Abstract

We present the results from e^+e^-–coincidence measurements in \(^{238}\)U + \(^{206}\)Pb collisions at a beam energy of 5.93 MeV/u, using an improved experimental setup at the double-Orange spectrometer of GSI. The capability of our device to detect Internal-Pair-Conversion (IPC) e^+e^- pairs from discrete nuclear transitions of a moving emitter is demonstrated by investigating the known 1.844 MeV (E1) transition in \(^{206}\)Pb and the 1.770 MeV (M1) transition in \(^{207}\)Pb, excited via Coulomb excitation and a neutron transfer reaction, respectively. The Doppler-shift corrected e^+e^-–sum-energy spectra show weak lines at the expected energies with cross sections being consistent with the measured excitation cross sections of the corresponding \(\gamma\) lines and the theoretically predicted IPC coefficients. No other e^+e^-–sum-energy lines were found in the measured spectra. The observed transfer cross sections show a strong dependence on the distance of closest approach (\(R_{\text{min}}\)), thus signaling also a strong dependence on the bombarding energy close to the Coulomb barrier.

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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 definitely ruled out by subsequent conclusive Bhabha-scattering experiments [3]. After this time it was become 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 less well understood than previously assumed, such that some of reported weak lines might be due to this process.

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 $\mu$b for the $^{238}\text{U} + ^{181}\text{Ta}$ system and some tenth of $\mu$b for $^{238}\text{U} + ^{208}\text{Pb}$ collisions [2]. Particularly for the last system, two $e^+e^−$–sum-energy lines at $(575 \pm 6)$ keV and at $(787 \pm 8)$ 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 $\theta_{e^+e^-} = 155^\circ - 177^\circ$, for which Doppler broadening is expected to be small for similar energies of both leptons.

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

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 [4], which allows to reveal narrow lines in the measured $e^+e^-$-sum-energy and $\gamma$-ray spectra [5].

It should be mentioned here that, from their experimental results reported most recently, the APEX collaboration [6] at ANL and the EPOS II [7] and ORANGE [8] collaborations at GSI have all failed to find evidence for the previously reported $e^+e^-$-sum-energy 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 ($\frac{1}{2}$)-field is generated by 60 iron-free coils. Electrons with emission angles $\theta_e^- = 38^\circ - 70^\circ$ and positrons with $\theta_{e^+} = 110^\circ - 145^\circ$ 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 [4]. 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 (see also Refs. [4, 8]).

The spectrometer accepts lepton pairs with opening angles, $\theta_{e^+e^-}$, from $40^\circ$ to $180^\circ$ in the laboratory system. This range can be subdivided into 10 bins of width $\approx \pm 10^\circ$. 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 $\theta_{\text{ion}} = 12.5^\circ - 35^\circ$ and $\theta_{\text{ion}} = 40^\circ - 70^\circ$ with a resolution of 1.0$^\circ$ and 0.5$^\circ$, respectively. The azimuthal-angle resolution of all (ion and lepton) detectors is $\Delta \phi = 20^\circ$.

For the detection of $\gamma$ rays we used a high resolution 70%-Ge(i) detector placed at $\theta_{\gamma} = 86^\circ$ relative to the beam axis at a distance of 40 cm from the target. An ionization chamber installed at $\theta = 40^\circ$ 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]. The measured FWHM of these sum-energy lines is $\sim 16$ keV, consistent with the sum-energy resolution of the lepton detectors.

### 3 Experiment and results

Data were taken for the collision system $^{238}$U + $^{206}$Pb using $^{238}$U beams and 800 $\mu$g/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 $\gamma$-transition energy of 1844 keV [9]. Following an event-by-event Doppler-shift correction to the Pb-like recoiling ion, a pronounced $\gamma$ line with a total excitation cross section of $\sigma_{\gamma} = (55 \pm 5)$ mb appears at $(1844 \pm 1)$ keV in the measured energy spectrum (Fig.2a).

The excitation probability, $P_{\gamma}(R_{\text{min}})$, was determined as a function of distance of closest approach, $R_{\text{min}}$, by normalizing the $\gamma$ yield in certain $R_{\text{min}}$ intervals with the corresponding number of elastically scattered ions. At large $R_{\text{min}}$ values, $P_{\gamma}$ shows an exponential decrease, whereas at small $R_{\text{min}}$ values $P_{\gamma}$ is cut off abruptly at $R_{\text{min}} \sim 17$ fm, where the nuclei come into contact. Such a behaviour is typical for Coulomb excitation (Fig. 2b). 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 $\sim 400$ $\mu$g/cm$^2$ thick targets. They report recently a measured cross section of $\sigma_{\gamma} = (44 \pm 7)$ mb [10].

From the 1844 keV transition we expect IPC pairs with a sum energy of 822 keV.
Multiplying the measured $\gamma$ cross section with the theoretically predicted IPC coefficient of $\alpha_{IPC} = 4.0 \times 10^{-4}$, for an electromagnetic transition with multipolarity E1, $Z\!=\!82$ and energy 1850 keV \cite{11}, we expect a total cross section for IPC of $\sigma_{IPC} = (22 \pm 2) \mu b$. In order to optimize the peak-to-continuum ratio in the $e^+e^-$-sum-energy spectra, we eliminated very 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. The event-by-event Doppler-shift corrected $e^+e^-$-sum-energy spectrum obtained under these conditions is shown in Fig. 2c. 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. 2c, 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 \cite{12}. The width of the Doppler-shift corrected line depends on the emitter velocity and on the angular resolution of the detectors. For the case of a rather slow emitter (i.e. $\approx 0.05c$), we expect line widths near the limit given by the detector sum-energy resolution, i.e. FWHM $\sim 16$ keV \cite{14}. As can be seen in Fig. 2c, at an energy of $(815 \pm 10)$ keV an excess of $(34 \pm 12)$ counts is observed, in accordance with our estimate of 35 counts.

We found an additional line in the $\gamma$ 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 $R_{min} < 20$ fm (Fig.3.a). In the $R_{min}$ parameter range selected ($17$ fm $< R_{min} < 20$ fm), the $\gamma$ 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. 3.b. 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 $R_{\text{min}}$ dependence were observed for a two-neutron transfer reaction, leading to the known 3.71 MeV $5^-$ level in $^{208}\text{Pb}$ \cite{9}.

The line at 1770 keV is assigned to a known M1 transition in $^{207}\text{Pb}$ from the $\frac{7}{2}^-$ (2.34 MeV) to $\frac{5}{2}^-$ (0.57 MeV) state \cite{9}, populated by neutron transfer from $^{238}\text{U}$ to $^{206}\text{Pb}$, with a total cross section of $\sigma_\gamma = (1.1 \pm 0.3)$ mb. The corresponding IPC production cross section is expected to be $\sigma_{\text{IPC}} = (0.3 \pm 0.1) \mu\text{b}$ with $\beta = 2.8 \times 10^{-4}$ \cite{11}, which should lead to a weak $e^+e^-\text{-sum-energy}$ line at $\sim 750$ keV with a FWHM of $\sim 40$ keV, and an intensity of about 10 counts. This is also weakly indicated in the corresponding Doppler-shift corrected $e^+e^-\text{-sum-energy}$ spectrum, shown in Fig. 3c, although one cannot distinguish its appearance from the expected statistical fluctuations, which are of the same order. The situation is similar for the line at $\sim 820$ keV, which is expected to have comparable intensity.

Note that the 1770 keV $\gamma$ 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 $\sim 400 \mu\text{g/cm}^2$ thick $^{206}\text{Pb}$ target \cite{10}. 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.

\section{4 Summary and Conclusions}

The results discussed in the previous section show that IPC processes after Coulomb excitation appear with typical cross sections of some $\mu\text{b}$ in the $e^+e^-\text{-sum-energy}$ spectra. Corresponding $\gamma$ lines resulting from Coulomb excitation have cross sections of some 10 mb. This is expected for IPC coefficients of the order of $10^{-4}$. The observed cross sections of the $\gamma$ lines, following nucleon transfer, show a peaked $R_{\text{min}}$ dependence and are in the order of 1 mb. They suggest corresponding $e^+e^-\text{-line}$ cross sections of some 0.1 $\mu\text{b}$, in agreement with the measurement.

Previously reported $e^+e^-\text{-sum-energy}$ lines, showing partially the characteristics of IPC transitions in the Ta-like nucleus \cite{4}, reveal cross sections of a few $\mu\text{b}$. From this limit, $\gamma$ transitions of at least 10 mb cross section are suggested. However, none of the corresponding Doppler-shift corrected $\gamma$-ray spectra exhibited lines with cross sections $\sigma_\gamma > 1$ mb,
thus excluding electromagnetic transitions with multipolarity $\ell > 0$ in the Ta-like nucleus as the source of the $e^+e^-$ lines. However, transitions without a $\gamma$ decay branch, namely $0^+ \rightarrow 0^+$ transitions, cannot be excluded by the $\gamma$ measurements.

Recently, a search for monopole transitions in $^{238}\text{U} + ^{181}\text{Ta}$ collisions at a beam energy of 6.0 MeV/u was conducted at GSI using conversion electron spectroscopy \[13\]. From these investigations, a limit of 0.3 mb for the production cross section of a K-conversion line in $^{181}\text{Ta}$ at an energy around 1.7 MeV is derived. This limit can be transformed into an upper limit of $\sigma_{IPC} \leq 10 \mu b$ for the production of corresponding $e^+e^-$ pairs, when an IPC-conversion-electron coefficient of $\eta = 0.03$ \[14\] for $^{181}\text{Ta}$ at an energy of 1.8 MeV is taken into account. In the case of our previously reported lines \[4\], this limit is not quite sensitive enough to exclude an E0 transition definitely.

In context with the 575 keV and 787 keV $e^+e^-$-sum-energy lines, observed previously in $^{238}\text{U} + ^{208}\text{Pb}$ collision at 5.9 MeV/u \[2\], one would expect $\gamma$ lines at 1.595 MeV and 1.807 MeV energy with cross sections of about 1 mb, assuming the $^{208}\text{Pb}$-like nuclei as emitters. Unfortunately, the corresponding $\gamma$-ray spectra were taken at that time with a low-resolution NaI detector \[2\], which was not sensitive enough for detection of such weak $\gamma$ lines. Consequently, no exclusion of electromagnetic transitions of any multipolarity is possible at this stage for this collision system.

In summary we conclude that IPC $e^+e^-$ pairs from discrete nuclear transitions of a moving emitter can be observed with production cross sections down to the tenth $\mu b$ level in heavy collision systems, in which the continuous distributions due to uncorrelated $e^+e^-$ emission and nuclear background are dominating. Apart from the observed weak IPC lines, no other lines could be found in the measured $e^+e^-$-sum-energy spectra of this collision system. The present sensitivity achieved is at the level of statistical fluctuations or weak $e^+e^-$-sum-energy lines observed in previous experiments.

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Figure Captions

**Fig. 1.** Schematic view of the ORANGE spectrometers. The setup consists of the following components: two Si-(PIN)-diode arrays (PAGODAs) for lepton detection, 19 PPACs to count the scattered heavy ions, an intrinsic Ge detector for $\gamma$-ray detection and a rotating target wheel.

**Fig. 2.** a) Spectrum of $\gamma$ rays from $^{238}\text{U} + ^{206}\text{Pb}$ collisions after Doppler-shift correction to the Pb-like ions, scattered in the $R_{\text{min}}$ range from 17 to 32 fm. The line at $(1844 \pm 1)$ keV belongs to the E1 transition $3^- (2.65 \text{ MeV}) \rightarrow 2^+ (0.80 \text{ MeV})$ in $^{206}\text{Pb}$.

b) The excitation probability of the 1844 keV $\gamma$ transition as a function of $R_{\text{min}}$.

c) The Doppler-shift corrected $e^+e^-$-sum-energy spectrum obtained under the assumption that Pb-like nuclei are the emitters for $R_{\text{min}} = 23 - 32$ fm and $e^+e^-$ energy differences from $-200$ to 175 keV. The contribution of random coincidences ($\sim 15\%$) is subtracted from the data. The smooth solid line is a reference continuous distribution gained by event mixing.

**Fig. 3.** a) Doppler-shift corrected $\gamma$-ray spectrum for rather central collisions ($R_{\text{min}} \leq 20$ fm). The line at $(1770 \pm 1)$ keV corresponds to the M1 transition $\frac{7^-}{2} (2.34 \text{ MeV}) \rightarrow \frac{5^-}{2} (0.57 \text{ MeV})$ in $^{207}\text{Pb}$, produced by 1n-transfer reaction.

b) Excitation probability as a function of $R_{\text{min}}$ of the 1770 keV $\gamma$ transition.

c) The same as in Fig. 2c, but for $R_{\text{min}}$ values between 17 and 20 fm.
\[ ^{238}U + ^{206}Pb \]

5.93 MeV/u

Figure 2
$^{238}\text{U} + ^{206}\text{Pb}$

5.93 MeV/u

Figure 3