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SEARCH FOR SPONTANEOUS POSITRON PRODUCTION IN HEAVY-ION COLLISIONS.

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I. INTRODUCTION

In collisions between heavy ions with heavy target atoms distances of closest approach deep within the atomic K-shell radii are achieved. When using projectile velocities which are slow compared to the orbital velocities of the inner-shell electrons, these electrons will adjust their orbitals during the course of such collisions, evolving for small internuclear separations into a quasiatomic system with a charge number Z_{ua} of the united atom (for an U+U-collision at 1.4 GeV projectile energy, for example, the distance of closest approach in a head-on collision is 17 fm while the K-shell radius¹ of an atom with $Z_{ua}=92+92=184$ amounts to ~ 120 fm). In this manner transient, collision constructed quasimolecules are formed, and their formation provides a vehicle through which the behaviour of electrons in extremely large Coulomb fields may be studied.²

^{*}Presented by H. Bokemeyer

In view of the adiabatic nature of heavy ion collisions a successful theoretical description of the behaviour of innermost electron wave-functions has been obtained using molecular basis-states which are solutions to the two-center Dirac equation as a function of inter-nuclear separation R .³ However, despite their adiabatic character, these atomic collisions are usually inelastic, and information on the most strongly bound $1s\sigma$ quasimolecular state may be gained by observation of its excitation and/or subsequent decay, namely δ -electrons⁴, molecular orbital (MO)⁵ and characteristic X-rays^{6,7,8}. Abundant experimental evidence now exists that quasimolecules are indeed formed in heavy ion atom collisions.

One of the most exciting consequences of the formation of quasimolecules is expected for close encounters between two very heavy ions, where Z_{ua} exceeds the critical value $Z_{crit}=173$.⁹ For such collision systems, the binding energies of the $1s\sigma$ -electrons are expected to be larger than twice the rest-mass energy of the electron, namely $2m_e c^2$. Under these conditions, vacancies in the $1s\sigma$ orbital may be spontaneously filled with the creation of a bound electron - free positron pair. The search for this process of spontaneous positron production is the central goal of the experiment described in this lecture and of similar measurements discussed in other contributions to this workshop by P. Kienle and H. Backe. Indeed, the study of strong field QED in the quasimolecular collision system⁹ is one of the principal subjects of this conference.

But this search is not uninterrupted by problems of a basic nature. Due to the time-variation of the Coulomb field during the course of such collisions, electrons can be excited from the negative energy continuum, both into empty quasimolecular orbits as well as directly to the positive energy continuum thereby leaving a hole in the negative energy continuum, which means creating a free positron. This so-called induced pair production process competes principally with the spontaneous process being sought. For quasiatoms where the two collision partners are moving on trajectories characteristic for pure Rutherford scattering, the spontaneous and the induced processes are predicted to result in a broad bell-shape like positron

energy spectrum centered at ~ 500 keV and it may thus not be possible to distinguish the two contributions experimentally. If, however, the time the quasistom remains at the distance of closest approach is prolonged (e.g. by forming a composite nuclear system of finite ($>10^{-21}$ sec) lifetime), then the two e^+ -production processes are expected to behave differently and to give rise to characteristic structures in the e^+ -energy spectra. Experimental complications arise furthermore from the excitation of nuclear states above 1 MeV during the course of the collision as positrons may be produced in the decay of these states via internal pair production. Thus any experiment seeking to distinguish spontaneous positron production from other sources of positron emission in heavy ion collisions should not only allow the measurement of the energy of the emitted positrons with good resolution but should also provide information about the impact parameter (respectively the distance of closest approach R_{min}) and the inelasticity of the corresponding collision and should also pursue a systematic investigation of the various processes as a function of Z_{ua} and the projectile energy.

We report at this time on our most recent results from such experiments. Anomalous behaviour of the particle angular distribution coincident to specific positron spectral energy regions as well as peaked structures in high resolution energy spectra measurements have been found. Section II discusses the experimental apparatus with which the measurements were performed. In section III results are presented and the possible relationship of the anomalous positron angular distributions and peaked structures to spontaneous positron emission is discussed.

II. EXPERIMENTAL SET-UP

Since the e^+ -production cross-section is rather small (~ 100 pbarn¹⁹) the apparatus had to be optimized for highest detection efficiency and background suppression. A solenoid-Si(Li) spectrometer system (figure 1) called EPOS¹¹ was constructed for this purpose and set up at the UNILAC in Darmstadt. The spectrometer combines high e^+ -detection efficiency for all relevant e^+ -energies

Fig. 1: Plane-view of the solenoid system EPOS used in the present experiment. Also shown is the magnetic field distribution along the solenoid axis.

With a simultaneous measurement of both scattered particles over a large angular range. The system exploits two basic features of solenoidal transport fields in order to achieve maximum background suppression: the opposite spiral directions of oppositely charged particles and the fact that the particles return to the field-lines passing through their point of creation.

A magnetic solenoid, perpendicular to the beam direction, is used to transport positrons on spiraling trajectories from the target to the positron counter. The magnetic field is produced by 12 'Donut'-coils¹² which can be moved separately. A suppression of δ -electrons being emitted in every heavy ion collision is achieved by a carefully constructed spiral baffle; these δ -electrons are several orders of magnitude more intense than the positrons, and therefore have to be suppressed in order to reduce the singles counting rates in the e^+ -detector and to avoid sum coincidences between positrons and electrons. The transport-efficiency for positrons is maximized by making use of a magnetic mirror on the side of the target opposite to the e^+ -detector and a field-decrease at the position of the spiral baffle. The resulting broad-band efficiency (figure 2) scales with B_t/η (B_t = magnetic field at the target, η = momentum of the positron). Thus the flat top of the efficiency curve can be moved to the e^+ -energy region of interest by simply adjusting the electric current in the coils.

Background counts in the e^+ -detector due to the leakage of scattered electrons through the baffle and due to other possible background sources outside the target are reduced by using a pencil-like e^+ -detector located along the solenoid axis. The coaxial geometry of the e^+ -detector combines maximum efficiency for target-produced positrons with minimum sensitivity for positrons and electrons which have been scattered or do not originate from the target.¹³ Positrons are identified by demanding coincidences between the e^+ -detector and at least one of the two 511 keV annihilation γ -quanta of the positron by using an eight-fold cylindrical NaI-detector array surrounding the e^+ -counter. By summing up the signals of the 8 separate NaI-crystals electronically and requiring a total γ -sum $E_\gamma \geq 440$ keV

Fig. 2: Transport and e^+ -detection efficiency as a function of B_t/η (B_t = magnetic field at the target position and $\eta = e^+$ -momentum in units of $m_e c$).
Insert: e^- -suppression factor (ratio of total e^- -transmission for opposite field-settings) as a function of the kinetic electron energy.

(to exclude low-energy γ -rays), the NaI-efficiency reaches $\approx 58\%$ per positron detected in the e^+ -counter.

The pencil-like positron detector (figure 3) consists of two coaxially drifted Si(Li)-detectors of 1 cm outer diameter, 2.5 mm sensitive thickness and 5 cm length each. The detectors are mounted closely one behind the other on a cooling-rod. To protect the (cooled) detector surface the detector vacuum is separated from the vacuum of the solenoid system by a 2 μ thick aluminized mylar-foil. Special precaution has been taken to avoid an electrical break-through along the front-surface of the detector in the presence of the strong magnetic field. The energy resolution of the e^+ -detector is better than 10 keV for the 662 keV conversion electron line of ^{137}Cs ; this resolution is much better than the expected width

of an e^+ -line measured in-beam, which will be mainly determined by the maximum Doppler-broadening $2\Delta E_D$ of the positrons emitted in flight, where ΔE_D is given in first order in $\beta = v/c$ by

$$\Delta E_D = E_e \beta / 2 (m_e c^2 / E_e) + 1$$

This broadening results in a width of $2\Delta E_D \approx 126$ keV (63 keV) for a 300 keV line and $\beta=0.1$ ($\beta=0.05$). The value of $\beta=0.1$ is typical if the emitting system is one of the heavy collision products. The $\beta=0.05$ value would be associated with a quasistom moving with the velocity of the center of mass in the laboratory.

Fig. 3: Enlarged view of the Si(Li) detector arrangement used to measure the kinetic energy of the positrons. The Si(Li)-detector is cooled close to liquid-air temperature by a temperature-controlled feed-through cryostat (not shown in the figure) of very slim shape in order to fit into the surrounding NaI-detector arrangement (see fig. 1).

Backscattering from the Si(Li)-detector leads to low energetic tails in the line-shape of the e^+ -detector. This effect is reduced in this set-up due to the repetitive return of scattered positrons (or electrons) to the counter in the presence of the solenoidal magnetic field. A typical line shape observed for an e^+ -conversion line is shown in figure 4. The shape for a single e^+ -line will have in addition a high energy tail due to the Compton-scattering of one or both of the 511 keV annihilation γ -rays in the Si(Li)-crystal. Because of the lack of a radioactive single-line e^+ -emitter this effect has been studied with a ^{22}Na -source (figure 5) and found to be of the order of 10 % for our e^+ -identifying condition $E_T \geq 440$ keV.

Fig. 4: Typical line-shape observed for conversion electrons emitted from a ^{113}Sn -source mounted at the target-position. The solenoid current was set to 450 Amp, providing optimal transmission for this energy region. The peak to total ratio is 70 %.

Fig. 5: Investigation of the summing of the e^+ -energy signal with a signal caused by additional scattering of one or both of the two 511 keV annihilation γ -rays in the Si(Li)-detector. The upper graph shows the e^+ -spectrum of a ^{22}Na -source obtained by requiring $E_{\gamma} \geq 440$ keV in the surrounding NaI-detector; this corresponds to our e^+ -identifying condition used in the analysis of the present experiment. The summing effect is clearly visible and can be quantitatively deduced by comparing this spectrum to the one obtained by requiring that both 511 keV γ -rays deposit all their energy in the NaI-crystal ($E_{\gamma} > 910$ keV) (lower graph).

Both the scattered projectile and the recoiling target nucleus are detected in two symmetrically arranged parallel-plate avalanche-detectors with continuous delay-line read-out.¹⁴ The cathodes of these detectors are structured as to form a 'meander' delay-line whose delay is directly proportional to the polar angle ϑ of the detected particle relative to the beam axis. The angular acceptance of each of the two particle detectors is $20^\circ < \vartheta < 70^\circ$ at constant $\Delta\theta=60^\circ$. In addition to the particle scattering-angle information the time of flight difference between both particles as well as a rough Z-information via the energy-loss of the particles in the detector-gas is obtained.

The coincident detection of both particles has several advantages. For asymmetric systems such as U+Pb, the impact parameter, respectively the distance of closest approach R_{min} , can be determined uniquely under the assumption of Rutherford scattering conditions from the kinematic $(\vartheta_1, \vartheta_2)$ -correlation (figure 6) For symmetric systems like U+U, the distinction of close from distant collisions is principally impossible. However, information on the energy-loss during the collision (Q-value) can be obtained from the sum of the two scattering angles $(\vartheta_1 + \vartheta_2)$, which should be 90° for elastic and $<90^\circ$ for inelastic events. This allows a study of the positron emission not only as a function of the scattering angle ϑ but also as a function of the inelasticity of the collision process. The Q-resolution obtained around 45° is about 35 MeV and is equally determined by the finite angular resolution of the detectors ($\Delta\vartheta \approx 0.4^\circ$) and small angle scattering in the target. Furthermore, the kinematic coincidence can be used together with the rough Z-identification of the detected ions to select desired reaction channels and discriminate against background from the target-backing and/or covering foils. Although the set-up allows for the selection of binary, so-called quasielastic events, it should be noted, that separation of reaction-channels involving the transfer of a few nucleons is not possible as long as both resulting nuclei are stable against fission.

Fig. 6: Intensity of scattered particles as a function of the two laboratory scattering angles ϑ_1 and ϑ_2 observed in the upper (Otto) and lower (Uwe) heavy ion detector, respectively, for the system $^{238}\text{U}+^{208}\text{Pb}$ at 5.9 MeV/u. Close and distant collisions can be separated completely with the exception of the 45° -region (an event in branch 1 corresponds to U being observed in 'Uwe' and Pb in 'Otto').

The contribution of positrons from nuclear internal pair creation amounts e.g. in U+U-collisions up to 30 % of the observed positron yield. To determine this contribution the corresponding γ -ray spectrum is measured by means of a $3''\times 3''$ NaI-detector operated in coincidence with the heavy ion detectors.¹⁵ As proposed in ref. 10 the nuclear e^+ -spectrum can be deduced from the unfolded γ -spectrum using the differential internal pair-conversion coefficient for high Z elements¹⁶. Since for this procedure the multipolarities of the γ -rays have to be known, they were established semi-empirically

through systematic studies of the e^+ -production in low Z systems (e.g. $^{238}\text{U}+^{151}\text{Sm}$, $^{238}\text{U}+^{155}\text{Ho}$) where quasiatomic e^+ -production has been proved to be negligible¹⁰.

The experimental data are fed via an event-type oriented electronic set-up to the GSI on-line data accumulation system. All information is stored event by event in order to allow for variable selective analysis of the data.

III. EXPERIMENTS AND RESULTS

In the first experiments with the new solenoid system EPOS, a pencil-like plastic-scintillator was used to measure e^+ -energies instead of the Si(Li)-detector presently installed. In these studies, measurements of the impact parameter dependence of positron production for the system $^{238}\text{U}+^{238}\text{U}$ at U-energies of 4.3 and 5.8 MeV/u have been carried out. For both bombarding energies the U+Cm-system, whose combined charge is $Z_{\text{uc}}=188$, is expected to become critical for scattering angles within the range subtended by the two particle detectors. The observed dependence for high and low positron energies on the distance of closest approach R_{min} is shown in figure 7.¹⁷ In the nearly symmetric U+Cm-system close from distant collisions could not be resolved experimentally; therefore it was assumed that the more intense branch of the Rutherford cross-section determines the R_{min} -value. Note that the nuclear contribution to the observed positron yield has been subtracted according to the procedures described at the end of section II. For the two $^{238}\text{U}+^{238}\text{U}$ -systems studied the nuclear background amounts with increasing R_{min} and for low (high) positron energies to 17%(8%)-23%(18%) and 17%(7%)-15%(14%) for $E(^{238}\text{U}) = 5.8$ MeV and 4.3 MeV/u, respectively. At both beam-energies the observed R_{min} -dependence for the atomic e^+ -production appears to be steeper for the lower than for the higher e^+ -energy group. As the opposite behaviour is expected for induced e^+ -emission, our findings could indicate for the first time the presence of an additional positron production process in the U+Cm-collision system at low positron kinetic energies.

Fig. 7: The atomic e^+ -production probability for low and high energy positrons as a function of the distance of closest approach $R_{\min}$ for the U+Cm-collision system at two projectile energies of 5.8 MeV/u (low E_e^+ : 250 keV $\leq E_e^+ \leq 500$ keV; high E_e^+ : 600 keV $\leq E_e^+ \leq 900$ keV) and 4.3 MeV/u (low E_e^+ : 200 keV $\leq E_e^+ \leq 500$ keV; high E_e^+ : 500 keV $\leq E_e^+ \leq 800$ keV).

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In subsequent experiments the Si(Li)-detector discussed in sect. II was employed to measure the e^+ -energies. In these studies we investigated in particular the two critical collision systems $^{238}\text{U}+^{248}\text{Cm}$ ($Z_a=188$) at $E(^{238}\text{U}) = 4.7, 5.9$ MeV/u and $^{238}\text{U}+^{238}\text{U}$ ($Z_a=184$) at $E(^{238}\text{U}) = 5.8, 5.9, 6.0$ MeV/u as well as the (for the range of scattering angles accessible to us) subcritical system $^{238}\text{U}+^{208}\text{Pb}$ ($Z_a=174$) at $E(^{238}\text{U}) = 5.9$ MeV/u. In addition, some low Z systems like $^{238}\text{U}+^{154}\text{Sm}$ have been studied to investigate the nuclear background component. With the exception of the 4.7 MeV/u run the U-beam energies are close to the Coulomb barrier and it is known that at these energies nuclear reactions are starting to occur. The analysis of these data is still in progress. We will therefore concentrate in the following discussion on one aspect of the data which we find particularly exciting.

Figure 8 shows the total e^+ -spectra observed for the two systems $^{238}\text{U}+^{238}\text{U}$ and $^{238}\text{U}+^{248}\text{Cm}$ at $E(^{238}\text{U}) = 5.9$ MeV/u. The spectra are integrated over all observed scattering angles ($20^\circ \leq \theta \leq 70^\circ$) and over all elastic and quasielastic two-body events. We note that these spectra are not corrected for nuclear e^+ -contributions and for the solenoid transport-efficiency, which partly determines the shape of the spectra at lowest and highest e^+ -energies. While the overall bell-shape form of the e^+ -spectra with a maximum around 500 keV is in agreement with earlier findings and theoretical predictions based on Rutherford trajectories for the two collision partners, there seems to exist the exciting possibility of additional peak-like structures. This possibility lead us to a detailed examination of the positron spectra under special kinematic conditions in order to try to elucidate the structure and gain information about its possible origins.

In figure 9b the most striking result for the $^{238}\text{U}+^{238}\text{U}$ -measurement at $E(^{238}\text{U}) = 5.9$ MeV/u is shown. The spectrum was obtained by selecting the time of flight difference and the anode pulse-height corresponding to binary events, by subtracting random events, and by requiring $11^\circ \leq |\Delta\theta| \leq 19^\circ$ and $89.2^\circ \leq \Delta\theta \leq 89.8^\circ$, where $\Delta\theta$

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Fig. 8: e^+ -energy spectra for the system ^{238}U , ^{238}U and $^{238}\text{U}+^{248}\text{Cm}$ at 5.9 MeV/u projectile energy integrated over particle scattering angles between 20° and 70° . The spectra are not corrected for the solenoid transport efficiency and for the line-shape of the Si(Li)-detector. The contribution of nuclear e^+ -production is not subtracted.

and $\Sigma\delta$ are defined by $\Delta\delta = \delta_1 - \delta_2$ and $\Sigma\delta = \delta_1 + \delta_2$, respectively. The kinematic window on $\Delta\delta$ corresponds to selecting events with $35.5^\circ \leq \delta_1 \leq 539.5^\circ$ or $50.5^\circ \leq \delta_1 \leq 54.5^\circ$ if elastic scattering is assumed. These two δ -regions can be considered together because of the symmetry of the experimental set-up around $\Delta\delta=0^\circ$. The window on $\Sigma\delta$ corresponds to slightly inelastic events (note that $\Sigma\delta=90^\circ$ for elastic scattering), and the selected width is equivalent to a Q-value window of about $\Delta Q = 15$ MeV (assuming inelastic scattering with no mass-transfer). With these conditions two peak-like structures centered around positron energies of ~ 320 keV and ~ 590 keV are observed. In connection with the rather narrow Q-window, which amounts to only approximately one third of the experimental Q-resolution it should be noted that these structures are still present - although less pronounced - if a very broad $\Sigma\delta$ -window of approximately 100 MeV centered around the maximum of the observed $\Sigma\delta$ -distribution is selected. The structures are obviously not produced by the Q-cut but rather found to be related to events of slight inelasticity.

In figure 9a the positron spectrum obtained for $25^\circ \leq |\Delta\delta| \leq 35^\circ$ (corresponding to $27.5^\circ \leq \delta_1 \leq 32.5^\circ$ and $57.5^\circ \leq \delta_1 \leq 62.5^\circ$) under otherwise identical conditions to the data in fig. 9b are shown. The shape of this spectrum is in agreement within statistics with the bell-shaped curve one expects theoretically by assuming Rutherford trajectories* (solid curve). By adjusting the height of this spectrum to the experimental one and using the theoretical impact parameter dependence, one obtains the corresponding theoretical spectrum for scattering angles satisfying $11^\circ \leq |\Delta\delta| \leq 19^\circ$, which is represented in fig. 9b by the solid line. The comparison clearly exhibits the additional structure observed in the experimental spectrum for $11^\circ \leq |\Delta\delta| \leq 19^\circ$. This $\Delta\delta$ -dependence itself excludes the possibility that the structure is caused by instrumental effects connected with the e^+ -detection. Moreover, the corresponding X-ray spectra observed for the relevant scattering angles are smooth and do not show any pronounced structure, implying that the structure does not originate from internal pair production. There remains, however, the possibility that there are strong E0-transitions occurring in the decay of the reaction products, which would not be

Fig. 9: Two selected e^+ -energy spectra observed in $^{238}\text{U}+^{238}\text{U}$ -collisions at 5.9 MeV/u and kinematic conditions as explained in the text. The spectra are not corrected for the solenoid transport-efficiency, the Doppler-broadening the Si(Li)-detector line-shape and nuclear background. The solid lines represent the theoretical spectra¹⁸ normalized to the upper spectrum.

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visible in the γ -ray spectrum but might contribute via internal pair production to the measured positron spectrum. However, possible E0-contributions from the decay of Coulomb-excited ^{238}U nuclei can be ruled out as a rather smooth $\Delta\beta$ -dependence is expected in this case in contrast to the observed behaviour. On the other hand, the $\Delta\beta$ - as well as $E\beta$ -dependence of the structure is consistent with expectations for products produced in reactions involving the transfer of a few nucleons. Although it is difficult to conceive how the roughly triangular shapes of e^+ -spectra resulting from the internal pair production of E0-transitions could possibly explain the form of the peaks observed, such an explanation can presently not be excluded.

Besides a possible nuclear origin of the observed structures there exists the possibility that they may signify the production of spontaneous positrons. If the times the collision systems remain critical are prolonged due to nuclear interactions, an enhancement of the spontaneous e^+ -production probability is expected at focused positron kinetic energies¹⁹ although rather long unexpected time delays of up to 10^{-20} sec would be required in this case²⁰ in order to explain the observed line-width of the structure. There may be also an alternative mechanism that could lead to peaked structures. Time delay processes could produce a phase-shift in the excitation amplitudes for dynamic positrons between incoming and outgoing parts of the nuclear trajectory, which would result in an interference pattern in the positron energy spectra²⁰ although again rather long time delays are required.

However, before drawing any far reaching conclusions from the experimental data presented, we feel that the following questions should be solved. First of all one must show by further analysis that the structures are not produced by some yet unknown background effects associated with one of the event selecting criteria. Secondly, the reproducibility of the effect has to be shown and its systematic dependence on Z_{ua} and the incident projectile energy must be studied. Finally it has to be demonstrated that the structures are not related to internal E0-pair conversion. An elegant way to

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distinguish between a quasideuteron and nuclear origin of the structures would be to measure the velocity of the emitting system via the Doppler-shift of the peaks. While the velocity β of the quasideuteron is the velocity of the center of mass ($\beta \approx 0.5$ for $5.9 \text{ MeV/u } ^{235}\text{U}$ impinging on ^{238}U) the velocities of the reaction products depend on β_1 and reach values up to $\beta \approx 0.1$. This different velocity behaviour results in different Doppler-shifts of the peaks when observed as a function of the relative angle between the recoiling reaction products and the $^+$ e $^-$ emission direction.

Obviously the studies of positron production in collision constructed quasimolecules are far from completion, but the present results suggest that their further pursue could lead to exciting insights in both the atomic and nuclear physics of heavy ion collision systems.

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