New results on $e^+e^-$--line emission in U+Ta collisions

The ORANGE Collaboration at GSI

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Abstract

We present new results obtained from a series of follow-up $e^+e^-$--coincidence measurements in heavy-ion collisions, utilizing an improved experimental set-up at the double-Orange $\beta$-spectrometer of GSI. The collision system $^{238}\text{U} + ^{181}\text{Ta}$ was reinvestigated in three independent runs at beam energies in the range $(6.0–6.4)\times\text{AMeV}$ and different target thicknesses, with the objective to reproduce a narrow sum-energy $e^+e^-$--line at $\sim$635 keV observed previously in this collision system. At improved statistical accuracy, the line could not be found in these new data. For the ”fission” scenario, an upper limit $(1\sigma)$ on its production probability per collision of $1.3\times10^{-8}$ can be set which has to be compared to the previously reported value of $[4.9\pm0.8(stat.) \pm 1.0(syst.)] \times 10^{-7}$. Based on the new results, a reanalysis of the old data shows that the continuous part of the spectrum at the line position is significantly higher than previously assumed, thus reducing the production probability of the line by a factor of two and its statistical significance to $\leq 3.4\sigma$.

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1 Introduction

Previous e⁺e⁻-coincidence measurements in heavy-ion collisions at the Coulomb barrier, performed at the UNILAC accelerator of GSI by the EPOS and ORANGE collaborations, have shown narrow e⁺e⁻-sum-energy lines with energies in the range 550–810 keV [1–4]. Their features were found to be complex, and did not fit into any conventional atomic and/or nuclear production process. In particular, the speculation that a hitherto unknown neutral particle (mass \( \sim 1.8 \text{ MeV}/c^2 \)), decaying into e⁺e⁻ pairs, might be involved [1], has conclusively been ruled out by subsequent Bhabha-scattering experiments [5]. Thus, the origin of this phenomenon has remained a puzzle, without a satisfactory explanation until now.

On the other hand, all the data reported previously were incomplete as far as a systematic dependence on the collision parameters and the lepton emission scenario is concerned, and were suffering from limited statistical significance. Even more, a consistent description of the line characteristics (i.e., energies, cross sections) could not be achieved by comparing the results of both groups. For instance, the cross sections of the lines reported by us for \(^{238}\text{U} + ^{238}\text{U}\) and \(^{238}\text{U} + ^{208}\text{Pb}\) collisions [2, 4] were found to be an order of magnitude smaller than those quoted by the EPOS collaboration [1, 3] and, in particular, a line at \( \sim 760 \text{ keV} \), initially reported by EPOS for \(^{238}\text{U} + ^{232}\text{Th}\) collisions [1], has not been observed in our experiments. From our investigations, the most distinct evidence exists for a sum-energy line at \( \sim 635 \text{ keV} \) observed in the collision system \(^{238}\text{U} + ^{181}\text{Ta}\) by using a beam energy of \( 6.3 \times A \text{ MeV} \) and 1000 \( \mu g/cm^2 \) thick \(^{181}\text{Ta}\) target [4]. The line was seen with the so far highest statistical significance (6.5σ) by selecting e⁺e⁻-pairs in coincidence with two heavy ions (HI), whose kinematics is consistent with fission of the U after the collision. However, the opening-angle distribution of the e⁺e⁻-pairs associated with this line, as measured directly in our experiments, was found to be rather isotropic, whereas the line energy is unequally shared between positrons and electrons, thus being in clear disagreement with a two-body decay scenario suggested previously [1, 2].

It is obvious that further experiments, which could be able to clarify this rather unsatisfactory situation, were urgently needed. We started a new round of experiments by upgrading the detection systems at the double-Orange spectrometer [6] and exploiting the new high-charge state injector at the UNILAC accelerator. Here we report the first
results from the new investigations, which explore with significantly improved sensitivity, the collision system $^{238}$U + $^{181}$Ta.

2 Experimental set-up

As in previous experiments [2, 4], we used two identical iron-free, orange-type $\beta$- spectrometers, facing each other with a common object point, at which a rotating target wheel is placed (Fig. 1). Positrons ($e^+$) emitted in the backward ($\theta_{e^+} = 110^\circ - 145^\circ$) and electrons ($e^-$) emitted in the forward hemisphere ($\theta_{e^-} = 38^\circ - 70^\circ$) are focussed onto position sensitive detectors. Each lepton detector consists of an array of high-resolution Si PIN diodes, called "PAGODA". Intrinsic to this set-up is the capability of focussing, at a given field setting, only a certain momentum interval of $e^+$ or $e^-$ by rejecting at once the opposite charge. This is a major advantage because the high $\delta$-electron background is therewith suppressed completely on the $e^+$–side, while the sharp low-energy cut-off on the $e^-$–side enables operation at high luminosities.

The leptons are identified by matching their momentum, derived from the hit-point on the PAGODA and the spectrometer field setting, with their energy, measured by the PIN diodes. This provides a clear signature for $e^+$ and $e^-$, and suppresses backgrounds due to $\gamma$ rays and scattered $\delta$-electrons efficiently [7]. An additional coincidence requirement with the 511 keV annihilation radiation is thus not necessary for the $e^+$ identification. The momentum-energy matching in addition rejects leptons backscattered from the PIN diodes almost completely, a unique feature of this set-up.

The old lepton detection systems [2, 4] are replaced by new ones each consisting of 72 segmented, high-resolution, 1 mm thick, Si PIN diodes which are mounted on 12 roofs of a pagoda-like structure, 6 detectors on each roof (see Fig. 1). Each detector chip has a trapezoidal shape (24 mm base, 16 mm top, and 16 mm height) and is tilted by $\sim 40^\circ$ relative to the spectrometer axis. Each detector is further subdivided into three electrically separated sectors, covering an azimuthal angular range of $\Delta\phi_{\text{lept}} = 20^\circ$. A set of three neighbouring sectors at the same azimuthal angle is connected to one preamplifier, recording information on energy and arrival time of a lepton. To identify the individual sector of the set, the rear of each sides of all detectors on each roof are read out additionally.
by another preamplifier. The $e^+e^-$-sum-energy and time resolution achieved in-beam amounts to $\sim 15$ keV and $\sim 4$ ns (FWHM), respectively, cooling down the detectors to $\sim -25^\circ$C. This is comparable to that of our old set-up.

The opening angle of the $e^+e^-$-pair, $\theta_{e^+e^-}$, is measured directly within a range of $40^\circ - 180^\circ$ in the laboratory. Using the $\phi$–separation of the PAGODA’s, this range can be subdivided into ten angular bins with a typical width of $\sim \pm 10^\circ$ and centroids at $\theta_{e^+e^-} = 70^\circ$, $73^\circ$, $80^\circ$, $90^\circ$, $102^\circ$, $116^\circ$, $131^\circ$, $145^\circ$, $159^\circ$, and $167^\circ$. Thus, the lepton opening angles are measured with an accuracy which is comparable to the effect of small-angle scattering in the targets (e.g. $\sim 24^\circ$ for a $1 \text{ mg/cm}^2$ thick target [4]). Each pagoda array covers a maximum momentum acceptance of $\Delta p/p = 30\%$ which corresponds to an energy interval of $\Delta E \sim 150$ keV at a lepton energy of 300 keV. Within this momentum interval, the full-energy peak efficiency is 10% and 11% of $4\pi$, for electrons and positrons, respectively. With respect to the $e^+e^-$-coincidence efficiency and the range of energy-difference distributions covered, this is an improvement by about a factor of two as compared to our previous set-up.

In addition, a modified set of heavy-ion counters (PPAC’s) measures the polar angles of the scattered ions in the ranges $13^\circ \leq \theta_{\text{ion}} \leq 35^\circ$ and $40^\circ \leq \theta_{\text{ion}} \leq 70^\circ$ with an accuracy of $1^\circ$ and $0.5^\circ$, respectively. The total azimuthal range is covered with a resolution in $\phi_{\text{ion}}$ of $20^\circ$. Finally, a high-resolution Ge(i) detector is used to measure $\gamma$ rays ($E_\gamma \gtrsim 1$ MeV) in coincidence with the scattered heavy ions (see Ref. [4]).

The performance of the lepton detection systems has been studied extensively in source measurements [4]. In particular, the $e^+e^-$-opening-angle resolving power is demonstrated by measuring the 1.76 MeV E0 transition in $^{90}\text{Zr}$ [4, 7] and the 1.77 MeV M1 transition in $^{207}\text{Pb}$ [4]. Even more important is the check of the capability of the set-up to detect narrow sum-energy lines under beam conditions. This has been proven by measuring the 1.844 MeV E1 transition in $^{206}\text{Pb}$, populated via Coulomb excitation in $^{238}\text{U} + ^{206}\text{Pb}$ collisions. By applying an event-by-event Doppler-shift correction assuming emission from the recoiling $^{206}\text{Pb}$ nucleus, a weak $e^+e^-$-sum-energy line at $\sim 820$ keV is observed, whose intensity is consistent with the yield expected from the corresponding $\gamma$ line at 1.844 MeV measured with the Ge(i) detector [8].

A considerable improvement in these experiments is achieved by exploiting the new
high-charge state injector with an ECR ion source at the UNILAC accelerator. The latter provides beams with an improved time structure (9 ns between micropulses compared to 37 ns of the old injector), which allows to double luminosity at a random coincidence rate reduced by a factor of two due to the lower micropulse intensity. Random coincidences were further reduced by the almost complete lack of plasma oscillations in the new source.

3 Experiments and results

With the new set-up we reinvestigated the system $^{238}$U + $^{181}$Ta in three independent runs, using beam energies of 6.0, 6.1, 6.15, 6.3, and 6.4×A MeV and target thicknesses of 600, 800, 1000, and 1200 µg/cm$^2$. These runs, summarized in table 1, completely cover the kinematical parameter space of the previous experiment. In the first of the new experiments the old injector was used, providing a 37 ns microstructure of the beam as it was the case in the old experiments [4]. The later runs were carried out with beams from the new injector with an improved microstructure of 9 ns.

The main goal of much better statistics could be reached successfully, as it is shown in table 1. In the following we concentrate on experiments with incident beam energy of 6.3×A MeV, since the line to be reproduced was found at this beam energy. A comparison of the field settings in the various dipole magnets in the beam line, used as a cross-check of the accelerator’s independent beam energy measurement, exhibited no significant differences (<1%) between the old and new experiments. Also the acceptance for both the heavy ions and the leptons has been essentially the same in all experiments discussed here.

We analyzed the new data by applying the same conditions as in the old experiment; i.e., all $e^+e^-$ opening angles, a cut in the $e^+e^-$-energy differences between −66 keV and 150 keV, and two coincident heavy ions with either peripheral quasi-elastic kinematics (18.6 fm < $R_{\text{min}}$ < 29.3 fm), or non-two-body kinematics covering the kinematical range of fission in two opposite 60° $\phi$-segments of the HI detector with $15^\circ < \theta_1 < 25^\circ$ and $40^\circ < \theta_2 < 70^\circ$. None of the resulting $e^+e^-$-sum-energy spectra revealed a line with the production probability per collision as previously deduced from the old experiment [4]. As an example, we show in Fig. 2 the corresponding sum-energy spectra, obtained from
non-two-body heavy-ion collisions ("fission scenario"), superimposed with the expected line intensities from the old result [4].

The 1σ upper limits for the production probability of a line at ~635 keV, derived from the new results, are much lower than the reported production probability from the old experiment [4]. These results are summarized in table 2. As can be seen, a summation of all the new results, taken at the beam energy of 6.3 A MeV, yields upper limits which are a factor of 15 (quasi-elastic collisions) and 37 (non-two-body collisions) smaller than the production probabilities derived from the old experiment.

Detailed studies of the new experiments showed that the shape of the continuous part of the sum-energy spectra for the fission scenario can be well described by the corresponding sum-energy spectra, measured in coincidence with quasi-elastic collisions, and smooth distributions generated with an event-mixing technique from the latter. This was a surprising new result, since different reaction kinematics can well produce different continua in the sum-energy spectra.

The various experiments were found to be generally in good agreement. In particular, we were able to understand and quantify a class of scattering events in the inner HI detector, which obscures the signature of non-two-body HI kinematics consistent with fission. The number of peripheral quasi-elastic collisions normalized to non-two-body collisions (fission) was found to be ~3 and ~9, for the data taken with the old and new injector, respectively. Detailed investigations have revealed that this is caused by a strong contamination of misidentified double hits in the inner PPAC, where three heavy ions from the same micropulse give a misleading signature of the fission scenario. In this case, a quasi-elastically scattered ion pair in the inner and outer counter, as well as an independently scattered ion in the inner counter, are detected simultaneously. Two of these ions hit the inner PPAC, thus causing loss of the unambiguity of the (θ, φ)–matrix identification, within it’s time resolution. A reanalysis of the old data showed that nearly 2/3 of the events in the sum-energy spectra (including also events of the peak), have to be attributed to such misidentified "fission events". In the data taken with the new injector, this contamination is reduced by more than a factor of three [7].
4 Discussion of the results

From our new investigations of the collision system $^{238}\text{U} + ^{181}\text{Ta}$, carried out with improved experimental sensitivity, we have not found evidence for the previously reported line [4] in any of the new data. This negative outcome represents therefore a serious discrepancy to our first measurement in this collision system, being obtained with lower statistical accuracy [4].

Since the relevant kinematical parameter space has largely been covered and extended by the new experiments (see table 1), and since possible target deterioration effects have been kept lower, or at most comparable to the previous measurements, we cannot attribute the absence of the line in the new experiments to an incorrectly chosen beam energy or deteriorated targets. Furthermore, detailed studies of the in-beam performance of our new set-up have not provided any evidence for a possible incapability of detecting narrow sum-energy lines. The signal/background ratio in the measured $e^+$ and $e^-$ spectra was found to be comparable to the old set-up. The production probabilities of the measured continuous spectra, around the expected line position, were found to be consistent in all the new measurements, and their values agree within 18% with those obtained from the old experiment [7]. This is also the case for the number of fission events normalized to the number of scattered heavy ions, when misidentified double hits (discussed above) are accounted for. The detection efficiency for fission fragments has been similar in all experiments.

From the discussion above, we have to conclude that it is difficult to find a physics-based working hypothesis which would corroborate both, the appearance of the line in the previous results and its absence in the new, improved experiments. Taking into account that we have not found any evidence that the reported line might be due to trivial effects or background processes, its statistical significance has to be reconsidered.

In Fig. 3 we show the $e^+e^-$ sum-energy spectrum with the reported line at $\sim 635$ keV [4], together with a polynomial fit (solid line) used at that time to describe the continuous part of the spectrum outside the line. Based on this background curve, the statistical significance of the line was deduced to $\sim 6.5\sigma$ [4]. However, recent reanalysis of these results has revealed that the formerly used polynomial fit might be incorrect, as demonstrated by
the new dashed background curve. The latter has been gained by making use of the new observation that the shape of the continuous part of the spectrum of non-two-body events (fission scenario) can be well described by event mixing of $e^+$ and $e^-$ obtained from quasi-elastic scattering (see sect. 3). Taking this background curve as a reference, the remaining excess around 635 keV has a statistical significance of $\lesssim 3.4\sigma$, and can be translated into a production probability of $[2.7\pm 0.8\, (\text{stat.}) \pm 0.6\, (\text{syst.})] \times 10^{-7}$. The corresponding value for peripheral quasi-elastic collisions amounts to $[2.7\pm 1.2\, (\text{stat.}) \pm 0.6\, (\text{syst.})] \times 10^{-7}$. These values are approx. a factor of two lower than those reported in the previous analysis (see table 2).

We shall note in this context that in some runs we found an indication for a narrow $e^+e^-$-line in the sum-energy spectra by applying slightly different cuts in the HI kinematics (see Ref. [7]). This line, however, could not be reproduced in the subsequent runs taken under similar experimental conditions and better statistics. Adding all data together taken at $6.3\times A$ MeV, we derive upper limits for the production probabilities of narrow lines at $\sim 635$ keV of $P(1\sigma) = 2.9 \times 10^{-8}$ for quasi-elastic collisions and $P(1\sigma) = 1.3 \times 10^{-8}$ for the fission scenario, normalized to peripheral quasi-elastic collisions. Finally, it should be pointed out that negative results were also reported by the APEX [9] and EPOS [10] collaborations, who focused on previous findings of old EPOS measurements [1, 2].

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Table 1: Summary of our new investigations in the collision system $^{238}\text{U} + ^{181}\text{Ta}$ (I–III). For comparison, the old data from the same collision system are also shown. As can be seen, the new data are obtained with significantly improved statistics.

|       | $^{238}\text{U} + ^{181}\text{Ta}$ | Beam energy [MeV/u] | Targ. thick. [$\mu$g/cm$^2$] | Beam struct. [ns] | True $e^+e^-$-pairs |
|-------|-----------------------------------|----------------------|-------------------------------|-------------------|----------------------|
| Expt. I | 6.3                               | 1200                 | 37                            | 22900             |
|        | 6.3                               | 600                  | 37                            | 14000             |
| Sum    |                                   |                      |                               | 36900             |
| Expt. II| 6.3                               | 800                  | 9                             | 43200             |
|        | 6.4                               | 800                  | 9                             | 16900             |
|        | 6.1                               | 800                  | 9                             | 9900              |
| Sum    |                                   |                      |                               | 70000             |
| Expt. III| 6.3                              | 1000                 | 9                             | 57000             |
|        | 6.15                              | 1000                 | 9                             | 51000             |
|        | 6.0                               | 600                  | 9                             | 40000             |
| Sum    |                                   |                      |                               | 148000            |
| Total I–III |                                |                      |                               | 254900            |
| Old exp. | 6.3                              | 1000                 | 37                            | 11200             |
Table 2: 1σ upper limits for the production probability per collision, $P_{max}(1\sigma)$, for a narrow sum-energy $e^+e^−$–line at $\sim$635 keV in $^{238}\text{U} + ^{181}\text{Ta}$ collisions at a beam energy of $6.3\times A\text{MeV}$. Also shown are the line production probabilities derived from the old experiment $^4$.

|                  | Expt. I | Expt. I | Expt. II | Expt. III | Old exp. | All Data |
|------------------|---------|---------|----------|-----------|----------|----------|
| Targ. thick. [$\mu g/cm^2$] | 1200    | 600     | 800      | 1000      | 1000     |          |

|                  | Peripheral quasi-elastic collisions |
|------------------|-------------------------------------|
| $E_{beam} = 6.3\times A\text{MeV}$ | |
| $P_{max}(1\sigma) [10^{-8}]$ | 7.4 | 8.6 | 4.5 | 4.5 | $47\pm12^a\pm10^b$† | 2.9 |

|                  | "Fission" normalized to peripheral quasi-elastic collisions |
|------------------|-----------------------------------------------------------|
| $P_{max}(1\sigma) [10^{-8}]$ | 4.5 | 5.2 | 1.5 | 1.5 | $49\pm8^a\pm10^b$† | 1.3 |

$^a$ statistical and $^b$ systematical uncertainty

† A recent analysis of these results yielded production probabilities for the line structure in case of peripheral quasi-elastic collisions of $[2.7\pm1.2(stat.)\pm0.6(syst.)]\times10^{-7}$ and $[2.7\pm0.8(stat.)\pm0.6(syst.)]\times10^{-7}$ for the fission scenario.
FIGURE CAPTIONS

Fig. 1: Schematic view of the new experimental set-up at the double-Orange device. Each of the \( \beta \)-spectrometers is equipped with a \( \beta \)-multidetector system of 72 Si (PIN) diodes (\( e^\pm \)-Pagodas). The forward spectrometer is surrounded by 18 position-sensitive heavy-ion detectors (PPAC), and contains a further PPAC detector in its center. Also shown is the rotating target wheel and the Ge(i) \( \gamma \)-ray detector.

Fig. 2: Summary of \( e^+e^- \)-sum-energy spectra obtained from inelastic U+Ta collisions at 6.3\( \times \)A MeV, leading to fission of the U nucleus, by different target thicknesses indicated. The data shown in a) and b) are from the run I, in c) and d) from the runs II and III, respectively (see table 1). The spectra are integrated over the whole \( e^+e^- \)-opening-angle range covered experimentally. The selection criteria (see text) are the same as those imposed on the previous results [4]. The superimposed peaks (dashed lines) at \( \sim 635 \) keV would correspond to the signal expected from the line intensity reported previously [4]. The difference in the signal/background ratios shown is due to the different contamination in misidentified double hits, discussed in the text.

Fig. 3: \( e^+e^- \)-sum-energy spectrum from U+Ta collisions at 6.3\( \times \)A MeV, obtained previously [4]. In this spectrum a prominent \( e^+e^- \)-line at \( \sim 635 \) keV is seen. The solid curve is a simple polynomial fit to the continuous part of the spectrum used in the first analysis [4]. The dotted-line distribution is based on recent reanalysis of these data by using event mixing (see text).
Figure 1
Figure 2
Figure 3