Figure 5a shows the uncorrected spectrum for the whole opening angle range of observation ($\theta_{\mathrm{e}^+\mathrm{e}^-} = 40^\circ - 180^\circ$). The spectrum was obtained under identical conditions to that shown in Fig. 4c. Without a Doppler-shift correction, no line is apparent at an energy around 820 keV and only a slight surplus can be recognized. According to a Monte Carlo simulation, we expect the IPC events from this transition in a broad distribution of FWHM $\approx$ 80 keV for $\mathrm{R}_{min} = 23 - 32$ fm, thus leading to a undetectable signal above the continuum.

As an important result with respect to previous observations we note that the weak 820 keV line is also present in the uncorrected $\mathrm{e}^+\mathrm{e}^-$–sum-energy spectrum, shown in Fig. 5b, when the $\mathrm{e}^+\mathrm{e}^-$–opening angles are restricted to the range $140^\circ \leq \theta_{\mathrm{e}^+\mathrm{e}^-} \leq 180^\circ$. For this particular case of $\theta_{\mathrm{e}^+\mathrm{e}^-}$ selection, the leptons are emitted nearly back to back with the result that their Doppler shifts cancel for leptons with similar energies. What we find in Fig. 5b, which was gained under the same kinematical conditions than Fig. 4c, is a surplus of (14 $\pm$ 7) events in the energy window 805 keV to 825 keV and (23 $\pm$ 8) events in the energy window between 805 keV and 835 keV. This corresponds to differential cross sections of $(\mathrm{d}\sigma/\mathrm{d}\Omega_{cm}) = (1.1 \pm 0.6)\ \mu\mathrm{b/sr}$ and $(1.8 \pm 0.6)\ \mu\mathrm{b/sr}$, respectively, for $\theta_{ion,cm} = 40^\circ - 70^\circ$ ($\mathrm{R}_{min} = 23 - 32$ fm). The Monte Carlo simulation of the expected line shape for the back-to-back scenario following the E1 transition is presented in Fig. 5c. The kinematical conditions are identical to those of Fig. 4c (i.e., $\mathrm{R}_{min} = 23 - 32$ fm, and $\Delta\mathrm{E} \leq 175$ keV). According to the simulations, we would expect in this spectrum about 12 IPC events at a position of about 820 keV.

We found an additional line in the γ spectra, when corrected on the Pb-like scattered ion, at an energy of (1770 $\pm$ 1) keV. This line appears only in central collisions with $\mathrm{R}_{min} <$ 20 fm (Fig. 6a). In the R_{min} parameter range selected (17 fm $< \mathrm{R}_{min} <$ 20 fm), the γ lines at 1770 keV and at 1844 keV have comparable intensities. The excitation probability for the 1770 keV line as a function of R_{min}, is shown in Fig. 6b. It peaks within a narrow R_{min} interval, typical for transfer reactions, for which the transfer probability is expected to become large when the nuclei come into contact. This also means that the excitation function should exhibit a rather narrow structure at energies close to the Coulomb barrier with a width of about 0.3 MeV/u. Similar narrow structures in the R_{min} dependence were observed for a two-neutron transfer reaction, leading to the known 3.71 MeV 5^- level in ^{208}Pb [12].

The line at 1770 keV is assigned to a known M1 transition in ^{207}Pb from the $\frac{7^-}{2}$ (2.34 MeV) to $\frac{5^-}{2}$ (0.57 MeV) state [12], populated by neutron transfer from ^{238}U to ^{206}Pb, with a total cross section of σ_γ =(1.1 ± 0.3) mb. The corresponding IPC production cross section is expected to be σ_{IPC} =(0.3 ± 0.1) μb with $\beta = 2.8 \times 10^{-4}$ [14], which should lead to a weak e^+e^--sum-energy line at ~750 keV with a FWHM of ~ 40 keV, and an intensity of about 10 counts. In the corresponding Doppler-shift corrected e^+e^-–sum-energy spectrum, shown in Fig. 6c, no surplus can be found in the energy window between 728 keV and 768 keV and one cannot distinguish the appearance of the line from the expected statistical fluctuations, which are of the same order. This leads to a cross section limit of < 0.9 μb/sr. The situation is similar for the line at ~820 keV, which is expected to have a comparable intensity.

Note that the 1770 keV γ line was not observed by the EPOS collaboration, who investigated the same collision system at a beam energy of 5.82 MeV/u and a ~ 400 μg/cm^2 thick ^{206}Pb target [13] compared with a beam energy of 5.93 MeV/u and a 800 μg/cm^2 thick ^{206}Pb target in our experiment. This may also be taken as an indication for a strong beam energy dependence of transfer reactions at the Coulomb barrier of heavy collision systems.

Figure 7a shows a γ-ray spectrum from the collision system ^{238}U + ^{206}Pb after applying an event-by-event Doppler-shift correction to the U-like heavy ion scattered in the R_{min} range 19.5–23 fm. The spectrum reveals a line at (1778 ± 2) keV with a total excitation cross section of σ_γ = (6 ± 1) mb. The measured excitation probability $P_\gamma(R_{min})$, shown in Fig. 7b, clearly points to a Coulomb-excited transition in ^{238}U. The line was also observed by the EPOS [13, 15] and APEX [16] collaborations as well as by Ditzel et al. [17]. Recently an experiment was carried out by Zilges et al. [18] to search for strong dipole excitations around 1.8 MeV in ^{238}U. In this experiment the existence of the 1780 keV transition in ^{238}U is confirmed and classified as electric dipole (E1) transition. For estimating the number of IPC pairs to expect from the 1778 keV γ line we assumed an E1 transition for which the largest IPC coefficient is expected. Calculating with an IPC coefficient of $\beta = 3.3 \times 10^{-4}$, an upper limit for the total cross section for IPC pair production of $\sigma_{IPC} \leq 2$ μb is expected.

A main problem arises thereby with respect to the performance of the Doppler-shift technique which is common to all experiments using ^{238}U beams, with the exception of ^{238}U + ^{238}U collisions. In peripheral collisions, in which the continuum background is small, the velocity of the ^{238}U–like ions is rather high, thus leading to IPC-line widths of nearly ∼40 keV in the Doppler-shift corrected e^+e^-–sum-energy spectra. This is mainly due to our limited angular resolution for e^+ and e^- emission angles, discussed in sect. 3. The broadening of the e^+e^- lines worsens the peak-to-continuum ratio in the corrected e^+e^-–sum-energy spectra, thus making IPC lines of small production yield unobservable. Therefore we tried a different approach. Figure 7c shows the e^+e^-–sum–energy spectrum, corrected for Doppler shifts, assuming emission from the U-like ion scattered in the R_{min} range 19.5–23 fm. In this case the emitter velocity is rather low ($\upsilon_{ion} \approx 0.05$ c) and hence the magnitude of the resulting Doppler shift is low, too. The corresponding e^+e^-–energy difference ranges from −200 to 175 keV.

From the spectrum shown in Fig. 7c, a cross section limit of $(d\sigma/d\Omega_{cm}) \leq 0.25\mu$b/sr for $\theta_{ion,cm} = 72^\circ - 100^\circ$ ($R_{min} = 19.5 - 23$ fm) is derived, which has to be compared with a calculated value of $(d\sigma/d\Omega_{cm}) \leq 0.17\mu$b/sr. The latter value has been obtained assuming an E1 transition which leads to an e^+e^-–sum-energy line at ∼758 keV with a width of ∼25 keV. Obviously, our experimental sensitivity has reached the detection limit in this case. In ^{238}U + ^{238}U collisions studied in earlier experiments, the U-like recoil has a low velocity which allows easier detection of IPC transitions, particularly in 180° geometry, without need of Doppler-shift corrections, and only negative energy differences were accepted which increases the signal-to-background ratio for IPC transitions.

4.2 The collision system ^{238}U + ^{181}Ta

With the collision system ^{238}U + ^{181}Ta data were taken using a ^{238}U beam at a bombarding energy of 6.3 MeV/u (slightly above the Coulomb barrier) and 1000 μg/cm^2 thick ^{181}Ta targets. After an event-by-event Doppler-shift correction to the Ta-like recoiling ion, a number of γ lines with cross sections between some mb and some 10 mb and energies below 1600 keV appear in the corrected γ–ray spectrum shown in Fig. 8a. The corresponding transitions are obviously hitherto unknown in the ^{181}Ta nucleus [12], but they were also measured with comparable cross sections by the EPOS [15] and APEX [16] collaborations as well as by Ditzel et. al. [17].

Figure 8b 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 1000 and 1600 keV. The dependence of the excitation probability on R_{min} is different than for known low energy γ lines in ^{181}Ta from Coulomb excitation. One notes particularly the nearly constant behaviour in the R_{min} range between 20 and 25 fm. What is more surprising in this context is the fact that some of the observed γ lines have energies which could be attributed within 1–2 keV to known transitions in ^{184}W [12]. Therefore one can not completely rule out a contribution from (1p2n) transfer reactions from ^{238}U to ^{181}Ta at energies close to the Coulomb barrier, governed by an anomalous deflection function of the scattering process.

All electromagnetic transitions observed are accompanied by e^+e^-–pair production via IPC with expected total cross sections between several 0.1 μb and several μb, assuming IPC coefficients of the order of 10^{-4}. In this case we should be able to observe the corresponding e^+e^-–sum-energy lines after appropriate Doppler-shift correction, as shown in the case of the ^{238}U + ^{206}Pb collision system. However, because the energies of the IPC lines from the strongest γ transitions are expected at e^+e^-–sum energies below 500 keV, their detection efficiency is strongly reduced by our particular choice of the momentum acceptance of both spectrometers. The spectrometer momentum acceptance was optimized for maximum detection efficiency at around 600 keV, dropping off slowly towards higher energies and relatively abruptly to lower energies, in order to search efficiently for lines at e^+e^-–sum energies around 600 keV (see Refs. [2, 10]). As a consequence of this efficiency cutoff at low energies, we can only observe in our experiment the high-energy part of the e^+e^- IPC pairs belonging to the energetically broad γ distribution between 1500 and 1580 keV with a total cross section of σ_γ =(15 ± 3) mb. In fact we can only expect to detect this part of the IPC spectrum centered around 550 keV which should lead to a rather narrow structure in the Doppler-shift corrected e^+e^-–sum-energy spectrum with a width of about 30–35 keV resulting from a Monte Carlo simulation (Fig. 9b). It is produced by several close-lying transitions in the energy range centered around 1550 keV. Assuming an IPC coefficient of 2×10^{-4} for a transition energy of 1550 keV with E1 multipolarity in a nucleus with Z = 73, a total cross section for IPC pair production of σ_{IPC} =(3.0 ± 0.8) μb is expected from the observed γ strength.

Figure 9a shows the e^+e^-–sum-energy spectrum in coincidence with one ion, scattered into the angular range: $40° \leq \theta_{ion,cm} \leq 62°$ (i.e., 22.4 fm $\leq R_{min} \leq$ 30 fm). In contrast to collisions with quasielastic R_{min}-dependance, which are governed by two-body kinematics, the U-Ta collisions, leading to excited nuclear states above 1 MeV, show a more complex R_{min}-dependance accompanied by a loss of events by a factor of 2.5 in the two-body final channel. Therefore we show in Fig. 9a only the e^+e^-–spectra in coincidence with one scattered ion (Ta-like), in order to obtain better statistics. In Fig. 9a the energies are corrected for Doppler shifts, assuming a Ta-like ion as the emitter of the observed pairs. In order to suppress the contribution of the continuum e^+e^-–pairs from the strong time-changing Coulomb field of both collision partners, very positive energy differences between the positrons and electrons were cut out, and we accepted only events which fall in an e^+e^-–energy-difference window between −150 and +100 keV. Furthermore, only rather peripheral collisions with $R_{min} > 22$ fm are accepted. In order to reduce the magnitude of Doppler shifts to be corrected, the acceptance is restricted to low velocity Ta-like recoils. This ensures a narrow IPC line width and thus improves the signal-to-background ratio. In the e^+e^-–sum-energy spectrum shown in Fig. 9a, a line structure with FWHM = 30 keV at an energy of (558 ± 10) keV with a surplus of (64 ± 21) counts in the energy range between 543 keV and 573 keV appears above the continuum, which is constructed by event mixing. As already pointed out above, the line shape is well reproduced by a Monte Carlo simulation shown in Fig. 9b. On the basis of the measured γ–ray spectrum, one would expect at an energy of ∼560 keV a line structure of about 8 counts only, as expected by an IPC detection efficiency of $\epsilon_{IPC} = (0.75 \pm 0.05) \times 10^{-3}$. This value was obtained by a Monte Carlo simulation assuming an isotropic e^+e^- angular distribution and multipolarity E1. The 64 counts observed correspond to a differential cross section of $(d\sigma/d\Omega_{cm}) = (18 \pm 6)$ μb/sr in the scattering angle range $40^\circ \leq \theta_{ion,cm} \leq 62^\circ$, which is a factor of 8 larger than expected from the corresponding γ-ray yield. This discrepancy is surprising and not yet understood. A possible explanation for the high line intensity might be due to an admixture of an E0 to an E2 transition between rotational states of an excited vibrational band to a state with the same spin $I \geq 2$ of the ground state rotational band.

Very interesting to note here is the fact that the line at 558 keV appears also in the uncorrected e^+e^-–sum-energy spectrum shown in Fig. 10, where the e^+e^-–opening-angles are restricted to the range $140^\circ \leq \theta_{e^+e^-} \leq 180^\circ$ and only energy differences ≤ 100 keV are accepted. The corresponding R_{min} range is 22.4 to 30 fm like in Fig. 9a. The line at (558 ± 10) with a FWHM of (20 ± 2) keV has an intensity of (31 ± 11) counts in the energy region between 548 keV and 568 keV above the continuum. The line position and width are in good accordance with our expectations from Monte Carlo simulations, but the intensity of the line is nearly a factor of 2 larger than expected from the experimental results in Fig. 9a which is also not well understood.

From the collision system ^{238}U + ^{181}Ta one should also expect IPC pairs from the Coulomb-excited 1778 keV transition, discussed at the end of the previous chapter. But two criteria make this system less favourable for detecting IPC lines: the total cross section of the excited 1778 keV γ transition is with 2 mb a factor of 3 reduced compared to the cross section obtained from the collision system ^{238}U + ^{206}Pb . Moreover, the e^+e^-–pair-detection efficiency at sum-energies around 760 keV is strongly reduced because of a different choice of the momentum acceptance of our spectrometers as compared to the ^{238}U + ^{206}Pb measurements.

5 Summary and Conclusions

In summary, we reported the observation of γ-transitions which could contribute to observable IPC lines in collisions of ^{238}U with ^{206}Pb and ^{181}Ta nuclei at bombarding energies close to the respective Coulomb barrier. The γ lines were observed after a Doppler-shift correction of the spectra with cross sections of several 10 mb in the case of Coulomb excitation and in the order of 1 mb for transfer reactions. We succeeded also to observe for most of the stronger nuclear transitions weak IPC lines in Doppler-shift corrected e^+e^-–sum energy spectra with the expected cross sections of typical several μb, in accordance with theoretically predicted IPC coefficients in the case that the transition multipolarity was known.

The transitions from Coulomb excitation show an expected dependance on the minimum distance of closest approach (R_{min}), with a sharp drop of the excitation probabilities at smaller R_{min} values, caused by nuclear contact, and an exponential decrease for larger R_{min} values. The nuclear excitation probabilities following transfer reactions at bombarding energies close to the Coulomb barrier show a quite different R_{min} dependance which is sharply peaked around a typical interaction distance. This reflects also a very strong threshold energy dependance at the Coulomb barrier. The R_{min} dependance of high excitations observed in ^{238}U + ^{181}Ta collisions is less well understood. This may reflect a not yet studied behaviour of multi-nucleon transfer reactions at bombarding energies close to the barrier.

Some weak e^+e^-–sum-energy lines, previously observed in ^{238}U + ^{181}Ta and ^{238}U + ^{208}Pb collisions by the Orange collaboration [2], show characteristics of IPC lines observed in our present work. According to the present experience, they may have well been caused by nuclear transitions accompanied by γ transitions observable only in high-resolution Doppler-shift corrected γ-ray spectra, Doppler-shift corrected e^+e^-–sum-energy spectra and 180° sum-energy spectra, like those presented here. Unfortunately, for the previously investigated collision system ^{238}U + ^{208}Pb at a bombarding energy of 5.9 MeV/u, for which we have observed at selected 180° e^+e^- emission angles, e^+e^-–sum-energy lines at 575 keV and 787 keV [2], the corresponding γ–ray spectra were measured with a low energy resolution Na(Tl)I detector [2] and thus the observation of weak γ lines was not possible.

Therefore these lines might have been accounted for by IPC transitions because for a 180° e^+e^- observation geometry in the Orange setup, the Doppler shifts nearly cancel in case of comparable e^+ and e^- energies as has been shown in Fig. 5b. Note also that the 575 keV and 787 keV e^+e^- lines, observed previously in ^{238}U + ^{208}Pb collisions, were not found in our present investigations of the collision system ^{238}U + ^{206}Pb. This clearly means that strong field effects can not be the origin of these lines.

There is still the unresolved problem of $0^+ \rightarrow 0^+$ monopole transitions in e^+e^-–pair spectroscopy. Until now no E0 transition in the interesting energy region could be identified uniquely in ^{238}U induced heavy-ion collisions. Recently a search for $0^+ \rightarrow 0^+$ monopole transitions in ^{238}U + ^{181}Ta collisions at a beam energy of 6.0 MeV/u was conducted at GSI using conversion electron spectroscopy [17]. A limit of 0.3 mb for the production cross section of a K-conversion line in ^{181}Ta at an energy around 1.8 MeV is derived. This cross section limit can be transformed into an upper limit for monopole pair production of $\sigma_{IPC} \leq 10\mu$b, assuming an IPC coefficient of $\eta = 0.03$ for ^{181}Ta and a transition energy of 1.8 MeV. This limit is unfortunately not sensitive enough to exclude E0 transitions from our measured e^+e^-–sum-energy spectra definitely.

The observed e^+e^-–sum-energy line centered at an energy of ~558 keV originates actually from several close-lying transitions in the Ta-like nucleus with energies between 1500 and 1580 keV, as suggested by the γ-ray spectrum shown in Fig. 8a. Assuming that the remaining intensity excess of the observed ~558 keV sum-energy line is due to several close-lying E0 transitions, the corresponding K-conversion lines are expected to be spread out over a width of ~80 keV, centered around 1470 keV with a total cross section of (0.7 ± 0.2) mb. The cross section limit of 0.3 mb for Ta-like nuclei and $E_{e^-} \approx 1.8$ MeV given by Ditzel et al. [17], however, refers to a line width of 20 keV. Even if one assumes that this cross section limit is also valid for $E_{e^-} \approx 1500$ keV, K-conversion lines with a total cross section of ~0.7 mb, spread out over an energy range of about 80 keV, could not be excluded by the measurements of Ditzel et al. [17].

Another open problem remains by considering IPC transitions in ^{238}U, which has been used as a heavy-ion beam in all our previous experiments to study e^+e^- pair creation in heavy collision systems. In ^{238}U + ^{238}U collisions an e^+e^-–sum-energy line has been observed at an energy of ~815 keV [2]. For this observation two selection criteria were applied: the line was observed only at e^+e^- emission angles nearly 180° and was enhanced by selecting negative energy differences. Both criteria resemble conspicuously those applied to the spectrum shown in Fig. 5b, and might therefore indicate IPC transitions in ^{238}U or in U-like nuclei. Unfortunately, this collision system was also investigated with the low resolution Na(Tl)I γ–ray detector, which does not allow to reveal weak γ lines in the measured spectra. On the other hand we have not observed a corresponding 1835 keV line in the γ-ray spectra after Doppler-shift correction to the U-like ions in ^{238}U + ^{206}Pb and ^{238}U + ^{181}Ta collisions studied in this work. Consequently, only a monopole transition in ^{238}U could explain the previous observation in ^{238}U + ^{238}U collisions provided that these lines were due to IPC transitions. The observed 1780 keV γ line could be the γ transition from the excited 0^+ state to the 45 keV 2^+ excited state of ^{238}U adding up to a 0^+ excitation energy of about 1825 keV, which could give rise to a 805 keV 0^+ - 0^+ monopole transition in close resemblance to the previous observation of a e^+e^- line at about 815 keV in ^{238}U + ^{238}U collisions.

Finally it should be emphasized that the conjectured possibility of the appearance of weak e^+e^-–sum-energy lines due to discrete nuclear transitions has been addressed for the first time in the ORANGE experiments (see e.g. Ref. [2]). Extensive Monte Carlo studies have revealed that IPC transitions from a moving heavy nucleus can lead to narrow lines in the measured e^+e^-–sum-energy spectra, even without a Doppler-shift correction, when restricting the e^+e^- opening angles to the region around 180° (see Fig. 7 in Ref. [2]). Our failure to identify such weak IPC transitions in the previous experiments is not yet well understood. It might be due to the limited experimental resolution of the Doppler-shift technique, most noticeably in the determination of the azimuthal angles for the leptons and heavy ions ($\Delta\phi = 60°$ compared to $\Delta\phi = 20°$ in the new measurements), applied at that time to the measured γ-ray and e^+e^-–sum-energy spectra. For instance, in the case of our previous setup with an overall angular resolution of $\Delta\phi = 60°$, the FWHM of the Doppler-shift corrected e^+e^-–lines is increased by about 10 keV.

In conclusion, the main progress of this work is the observation of weak IPC e^+e^- lines together with the accompanying γ transitions. Furthermore we may state that the weak e^+e^- lines, reported in previous experiments by the Orange collaboration [2], could have been caused most likely by weak IPC transitions, selected by the nearly Doppler-shift-free 180° measurements of the Orange setup and the negative e^+e^- energy differences. The only exception seems to be the observation of a strong e^+e^- line at $\sim$630 keV found previously in ^{238}U + ^{181}Ta collisions [2] which, however, could not be reproduced by our improved experiments [10].

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. Schematic view of the ORANGE spectrometers. The setup consists of the following components: two iron–free orange-type magnetic spectrometers, two Si-(PIN)-diode arrays (PAGODAs) for lepton detection, 19 PPACs to count the scattered heavy ions, an intrinsic Ge detector for γ-ray detection and a rotating target wheel (see text for details).

Fig. 2. Experimental signature of the detected positrons. The abscissa shows the normalized difference between the momentum of the focused positrons calculated from the pulse height of the Si detectors and their momentum determined from the magnetic field of the spectrometer. Only events falling in a narrow window centered around zero are accepted in the analysis.

Fig. 3. e^+e^-–sum-energy spectra obtained by a Monte Carlo simulation of the 1844 keV IPC (E1) transition in ^{206}Pb for ^{238}U + ^{206}Pb collisions and peripheral ion kinematic ($\theta_{Pb,cm}$ =50°–70°) in the laboratory (solid distribution) and after an event-by-event Doppler-shift correction to the emitting Pb nucleus (dashed distribution). The broad distribution in the laboratory is centered around 815 keV and has a FWHM of ∼90 keV, whereas the corrected one appears at ∼822 keV with a FWHM of ∼ 16 keV.

Fig. 4. **a)** Measured spectrum of γ rays from ^{238}U + ^{206}Pb collisions after Doppler-shift correction to the Pb-like ions, scattered in the R_{min} range from 23 to 32 fm. The line at (1844 ± 1) keV belongs to the E1 transition 3^- (2.65 MeV) $\rightarrow$ 2^+ (0.80 MeV) in ^{206}Pb.
b) The excitation probability of the 1844 keV γ transition as a function of R_{min}.
c) The Doppler-shift corrected e^+e^-–sum-energy spectrum obtained under the assumption that Pb-like nuclei are the emitters. For R_{min} = 23 –32 fm and e^+e^- energy differences from −200 to 175 keV. The contribution of random coincidences (∼ 15%) is subtracted from the data. The smooth solid line is a reference continuous distribution gained by event

mixing.

Fig. 5. **a)** Uncorrected e^+e^--sum-energy spectrum for the whole opening angle region accepted ($\theta_{e^+e^-} = 40^\circ - 180^\circ$) taken with the collision system ^{238}U + ^{206}Pb . The spectrum was obtained under identical conditions compared to that of Fig. 4c.
b) Uncorrected e^+e^--sum-energy spectrum measured in ^{238}U + ^{206}Pb collisions. The full-line histogram corresponds to the opening-angle bin of 180° ($\theta_{e^+e^-} = 140^\circ - 180^\circ$), while the dashed-line histogram displays the remaining opening-angle range of observation. The latter was adjusted in the height to fit the total intensity of the spectrum obtained for the 180° bin. The R_{min} values range from 23 to 32 fm and $\Delta E \leq 175$ keV.
c) Uncorrected e^+e^--sum-energy distribution for the 820 keV IPC transition in ^{206}Pb obtained by a Monte Carlo simulation for the opening angle range $\theta_{e^+e^-} = 140^\circ - 180^\circ$ and $R_{min} = 23 - 32$ fm.

Fig. 6. **a)** Doppler-shift corrected γ-ray spectrum measured for rather central collisions ($R_{min} \leq 20$ fm). The line at (1770 ± 1) keV corresponds to the M1 transition $\frac{7^-}{2}$ (2.34 MeV) $\rightarrow$ $\frac{5^-}{2}$ (0.57 MeV) in ^{207}Pb, produced by 1n-transfer reaction.
b) Excitation probability as a function of R_{min} of the 1770 keV γ transition.
c) The same as in Fig. 4c, but for R_{min} values between 17 and 20 fm.

Fig. 7. **a)** γ–ray spectrum from the collision system ^{238}U + ^{206}Pb after Doppler-shift correction to the U-like ion, scattered in the R_{min} range 19.5–23 fm. A line appears at an energy of (1778 ± 2) keV.
b) Excitation probability as a function of R_{min} of the γ line at 1778 keV.
c) The Doppler-shift corrected e^+e^-–sum-energy spectrum obtained by assuming that U-like nuclei are the emitters for R_{min} = 19.5–23 fm and e^+e^- energy differences from −200 to 175 keV.

Fig. 8. **a)** Doppler-shift corrected γ–ray spectrum observed in the collision system

^{238}U + ^{181}Ta . Ta-like recoiling ions for rather peripheral collisions (R$_{min}$ = 22.4–30 fm) are assumed to be the emitter. Several lines appear at energies below 1600 keV.
b) Excitation probability as a function of R$_{min}$ of the line at 1380 keV.

Fig. 9. **a)** e^+e^-–sum-energy spectrum obtained after Doppler-shift correction to the Ta-like ion in the R$_{min}$ range 22.4–30 fm and e^+e^- energy differences from −150 to +100 keV. The spectrum was measured in coincidence with only one scattered heavy ion.
b) Doppler-shift corrected e^+e^-–sum-energy spectra obtained by a Monte Carlo simulation of the transition in the Ta-like nucleus centered around 560 keV. The underlying kinematical conditions are identical to that of Fig. 9a. The rather narrow line width of 30–35 keV is caused by the spectrometer momentum acceptance.

Fig. 10. Uncorrected e^+e^-–sum-energy spectrum measured with the collision system ^{238}U + ^{181}Ta . The full-line histogram corresponds to the opening-angle bin of 180°. The dashed-line histogram displays the remaining opening-angle range of observation. The latter was adjusted in the height to fit the total intensity of the spectrum obtained for the 180° bin. The R$_{min}$ values range from 22.4 to 30 fm and the energy differences are restricted to -150 keV $\leq \Delta E \leq +100$ keV.

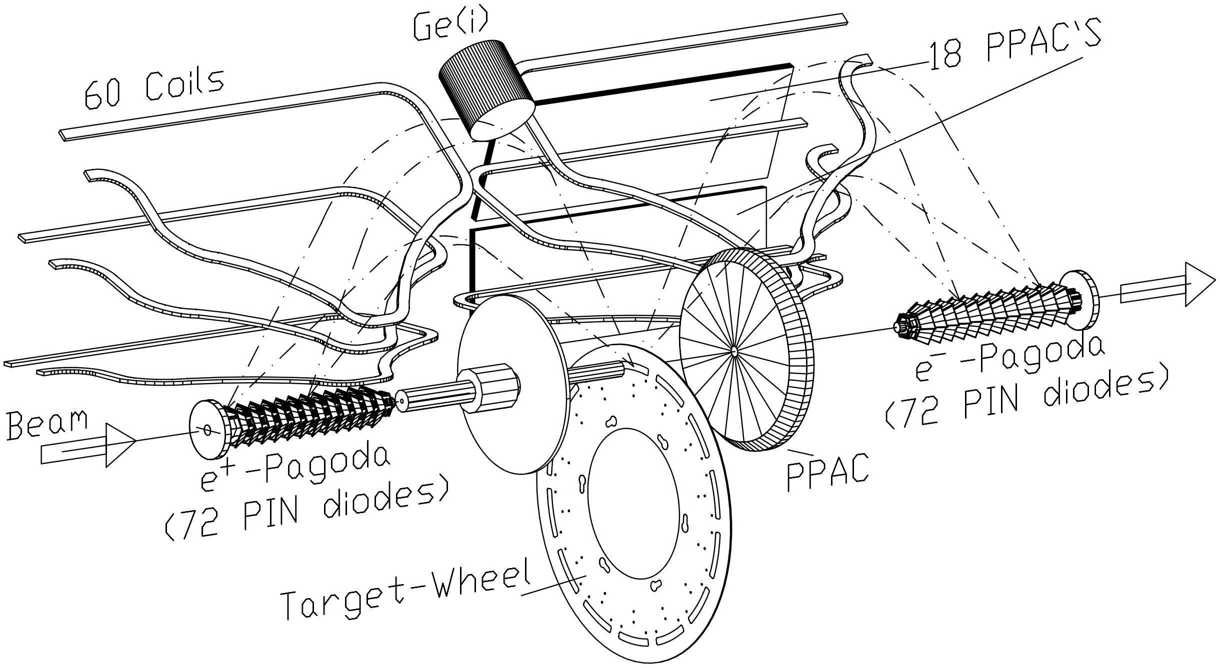

Figure 1

(S. Heinz *et al.*, Z. Physik A)

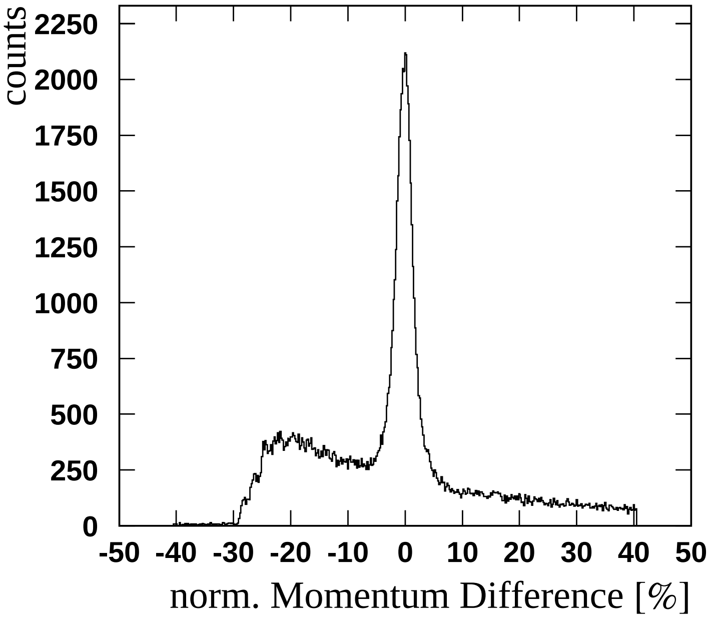

Figure 2

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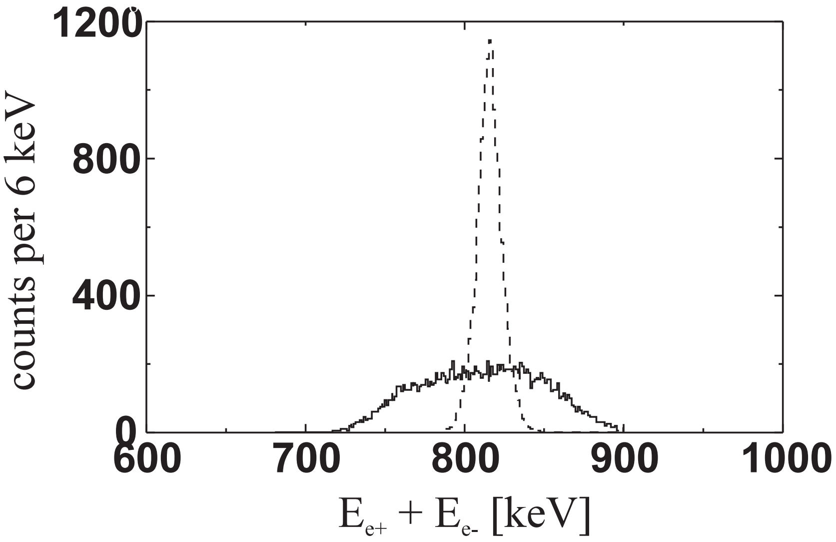

Figure 3

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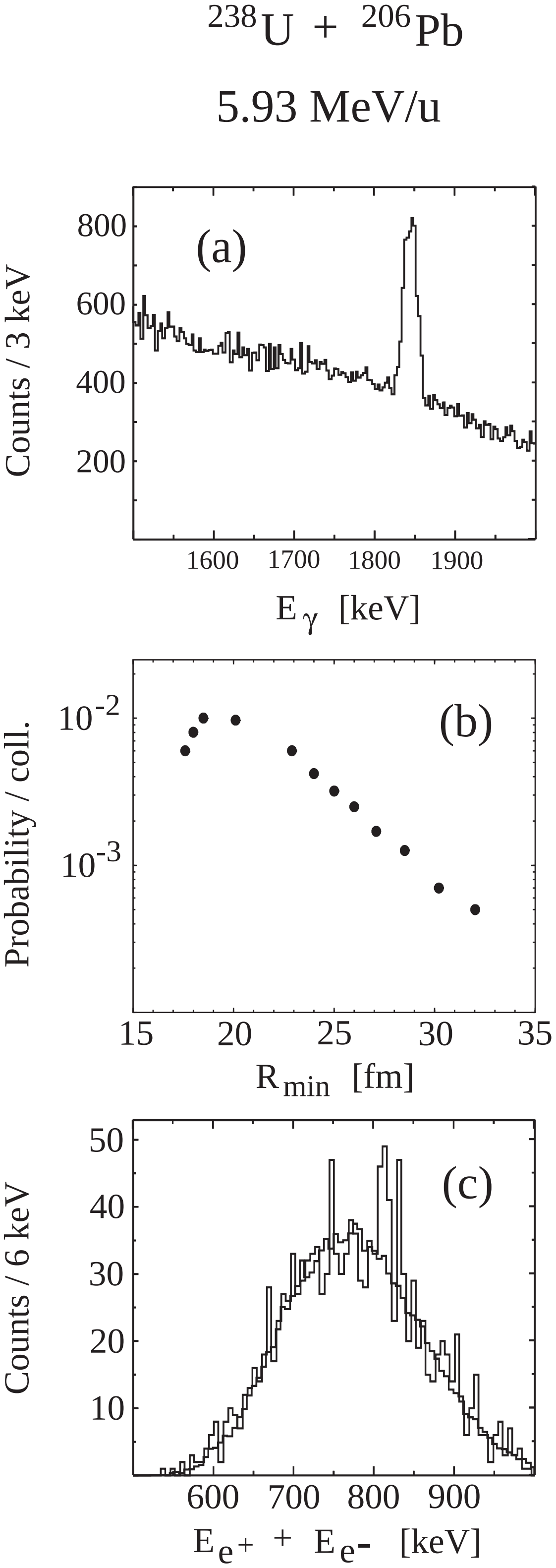

Figure 4

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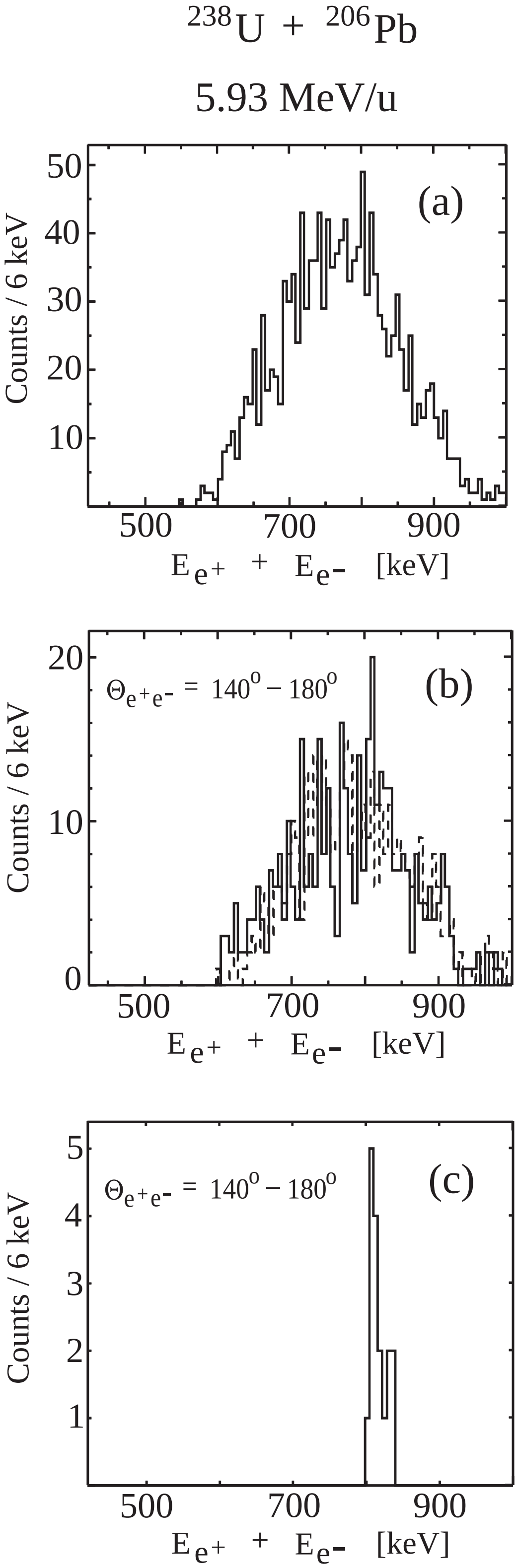

Figure 5

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$^{238}U + ^{206}Pb$

5.93 MeV/u

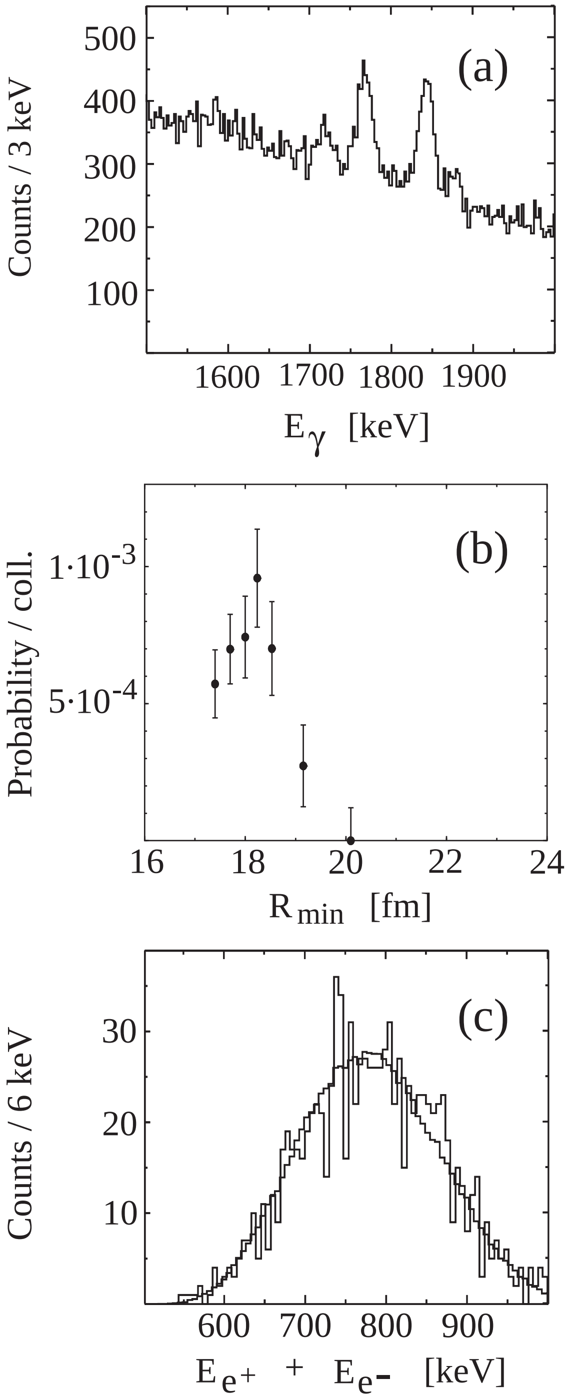

Figure 6

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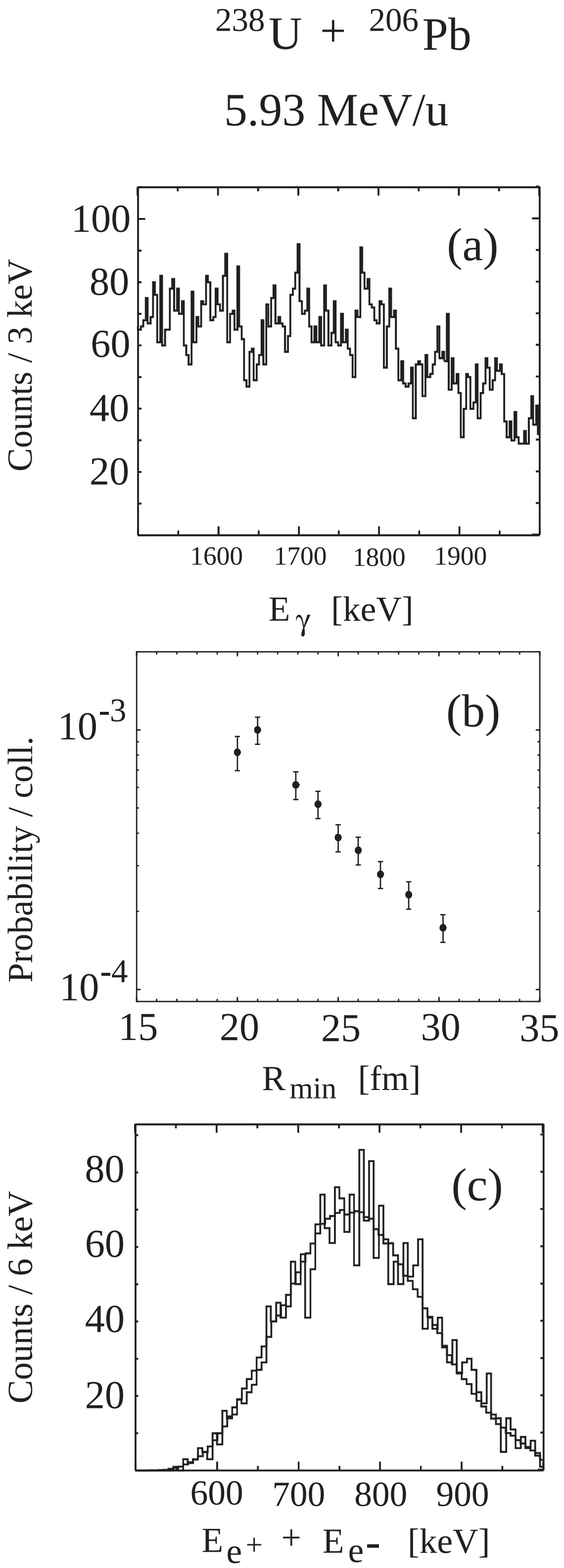

Figure 7

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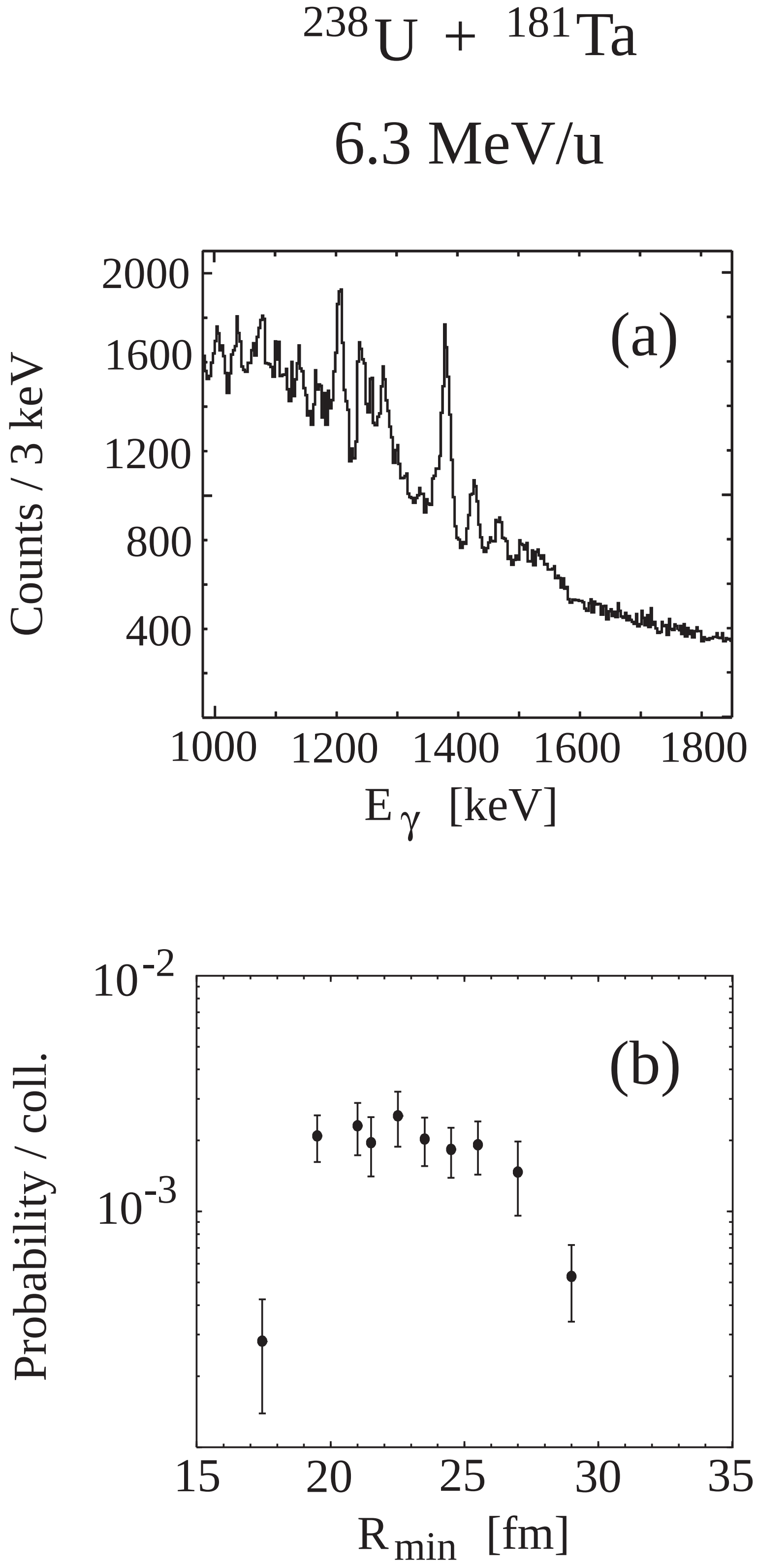


$^{238}U + ^{181}Ta$

6.3 MeV/u

Figure 8

(S. Heinz *et al.*, Z. Physik A)

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

6.3 MeV/u

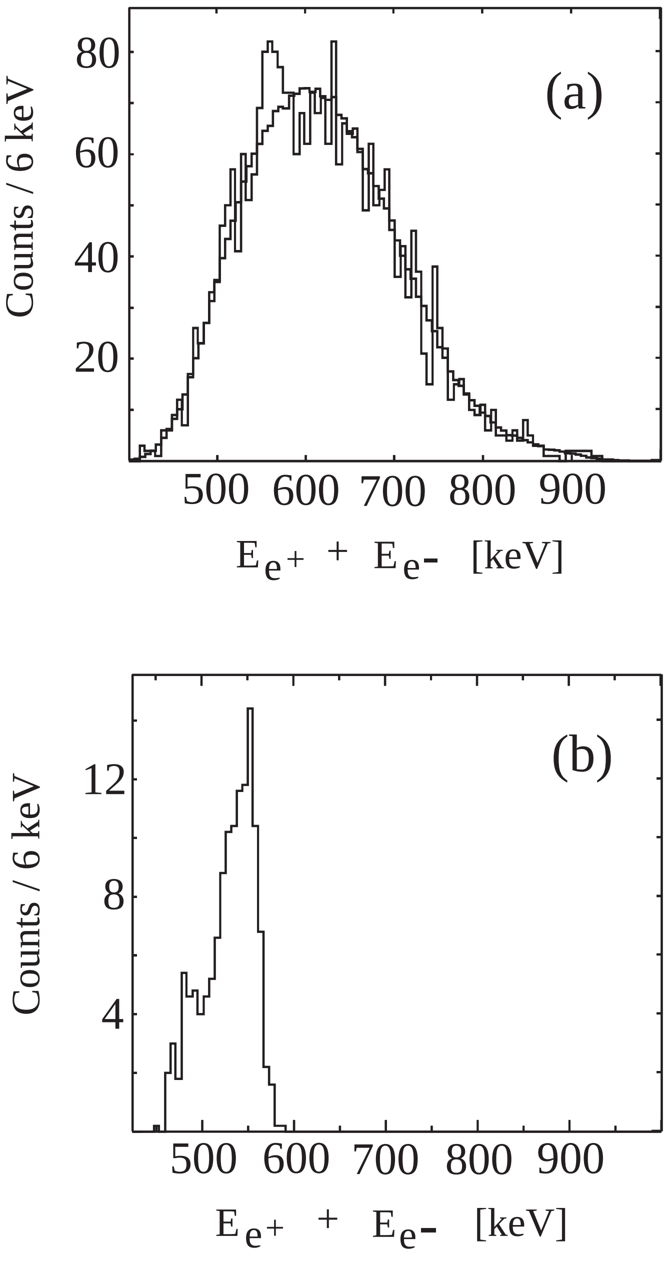
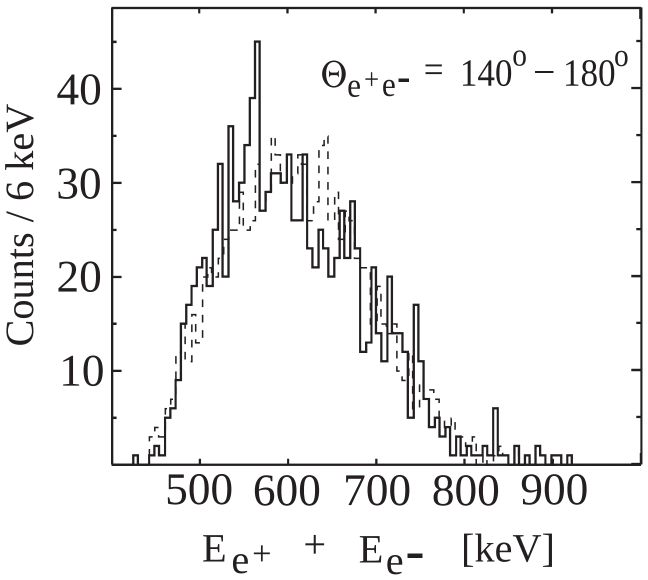


Figure 9

(S. Heinz *et al.*, Z. Physik A)



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

6.3 MeV/u

Figure 10

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