Strong Field Atomic Processes

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With the construction of UNILAC by Christoph Schmelzer and his team at GSI Darmstadt, it became possible for the first time to accelerate all ions up to uranium to energies higher than the Coulomb barrier for collisions with the heaviest nuclei. This opened in atomic physics a new field of research: the study of atomic processes in strong electromagnetic fields with coupling constants $(Z_1 + Z_2)\,\alpha > 1$ ($\alpha = 1/137$ being the fine structure constant). The strong fields are produced by the charges Z_1 and Z_2 of two colliding heavy nuclei at internuclear distances R which may become as small as the sum of the radii of both nuclei ($R \cong 20$ fm). The Coulomb field is strongly time dependent. Its rate of change (dV_c/dt) is determined by the relative velocities (v) of the nuclei along the collision trajectories, which may amount to about 10% of the speed of light at bombarding energies around the Coulomb barrier. The varying Coulomb field $V_c(Z_1, Z_2, R\,(t))$ may adiabatically transfer energy and momentum to the atoms' electrons thus increasing their binding energies and broadening their momentum distributions, and may simultaneously induce transition processes like ionisation of inner electron shells and the production of electron-positron pairs.

For a slow collision $(v/c) \cong 0.1$, the electron distribution shrinks and the binding energy increases, following adiabatically the decreasing internuclear distance R, to reverse again in the exit phase of the collision. When the internuclear distance becomes smaller than the radii of their charge distributions, so-called quasiatoms are formed with a common K-orbit that for $Z_u = Z_1 + Z_2 = 180$ has a radius of the order of 150 fm (1.5×10^{-13} m). Because of the relativistic increase of monopole matrix elements for Z_u around 180, the binding energies E_b of the K-electrons of quasiatoms increase vertiginously with Z, approaching about Z_u^{20}. When the binding energy becomes larger than 2 m_ec^2 (twice the electron rest mass of 0.511 MeV) for quasiatoms with Z_u greater than a critical value of $\cong 173$, the originally discrete K-state mixes with the negative energy continuum (Dirac sea) and becomes a resonance, spreading its strength over the continuum with a characteristic width Γ.

The binding energy of the K-electron for a quasiatom with $Z_u = 184$ ("double uranium") is expected to be 1.321 MeV with a spreading width $\Gamma = 2$ keV. It has been shown that if such an "overcritical" state is not completely occupied with electrons, it becomes unstable and spontaneously decays by the creation of an electron-positron pair. The electron remains bound in an unoccupied K-state and the positron is emitted with a kinetic energy corresponding to the "diving" energy of the resonance in the Dirac sea. The decay time τ of the overcritical state is connected to the spreading width ($\tau = \hbar/\Gamma$) and is 3×10^{-19} s for the U-U quasiatom.

The non-adiabaticities of the collision caused by the rapidly changing Coulomb field induce transitions during the quasiatom formation and decay. Some relevant atomic processes are illustrated in Fig. 1 in which the time dependence of the internuclear distance $R(t)$ and the total energies of three quasimolecular states formed in central U-U collisions at 5.9 MeV/u bombarding energy are sketched in a semi-classical picture. At the critical distance $R_{cr} \cong 27$ fm, the 1 sσ quasimolecular state dives into the Dirac sea for a short time of about 2×10^{-21} s. The transitions induced lead to ionisation of the quasimolecular or quasiatomic states, which in turn results in the emission of δ-rays (high energy electrons) and the formation of inner shell vacancies. The latter may be filled again by the emission of quasimolecular X-rays if the internuclear distance is still small enough so that the electrons are bound in quasimolecular states, or by the emission of X-rays characteristic of the separated atoms.

A strong rapidly changing Coulomb field may also induce, with small probability, tunnelling transitions from the negative to the positive continuum, thereby creating e^+-e^- pairs. Direct as well as two step transitions *via* intermediate inner shell vacancies have been postulated. However, as the collision time is short in comparison with the time for spontaneous positron emission (unless it is prolonged by nuclear contact) there can be no line spectrum of the positron emissions from this source.

Quasiatomic Processes

The formation of heavy quasiatoms in adiabatic heavy ion collisions was confirmed by studies of the impact parameter dependence of K-hole production, the spectroscopy of the δ-rays emitted, and from the collision kinematics and Z dependence of positron creation.

The first of these came from X-ray-particle coincidence measurements and showed that K-hole production probabilities for Pb + Cm collisions reach values of up to 15% for small impact parameter b, and then drop approximately ex-

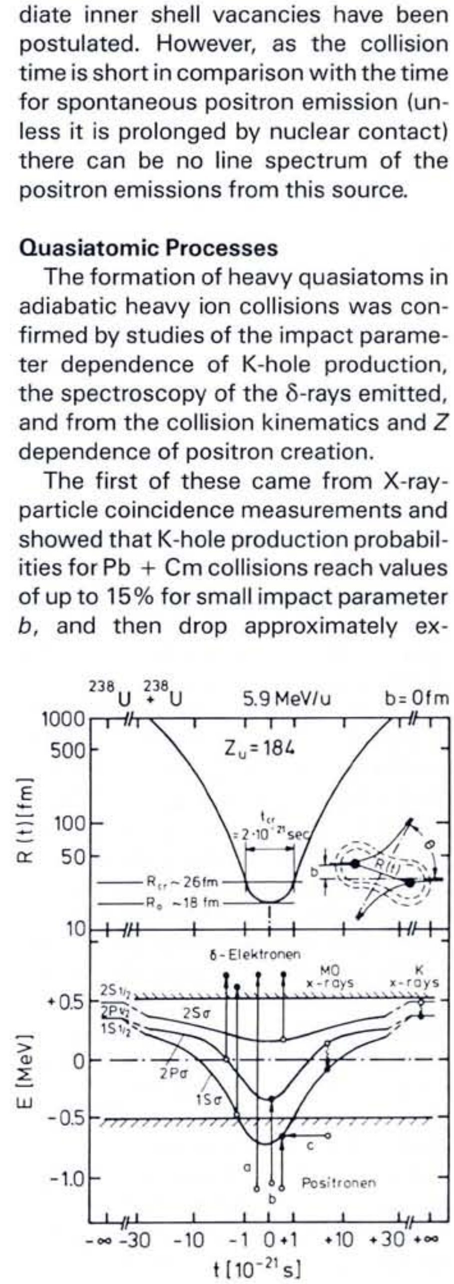

Fig. 1 — Internuclear distance and energies of quasimolecular states as a function of the collision time for a U-U-collision at 5.9 MeV/u and impact parameter b=0.

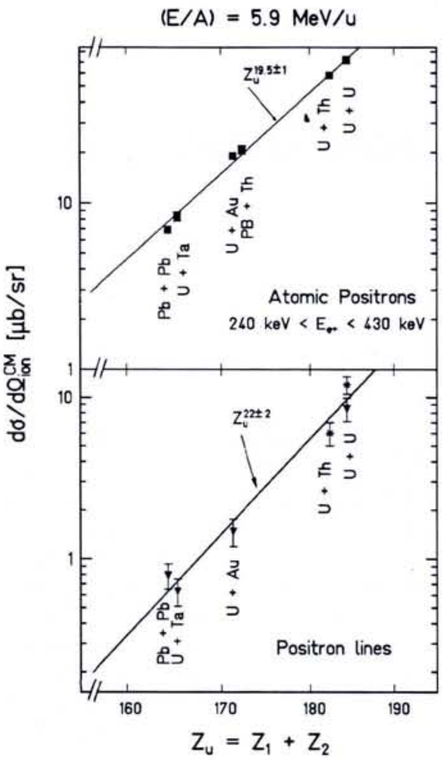

Fig. 2 — Positron continuum and line production cross sections for high Z_u quasiatoms.

ponentially with b or with the distance of closest approach R_o according to a scaling relation:

$$P(R_o) \cong \exp(-2 q_o R_o) \qquad (1)$$

where q_o is the minimum momentum transfer for an energy transfer ΔE in a collision with relative velocity v given by $q_o = \Delta E/\hbar v$. The scaling law implies that the strongly bound electrons (large ΔE) are most probably emitted at small internuclear distances when the quasiatomic states are formed, and that an energy transfer of approximately 1 MeV is required to produce a K-hole. This means that the ionisation occurs preferentially in the quasiatom with $Z = 178$ for which a K-binding energy of about 2 m_ec^2 is expected. The large absolute value of $P(R_o)$ at small R_o reflects the large value of the monopole matrix element due to the relativistic contraction of the electron-wave functions at the origin of a high-Z atom. This feature has been directly observed by measurements of the energy spectra of δ-rays emitted in quasi atomic collisions. They reveal very high energy tails which directly reflect the momentum components expected for a relativistically contracted electron shell with binding energies exceeding 2 m_ec^2. It has been possible to extract from such measurements the form factors of the electron distribution in high-Z quasiatoms.

On the basis of the so-called quasiatomic collision model it has also become possible to understand part of the features of the quasiatomic positron production like the impact parameter dependence governed by the scaling relation (1) for K-hole production. Most important for the development of theories on positron production was the early observation that the production cross-section was proportional to Z_u^n, *i.e.* the atomic number of the quasiatom Z_u raised to a high power n, the exponent reaching values as large as $n = 19.5 \pm 1$, Fig. 2 (upper part). This dramatic dependence on Z made its observation possible for systems with $Z > 160$ despite the presence of an unavoidable background originating from the internal pair decay of nuclear states with energies larger than 2 m_ec^2 populated by Coulomb excitation or nuclear reactions. Exponents as high as $n \cong 20$ had been predicted by theory assuming quasiatom formation during the collision.

Using a semiclassical description of the scattering process and summing all transition amplitudes in a coupled channel treatment along a classical trajectory, one can calculate, with quasimolecular wave functions as basis states, all the observable quantities of inner shell ionisation, δ-ray production and also e^+-creation with the exception of a very puzzling feature of the e^+ spectra which will be discussed below. In order to illustrate the degree of understanding of quasiatomic processes on the one hand and the puzzling deviations on the other, Fig. 3 shows positron spectra from two collision systems U-U and U-Th gained at the same bombarding energy but different scattering angles and thus different distances of closest approach. The background from nuclear excitation (N) is small and has already been subtracted. Curves (a) are theoretical predictions on the basis of the quasiatomic model with a normalization factor of 0.8 for both systems. One notes that the e^+ spectra for both systems taken under quite different kinematic conditions are reproduced quantitatively except the puzzling broad line-like structures around 300 keV. Such line structures were subsequently discovered in a series of heavy collision systems as illustrated by data from the EPOS collaboration (cover illustration).

Monoenergetic Positron Lines

High resolution data of positron spectra produced recently by the Orange collaboration at GSI have made it possible to resolve a series of e^+ lines with energies between about 260 and 410 keV which in earlier measurements appeared mainly as a broad structure. The lines were observed in heavy collision systems like U-U but also in subcritical ones ($Z_u < 173$) like Pb-Pb ($Z_u = 164$) in which spontaneous pair creation, an originally suggested source of such lines should not occur. The line energies seem to be independent of the system. As an illustration of the data from subcritical systems, Fig. 4 shows high resolution e^+ spectra from U-Au and Pb-Pb collisions which were added together to improve the statistics. Superimposed on a continuous spectrum, composed of the nuclear background and the quasiatomic positrons, lines appear at energies of 260 keV and 340 keV with possible indications at higher energies. Such lines were seen in a series of collision systems in which quasiatomic positrons could also be identified above the nuclear background with a relative strength independent of Z. This means that the e^+-line production cross-section also rises as Z_u^n ($n = 22 \pm 2$), similar to the continuous part of quasiatomic origin in the energy regime of 240 keV $< E_{e+} <$ 430 keV, in which the lines appear. There is also evidence that the dependence of the e^+-line production cross-

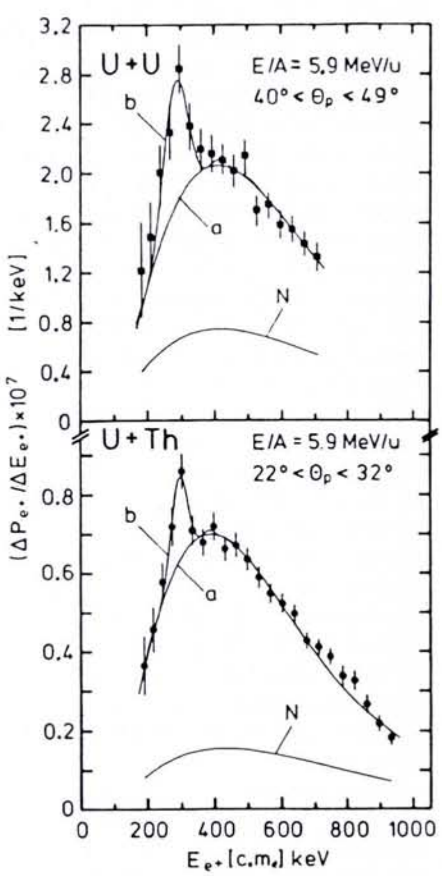

Fig. 3 — Positron spectra of U-U and U-Th collisions at 5.9 MeV/u bombarding energy in coincidence with heavy ions detected in scattering angular ranges indicated with nuclear background subtracted. Curves (a) are quasimolecular calculations with normalization factors 0.8.

section on the distance of closest approach R_0 and relative velocity v follows the scaling relation (1) as all the other quasi atomic processes. Thus there exist strong indications that the source of the e^+ lines is the strong rapidly changing Coulomb fields acting in the quasiatoms, not nuclear processes. Nuclear origins are also excluded in a direct way by the failure to detect other decay channels (γ-rays and conversion electrons) especially in Pb-Pb collisions where the nuclear background is small and very well understood. The narrow

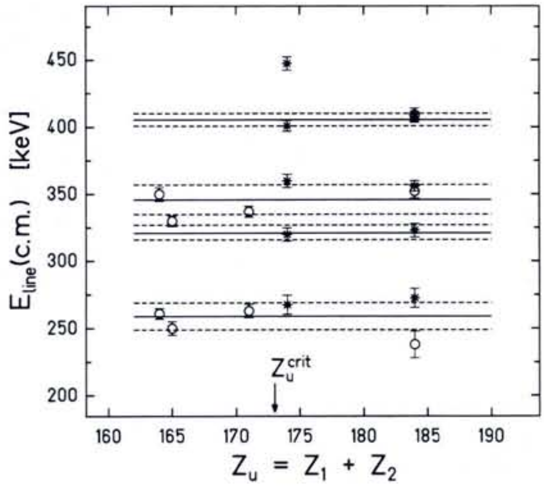

Fig. 5 — Plot of half of the energies (c.m.) of the sum lines from this work (*) together with the energies of the single e^+-lines found previously (○) versus Z_u. For all systems studied, the data suggests at least four common lines with mean energies of: (259±10) keV, (321±6) keV, (346±5) keV and (405±5) keV. There is also an indication for a fifth line around 450 keV. These average energies together with their corresponding statistical uncertainties are illustrated by the full and dashed lines, respectively.

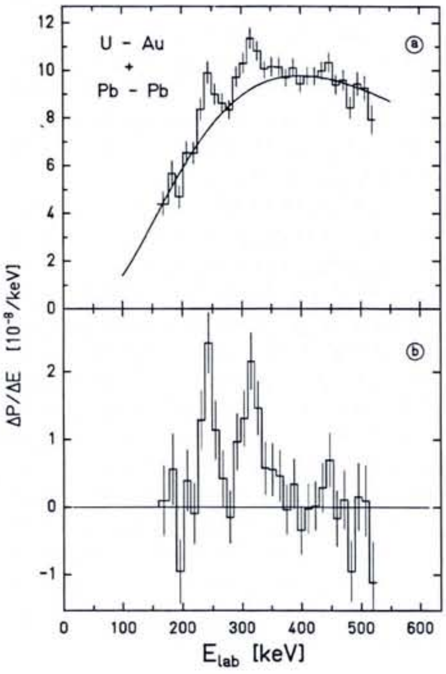

Fig. 4 — Positron spectra from summing the U-Au and Pb-Pb results (a) and after subtraction of the sum of the smooth contributions from nuclear and quasi molecular transitions (b).

line width < 30 keV indicates that the source of the e^+ lines lives longer ($\tau > 5 \times 10^{-20}$ s) than the quasiatom in which it is formed and that its velocity distribution in the centre-of-mass system is narrow ($\Delta(v/c) \cong 0.03$).

A summary of the energies of the e^+ lines as observed by high resolution e^+ single and e^+e^--coincidence measurements, which will be discussed below, is given in Fig. 5 for quasiatomic systems with atomic numbers ranging from 164 to 184. The lines seem to appear in several groups with energies independent of Z_u. There is no complete consistency between the three independent data sets shown in Fig. 5 but this might be due to insufficient statistics in all parts of the spectra available up to now. Nevertheless about five groups of Z_u independent e^+-lines centred around (259±10) keV, (321±5) keV, (346±5) keV, (405±5) keV and (450±10) keV are indicated although not all of them have been clearly observed in all systems investigated. For spontaneous e^+-production in high Z quasiatoms one would expect a single line with a Z_u^{20} energy dependence and no lines for quasiatoms with $Z_u < 173$. Thus it is not possible to assign at this point any of the observed lines to spontaneous positron production.

Monoenergetic e^+e^- Pairs

In the first e^+-e^- coincidence measurements performed by the EPOS collaboration, energy correlated e^+ and e^--lines were observed with kinematic characteristics expected for a two body decay of neutral particles produced with a small kinetic energy distribution in the centre of mass (c.m.) of the quasiatomic collision system. As shown in Fig. 6, the e^+-e^- coincidence spectra show narrow lines in the sum-energy spectra ($E_{e^+} + E_{e^-}$) and broader lines in the difference energy spectra ($E_{e^+} - E_{e^-}$) although the positrons and electrons were detected over a wide angular range perpendicular to the beam. In a scenario in which a neutral particle is produced with only a modest range of velocities in the c.m. system of the collision (moving with $v/c \cong 0.05$ in the direction of the beam) and decays into an e^+-e^- pair, after the quasiatom has already disappeared, one would indeed expect a narrow sum line and a broad difference line. In the sum the Doppler shifts of positrons and electrons emitted from the neutral particle moving along the beam direction with c.m. velocity would cancel to a first order whereas in the difference spectrum they would add up.

In order to put this puzzling particle hypothesis to a test, the Orange collaboration measured the momentum correlations of the e^+e^- pairs produced in quasiatomic collisions using a double orange spectrometer. This allowed them to determine the momentum vectors of the positrons and electrons from which invariant mass spectra can be deduced.

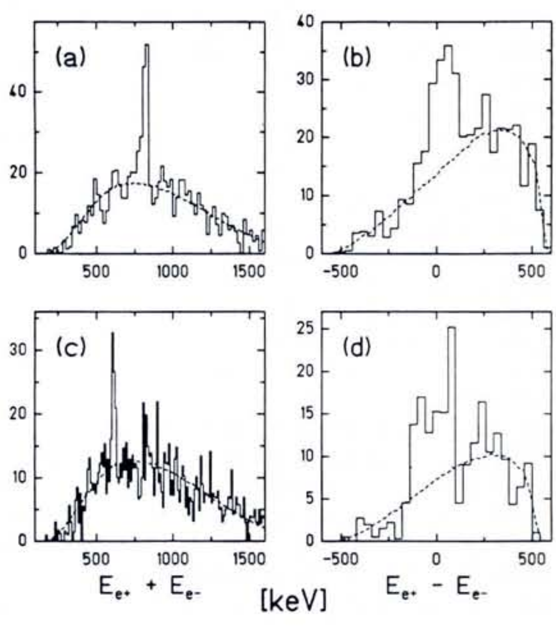

Fig. 6 — The sum energy from e^+-e^- coincidence measurements in U-Th collisions at beam energies around 5.87 MeV/u (left part) is significantly narrower than the corresponding energy difference peaks (right part).

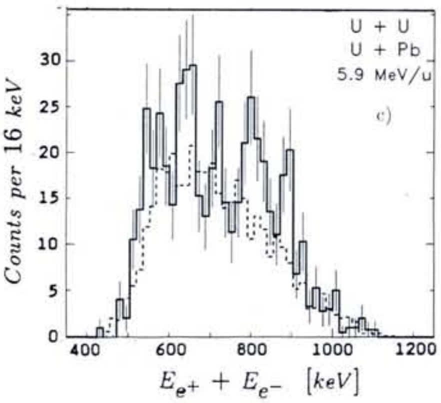

Fig. 7 — The combined (e^+e^-) sum-energy ($E_{e+} + E_{e-}$) spectra obtained for U+U and U+Pb collisions at 5.9 MeV/u, integrated over negative energy differences −150 keV ≤ ($E_{e+} + E_{e-}$) ≤ 0 keV. The full lines correspond to the opening-angle bin of (180±20)°, while the dashed lines display the remaining opening-angle range of observation (40° ≤ $\theta_{e^+e^-}$ ≤ 170°). The latter spectra were normalized to the solid angle of the 180° bin and corrected with respect to the expected anisotropy of (e^+e^-)-uncorrelated emission.

Fig. 7 shows the e^+e^- sum-energy spectra for U-U and U-Pb collisions, which were added together, because both collision systems showed indications of lines at similar energies. For the histogram with solid lines a constraint was set on the e^+e^- opening angle, $\Theta_{e^+e^-} = (180 \pm 20)°$ thereby selecting events in which the positrons and electrons were emitted back to back. By setting a window in the energy difference of the Doppler shifted e^+ and e^- spectra only those decays from a source which moved approximately with the centre of mass velocity could be picked out. The dashed line histogram is obtained from the sum-energy spectra of e^+e^- pairs with $40° < \Theta_{e^+e^-} < 150°$ after proper normalisation of the solid angles and a small correction for the known emission anisotropy of quasi atomic and nuclear pairs.

In the sum-energy spectrum of e^+e^- decays centred around $\Theta_{e^+e^-} = 180°$, which is approximately equivalent to an invariant mass spectrum, several lines superimposed on a smooth background are indicated. Yet the e^+e^- sum-energy spectrum for $40° < \Theta_{e^+e^-} < 150°$ taken with better statistics shows a completely flat distribution and can be reproduced by a Monte Carlo simulation for uncorrelated pair production. Also 180° sum-energy spectra taken at energy differences, for which one expects internal pair conversion as the main contribution show no lines. Thus we conclude that lines in the invariant mass spectrum do not originate from nuclear decays. Their characteristics fulfil all criteria for a two body decay of a series of neutral resonances with invariant masses of 1.56, 1.66, 1.74 and 1.92 MeV/c^2. Most of these lines have corresponding e^+ single lines observed independently also in other collision systems.

In view of the limited statistical significance (3-4 standard deviations) the results need confirmation, but if they are confirmed, they point to the existence of narrow resonances in the e^+e^- continuum, which could be excited states of an extended neutral particle.

Search for Resonances in Bhabha-Scattering

Various searches for resonances in the e^+e^- continuum have been performed recently by scattering monoenergetic positrons from weakly bound electrons, notably at the high flux reactor of ILL in Grenoble. Resonant Bhabha scattering is a very interesting way of producing them because the sensitivity is independent of details of form factor and structure and is determined by the resonance strength and the energy resolution only. From the integrated cross-section measured at a resonance energy of 1.83 MeV and scattering angles around 90° we obtained a limit for the resonance width of $\Gamma < 1.9$ meV assuming a resonance with zero spin. This corresponds to a life time limit $\tau > 3.5 \times 10^{-13}$ s which is a factor of two lower than the most stringent bounds derived for the contribution of a hypothetical point-like scalar particle of about 1.8 MeV/c^2 mass to the precisely measured (g-2) factor of the electron. Nevertheless one should note that there is still a large life time range for these resonances of 10^{-10} s $< \tau < 3.5 \times 10^{-13}$ s not yet covered by Bhabha-scattering experiments. Thus further more sensitive searches are needed.

Summary and Theoretical Aspects

In summary, one notes that the study of high field processes in adiabatic heavy ion collisions has shown that high Z_u quasiatoms are formed and that striking properties of their binding energies, form factors and monopole matrix elements could be extracted from K-hole ionisation probabilities, δ-ray and positron spectra. In particular the characteristics of the continuous part of the positron spectra (atomic contribution) is quantitatively explained by the theory of quasiatom formation and strong transient fields.

On the other hand there is not yet a theory for the origin of the narrow positron lines. Most likely the observed lines originate from the two-body decay of neutral particles which are produced by the time changing Coulomb field. Various models for new particles have been suggested. Those which assume point-like elementary particles could be discarded by a series of experiments tailored to look for them. Models based on composite, extended particles with certain modes of excitation can reproduce the observed mass spectrum. They assume that a linear potential $V(\vec{r}) = \lambda r$ acts between charged constituents as in string models of hadrons. It is possible to reproduce with one value of the string tension λ all five lines indicated in the mass spectrum surprisingly well. The mean square radii of these resonances should range between 1000 and 2000 fm, which would also explain why they have not been observed in high energy collision processes.

In some of the models it is conjectured that the new particles are formed in a new QED confining phase which may be generated by the high Coulomb field. Unfortunately there are controversial theoretical arguments about the existence and the formation of such a phase. In this situation more theoretical insight into the relativistic interaction problem is needed and even more important, experimental verification of the suggested mass spectrum. If its existence should be confirmed, a more detailed study of the production process, the decay of these states and their interaction with matter must be undertaken.

FURTHER READING

Greiner W., Müller B. and Rafelsky J., *Quantum Electrodynamics of Strong Fields* (Springer, Berlin-Heidelberg) 1985.

Kienle P., 'Positrons from Heavy Ion Collisions', *Ann. Rev. Nucl. Part. Science* **36** (1986) 605.

Cowan T. and Greenberg J.S. in *Physics of Strong Fields*, ed. W. Greiner, Series B: Physics Vol. 153 (Plenum Press, New York) 1987, p. 111.

Berdermann E. *et al.*, 'Monoenergetic (e^+e^-) Pairs from Heavy Ion Collisions', *Nucl. Phys. A* **488** (1988) 683c.

Tsertos H. *et al.*, 'Sensitive Search for Neutral Resonances in Bhabha Scattering around 1.8 MeV, *Phys. Lett. B* **207** (1988) 273.

Chodos A., 'Narrow e^+-w^- Peaks in Heavy Ion Collisions: Fact and a Fancy, Comments', *Nucl. Part. Phys.* **17** (1987) 211.

Peccei R.D., 'A New Phase for an Old Theory', *Nature* **332** (1988) 492.

Müller Berndt, 'Quantum Electrodynamics (QED) in Strong Coulomb Fields, Charged Vacuum, Atomic Clock and Narrow Positron Lines' in *Atomic Physics of Highly Ionized Atoms*, ed. R. Marrus (Plenum Press, New York) 1989.