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INVESTIGATIONS IN ATOMIC PHYSICS BY HEAVY ION PROJECTILES

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1. What happens to an atom in a high energy heavy ion collision?

In every nuclear reaction process when any target is bombarded by a heavy ion beam, not only nuclear but also atomic processes are present /even at GeV impact energies; e.g. in ref. 1-2/ as a result of the interactions of the projectile ions with the atoms of the target which contains atoms /maybe in molecular or solid connections/ in every case, but no bare ions in general. By investigating the particles coming out of these atomic processes /ion-atom collisions/ very valuable atomic physics information can be obtained. /Out of the numerous good surveys in this field we refer here to three recent edited volumes including several excellent papers[3-5]./

If a heavy ion impacts on an atom, the following atomic processes will take place as a consequence of the interactions among the electrons of the target atom and the /screened/ projectile nucleus and similarly among the electrons accompanying the projectile and the /screened/ target nucleus as well as among the electrons of the projectile and the target:

- excitation or ionization of the /recoiled/ target atom /with a simultaneous emission of an electron of continuous energy distribution in the latter case/,
- excitation or ionization of the /scattered/ projectile /with a similar electron emission as above/,
- a capture of electrons by the projectile from the electron cloud of the target atom /and vice versa if the target is also an ion/. It is shown schematically in Fig. 1.

Thus, there are processes which take place in the collision itself /see above/ but monoenergetic /Auger/ electron and X-ray /as well as light/ emission also appear after the collision during the deexcitation of the ions /atoms/ involved in the collision.

The next question is what can be measured when studying the ion-atom collisions. Electrons, electromagnetic radiations, heavy ions come out from the collision and the following measurements can be carried out on them:

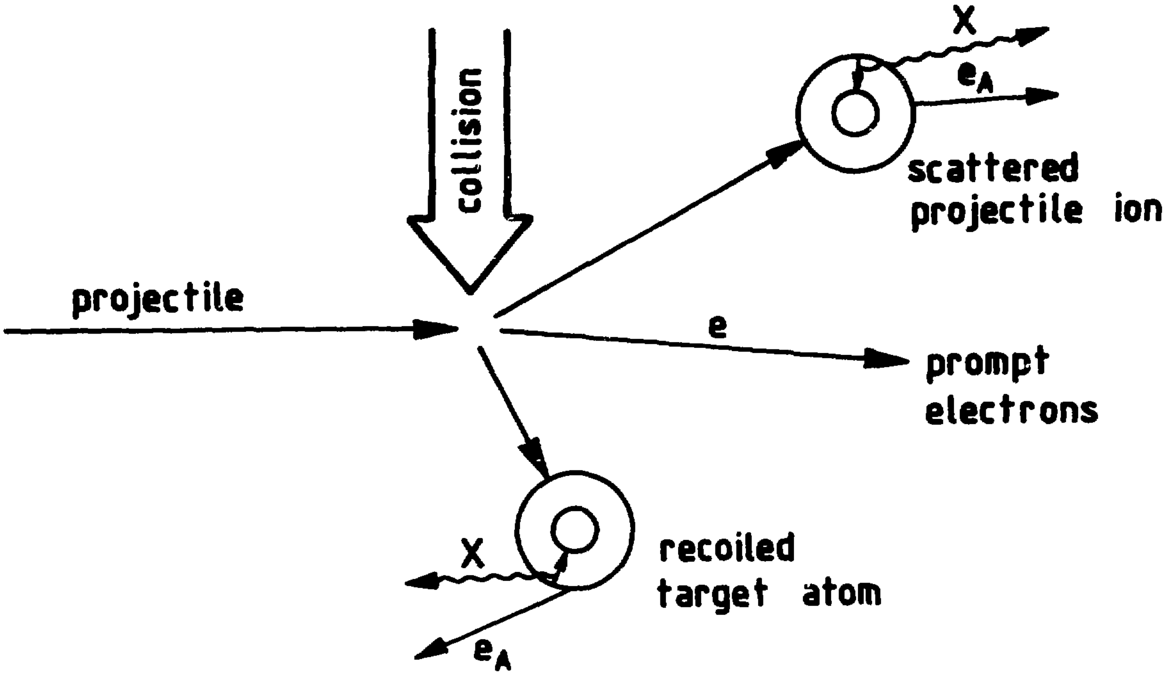

Fig. 1. A sketch of an atomic collision.

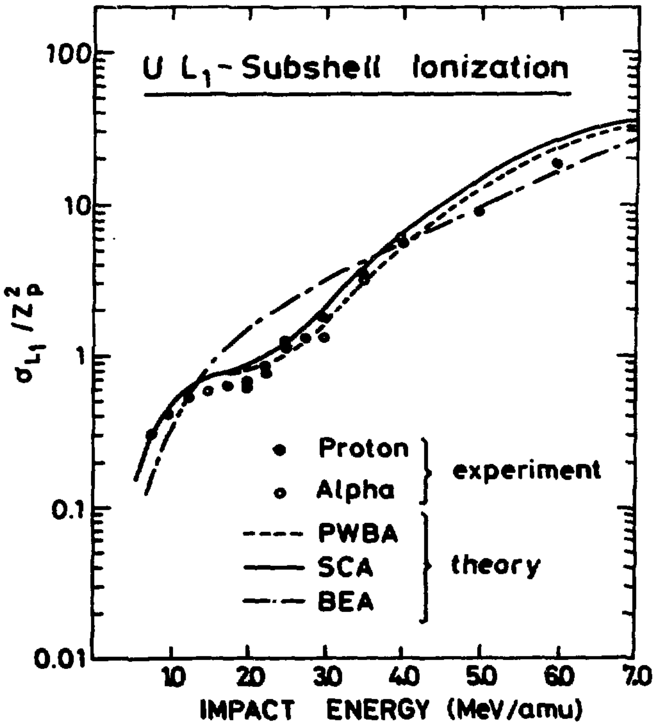

Fig. 2. Comparison of the experimental ionisation cross-section data and the different approximations in the frame of the direct Coulomb interaction model in a concrete collision /after ref. 10 and 11/.

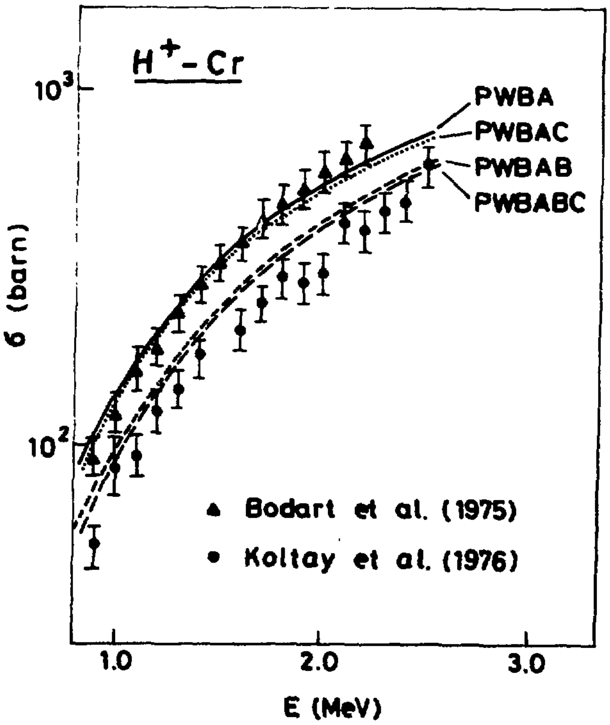

Fig. 3. Demonstration of the effect of Coulomb deflection /PWBAC/ and binding energy /PWBAB/ corrections and those together /PWBABC/ /from ref. 19/.

electrons X-rays[x]	energy and angular distribution, polarization state
ions /scattered and recoiled/	energy and angular distribution, charge and excitation state.

The probability of a certain process can be determined /cross sections/ as a function of the type, energy, charge and excitation state of the projectile. The coincidence measurements /including the delayed ones/ are also very informative /e.g. between X-rays and projectiles scattered into different directions for studying impact parameter dependence of inner shell vacancy production/.

In the present survey I do not intend to go into the instrumental details and so I refer here to an excellent recent review on the techniques of Auger electron and X-ray spectroscopy in energetic ion-atom collison[7] which covers a substantial part of the related experimental techniques.

It seems to be useful, however, to mention here that usually three regions of impact energies, or to be more accurate, velocities are distinguished, namely low /$v \ll v_0$/, intermediate /$v \sim v_0$/ and high /$v \gg v_0$/ velocity region /v_0 is the Bohr velocity/.

2. What information can we get on the atom from the study of the collisions concerned?

There are three main groups of issues on which information can be obtained by studying the high energy ion-atom collision processes. They are as follows:

- collision mechanism,
- structure of highly ionized and excited atoms,
- fundamental issues /e.g. test of quantum electrodynamics in the strong field domain, superheavy quasiatoms/.

In this section the first two groups will be treated in some details while a separate section is devoted to the third one.

It is worth-while mentioning here that the significance of the field concerned is due not only to the physical point of view;

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[x] Continuous electromagnetic radiation is also emitted in the collisions /see e.g. ref. 6/.

without it e.g. it is impossible to understand a number of processes in astrophysics and the importance of these phenomena is more and more increasing in the controlled thermonuclear research as well /cf. inertial confinement by heavy ions/.

2.1. Collision mechanism.

To have an unifying model for the explanation of all the phenomena of ion-atom collisions seems to be far away. Now there are different models which are valid only in a certain region of the projectile energy and charge state as well as the atomic number of the projectile and target atomic number. Furthermore, to explain some special processes in this field, additional mechanism should be supposed /e.g. for the explanation of the so-called "cusp" in the velocity spectrum of electrons emitted in ion-atom collisions in forward direction with an energy corresponding to the projectile velocity; cf. e.g. shortly in ref. 8 and in detail in ref. 9/.

In the present review only the most important collision mechanisms will be shown shortly.

2.1.1. Direct Coulomb interaction.

If

$$Z_p << Z_t$$

/Z_p and Z_t are atomic number of the projectile and the target, respectively/ and/or

$$\frac{v_p}{v_s} > 1$$

/v_p and v_s are the velocity of the projectile and that of the electron in the shell in question of the target atom/, then the excitation and ionization of the target atom can be interpreted by the Coulomb interaction between the projectile and the electrons of the target atom. In this model the projectile is regarded as a point charge and the interaction is treated as a perturbation of the atomic states of the target.

The actual calculations in the frame of this collision mechanism can be carried out in the terms of different approximations, as e.g. PWBA /= plane wave Born approximation/[12], BEA /= binary encounter approximation/[13], SCA /= semiclassical approximation/[14], PSS /= perturbed stationary state approximation/[15/] which all have their region of validity and each of them can describe the experimental data by the direct Coulomb mechanism only if some further conditions are satisfied. We will not go into the details here, but as an example we mention the case of BEA. In this approximation the collision is treated as a classic /Rutherford/ encounter between the projectile and one of the bound electrons of the target. The interaction between this electron and the target nucleus is taken into consideration by the velocity distribution of the electron in the corresponding nuclear field /this is the only quantum-mechanics in this approximation/. An example how the different approximations work is illustrated in Fig. 2.

To the above approximations different corrections are needed, such as the Coulomb deflection[16/] of the impact ion in the field of the target nucleus, the modification of the binding energy[17/] as a consequence of passing through the projectile inside the orbital in question, the relativistic effect[18/] for bound electrons of the target. There are additional corrections as well. In Fig. 3 an example is given for the comparison of the experimental data and the calculations with different corrections.

2.1.2. Quasi-molecular collision mechanism. If both collision partners have high Z and

$$v_p < v_s$$

then the experimental data can be interpreted by the supposition of a transient molecule /atom/ during the collision[20,21/]. Fig. 4 shows the energy level structure as a function of the interatomic distance. The ionization and excitation are produced here due to the so-called electron promotion, i.e. electrons are promoted from their original level to vacant higher-lying levels of the combined system. When the two colliding atoms /ions/ are separating, they do not return back to their original level.

Figure 5 shows the region of validity of the direct Coulomb interaction and the quasi-molecular collision mechanism for different collision systems. It is visible that for Ne-Ne collision the overwhelming role of the direct mechanism starts from about several MeV, while for Kr-Kr it is from about several hundred MeV incident energy.

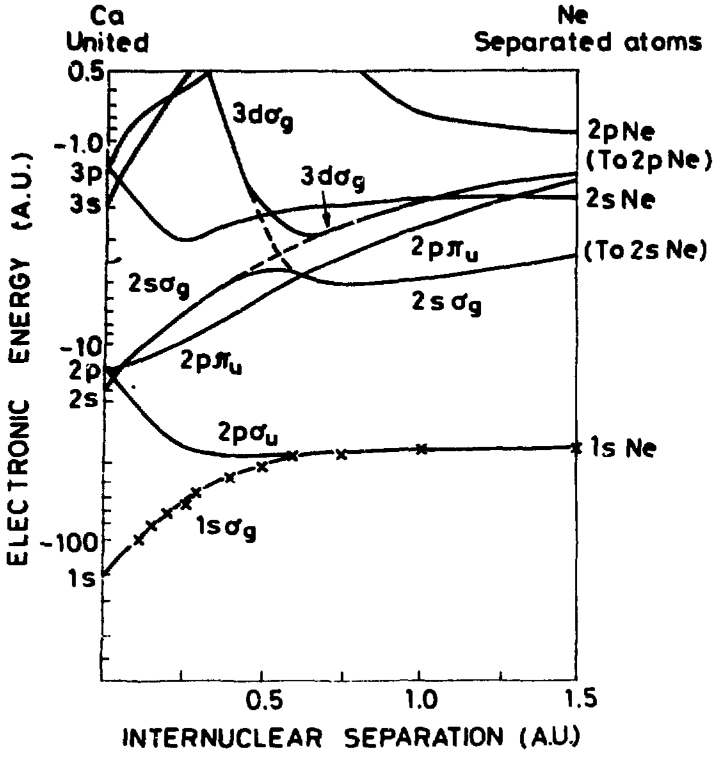

Fig. 4. Level diagram for the Ne-Ne collision system /after ref. 22/.

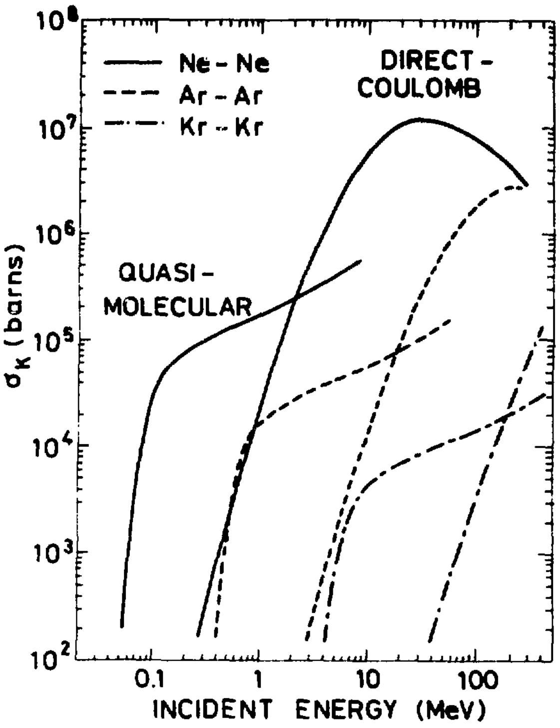

Fig. 5. The regions of validity of the direct Coulomb and the quasi-molecular collision mechanism /after D. Burch in ref. 23/.

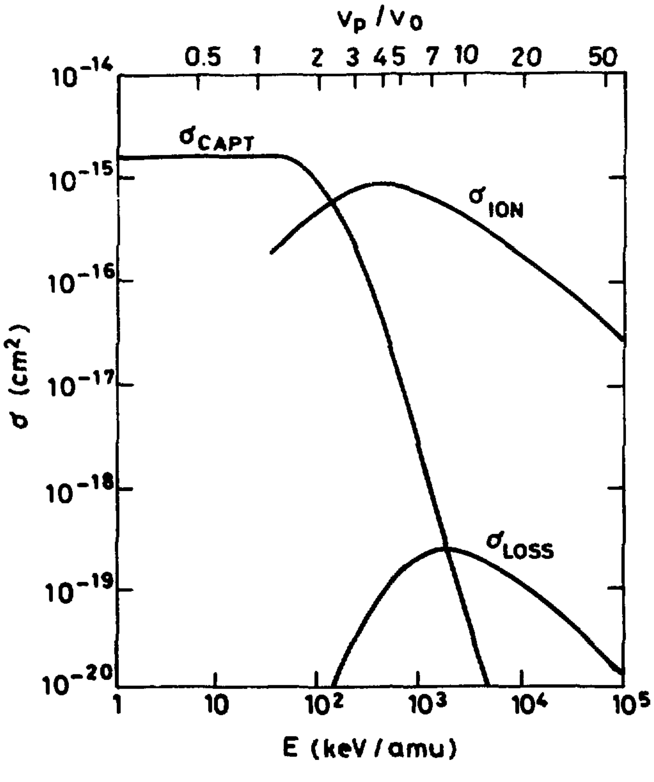

Fig. 6. Cross sections for electron capture by the projectile ion, for the ionization of the target atom and for the loss of the projectile electron in the case of the O^{7+}-He collision /from ref. 28/.

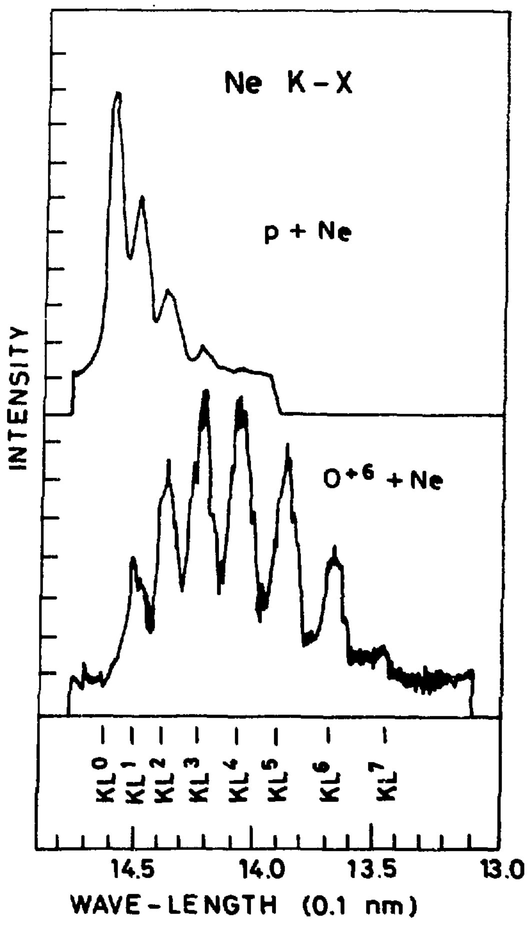

Fig. 7. Ne K X-ray spectra at 500 keV proton and at 35 MeV O^{6+} impact. /after ref. 29/.

2.1.3. Other collision models.

There are different additional mechanisms the region of validity for which is more limited than that of the models above.

Here some of these models will be just mentioned. Thus there is a possibility for a process in ion-atom collision in the course of which the projectile ion captures the electron/s/ from the electronic cloud of the target atom /charge exchange/[24/]. The electron loss phenomena for projectiles carrying bound electrons can be treated in the center-of-mass system by direct Coulomb mechanism[25/]. Depending on the velocity, the atomic number and the charge state of the projectile, a multiple ionization of the target atoms occurs[26,27/]. In Fig. 6 an example is given for the variation of the cross section for loss, capture and target ionization /by the direct Coulomb ionization/ mechanism as a function of the impact energy in the case of O^{7+}-He collision.

Finally still only one more mechanism should be mentioned, namely the charge transfer to the continuum /CTC/ i.e. electron capture to the continuum states of the projectile. By these models the cusp-like peak /mentioned in the beginning of this section/ at the electron velocity equal to the projectile velocity in forward direction has been tried to be interpreted /cf. in. ref. 9/.

2.2. The structure of highly ionized and excited atoms.

Originally the atomic physics contained first of all the phenomena connected with the valence electrons based on the experimental results of optical spectroscopy and the X-ray processes, with one vacancy in the whole electron cloud of the atom. Due to the study of ion-atom collision and the application of accelerators in the investigation of atomic phenomena, in some way the whole atomic cloud became the subject of atomic physics. In these studies information can be obtained on the behaviour of atoms in collisions /collision mechanism; see the former subsection/, and on the structure and on the different processes in multiply ionized atom, including e.g. hydrogen-, helium- or lithium-like heavy ions,i.e. ions with the nucleus of a heavy atom having only one, two or three electrons as in the case of H, He or Li atoms. It is worthwile to mention here, however, that in many cases any rigid separation of the phenomena, connected to the collision mechanism from those of the subsequent decay /atomic structure/ processes, is not possible.

In the following some of the characteristic phenomena of highly-ionized atoms will be shortly introduced.

2.2.1. Satellite structure. If there is a single vacancy in the inner shells of the atom, the so-called diagram lines are produced in the X-ray and Auger spectra. If there are other vacancy/s/ in addition to the hole resulting in the diagram lines, satellite lines can be observed beside the diagram lines in the spectra. Fig. 7 shows the difference in Ne K X-ray spectra, depending on the type of the projectile /proton or O^{6+}/.

The satellite structure depends also on the charge state of the projectile i.e. if only the charge state and not the type of the projectile changes /see Fig. 8 illustrating the Ne Auger spectra for Ne^{3+} and Ne^{10+}/. The calculated energy values of the diagram and satellite lines of the Auger spectra of Ne, having a single K-shell vacancy for all possible ionization states of the target atom after the collision are given in Fig. 9.

A special type of the satellites both in the X-ray and the Auger spectra is the so-called hypersatellite. These are the X-rays or Auger electrons in a transition in which the initial state has double K-shell vacancy. In Fig. 10 Ne K Auger spectra are shown for F^{7+}, F^{8+} and F^{10+} impact. The hypersatellites can be observed only in the case of F^{10+}.

2.2.2. One-, two- and three-electron systems. Especially interesting cases of the multiply ionized atoms are those in which only one, two or three electrons remain around a heavier nucleus. These are the hydrogen-, helium- and lithium-like heavy atoms. In Fig. 10 e.g. one can see an individual peak on the low energy side of the spectrum which corresponds to Auger transitions in a Li-like Ne. This peak is observable only at F^{9+} impact here i.e. in the case of bare projectile.

Fig. 11 shows the X-ray spectrum near the Lyman series limit in H-like oxygen. The $\gamma, \delta, \varepsilon$ peaks correspond to the hypersatellites, while the peak at the series limit /high energy end/ are enhanced at relatively long time after excitation, i.e. it corresponds to metastable states.

In Fig. 12 the Li Auger spectrum /excited by 100 keV protons/ and the Auger spectrum of Li-like Ne /excited by 200 MeV Xe^{31+}/ are given for comparison. It should be mentioned here that the angular

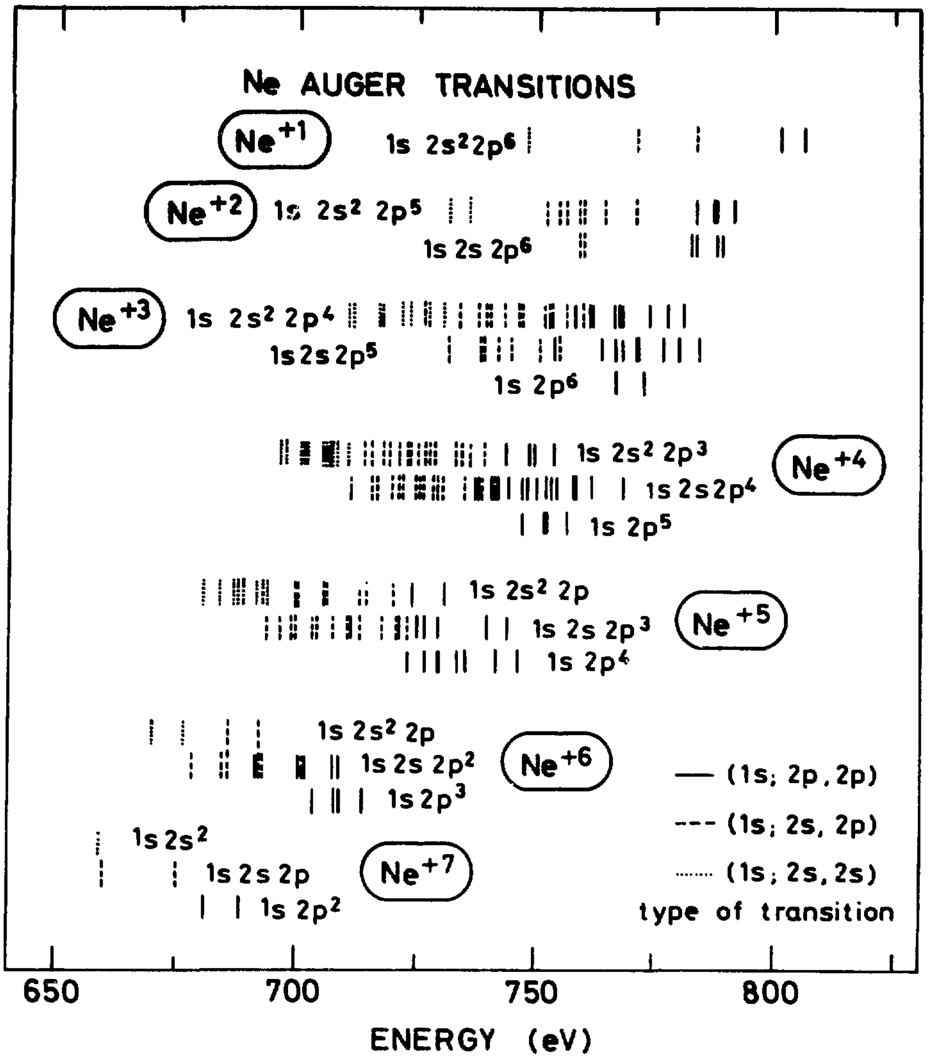

Fig. 9. All possible diagrams and satellite K-Auger transition energies for Ne /from ref. 31/.

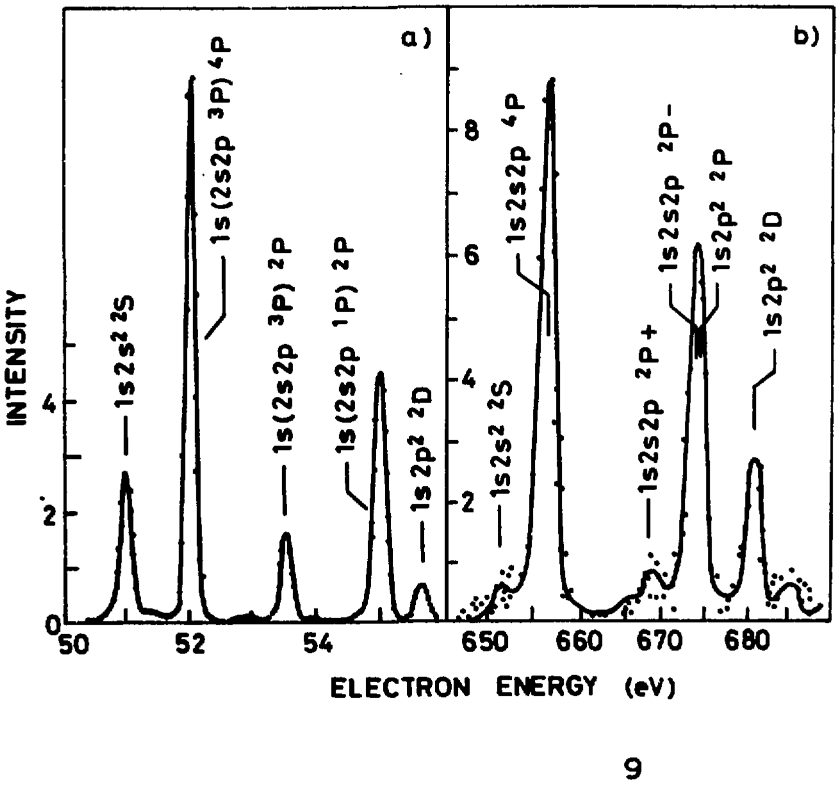

Fig. 12. a: Auger /autoionization/ spectrum of Li /100 keV p impact/; b: Auger spectrum of Li-like Ne /200 MeV Xe^{31+} impact/ /after ref. 34 and 35/.

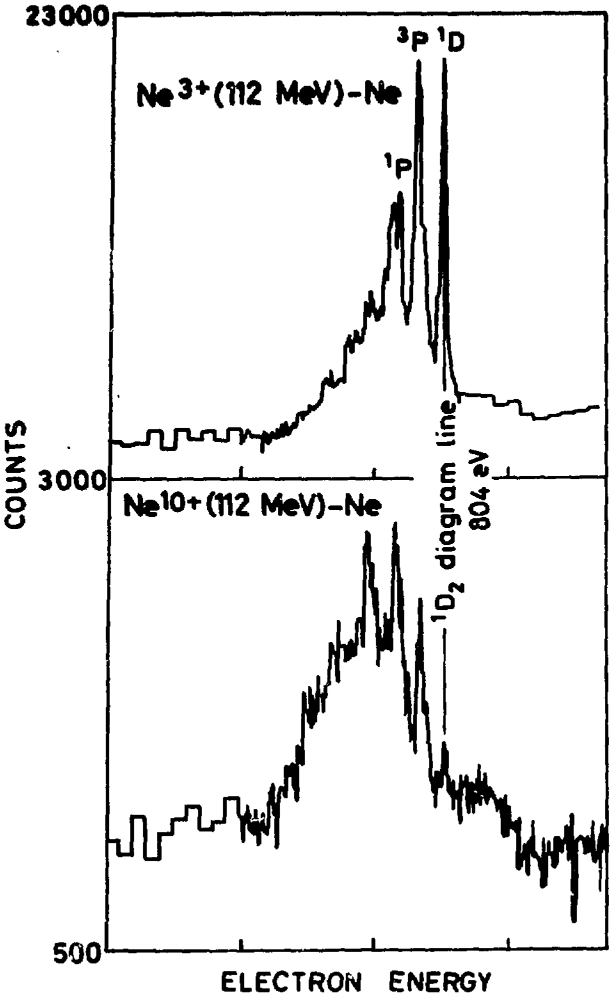

Fig. 8. Ne K Auger spectra for Ne^{3+} and Ne^{10+} projectile /ref. 30/.

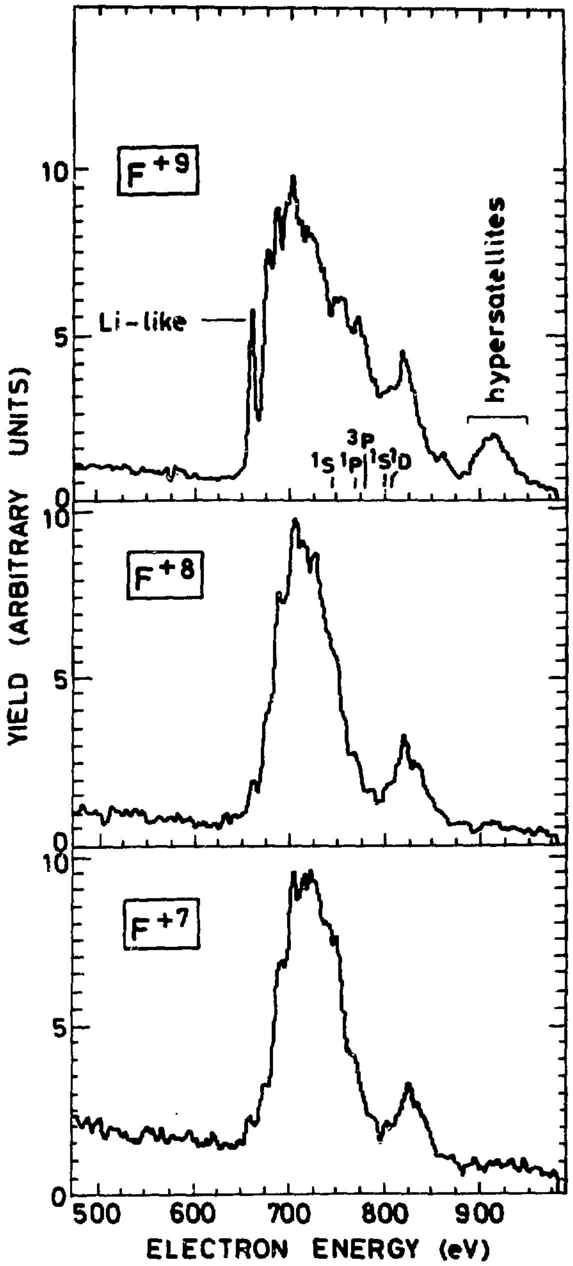

Fig. 10. Ne K Auger spectra for 25 MeV F^{7+}, F^{8+}and F^{10+} impact /ref. 32/.

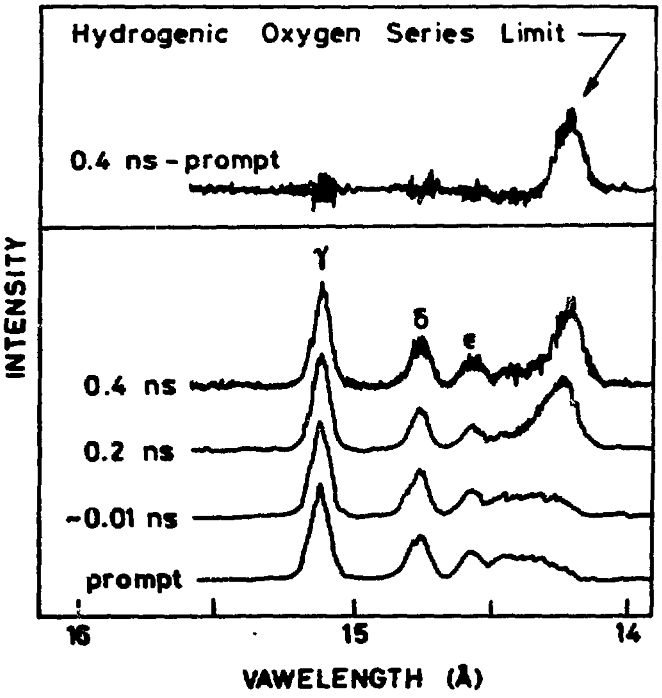

Fig. 11. X-ray spectra in the region near the series limit of hydrogenic oxygen Lyman series as a function of observation time after excitation /from ref. 33/. The uppermost spectrum is a difference of the spectrum taken at 0.4 nsec and the prompt spectrum.

distribution measurements for the Auger electrons in the latter case proved that the magnetic sublevels of the states are populated differently[35].

2.2.3 Fluorescence yields. If a number of electrons is missing from the electron cloud, a change in the fluorescence yield can be expected. This phenomenon was studied by several authors[36-38]. Fig. 13 shows the variation of the K fluorescence yield for Ne as a function of the L-shell vacancies. One can see how strongly the fluorescence yield at high charge state ions increases, and how relatively big differences are between the theoretical and semiempirical /deduced from experiments/ values[38].

3. What can we know on the fundamental issues?

The high energy ion-atom collisions can give us information not only on the collision mechanism and on the structure of the highly ionized atoms but some knowledge of fundamental interest can be also obtained from the different studies on them. Three of such issues will be treated here shortly, namely the Lamb shift of H-like heavy ions, the superheavy quasi-atoms and the positron production in supercritical fields.

3.1. Lamb shift in H-like heavy ions. The importance of heavy ions having only a few electrons have been shown above from the point of view of the knowledge of the structure of highly excited atoms. The comparison of the experimental and theoretical values of the Lamb shift, i.e. the $2S_{1/2} - 2P_{1/2}$ level splitting /Fig. 14/ for high-Z hydrogenic /or He-like/ atoms, however, is the most precise and sensitive test of the validity of quantum electrodynamics in strong fields[39].

To test the quamtum electrodynamics in this way there was a systematic effort in the last decade to extend the measurements upward in Z, i.e. for stronger fields. There are now experimental date e.g. for P^{14+} [40], Cl^{16+} [41] and recently even for Fe^{25+} [42] with an error of about 1 per cent or less. Only smaller deviations were found from the theoretical calculations which might be due to other as QED terms in most cases.

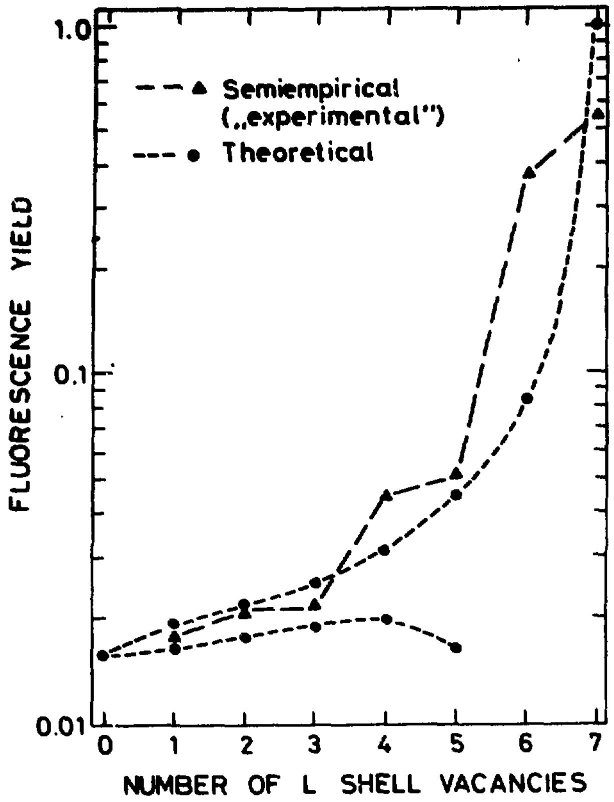

Fig. 13. Variation of K fluorescence yield for Ne as a function of the number of L-shell vacancies /ref. 38/. Semiempirical values are deduced from experiments. The lower theoretical values correspond to the states with no 2s subshell vacancies.

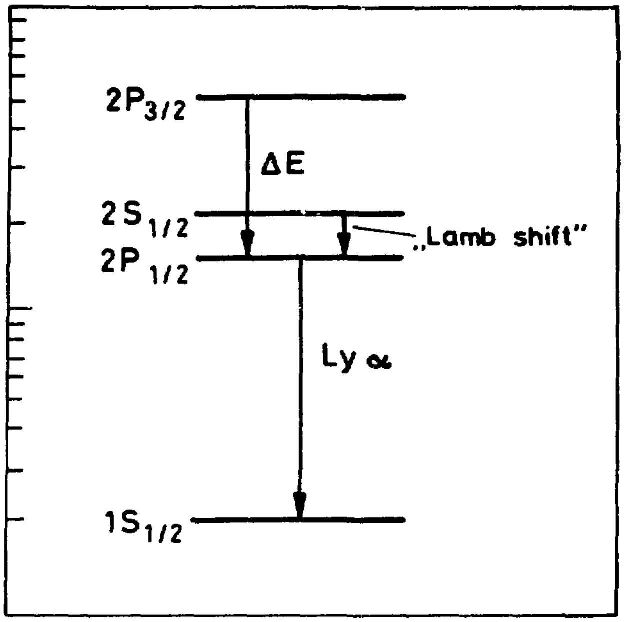

Fig. 14. The scheme of the lower levels for H-like atoms and the Lamb shift.

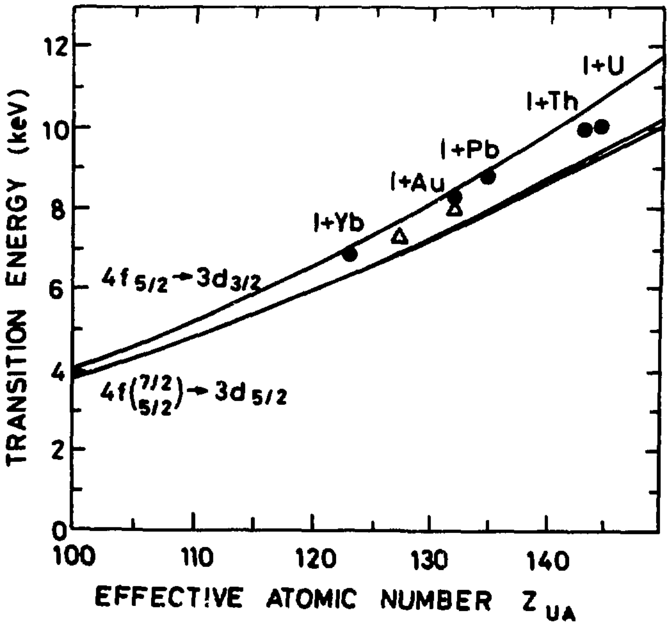

Fig. 16. Experimental and calculated transition energy /peak position/ in superheavy quasi-atomic systems as a function of the effective atomic number of the superheavy quasi-atom /ref. 47/.

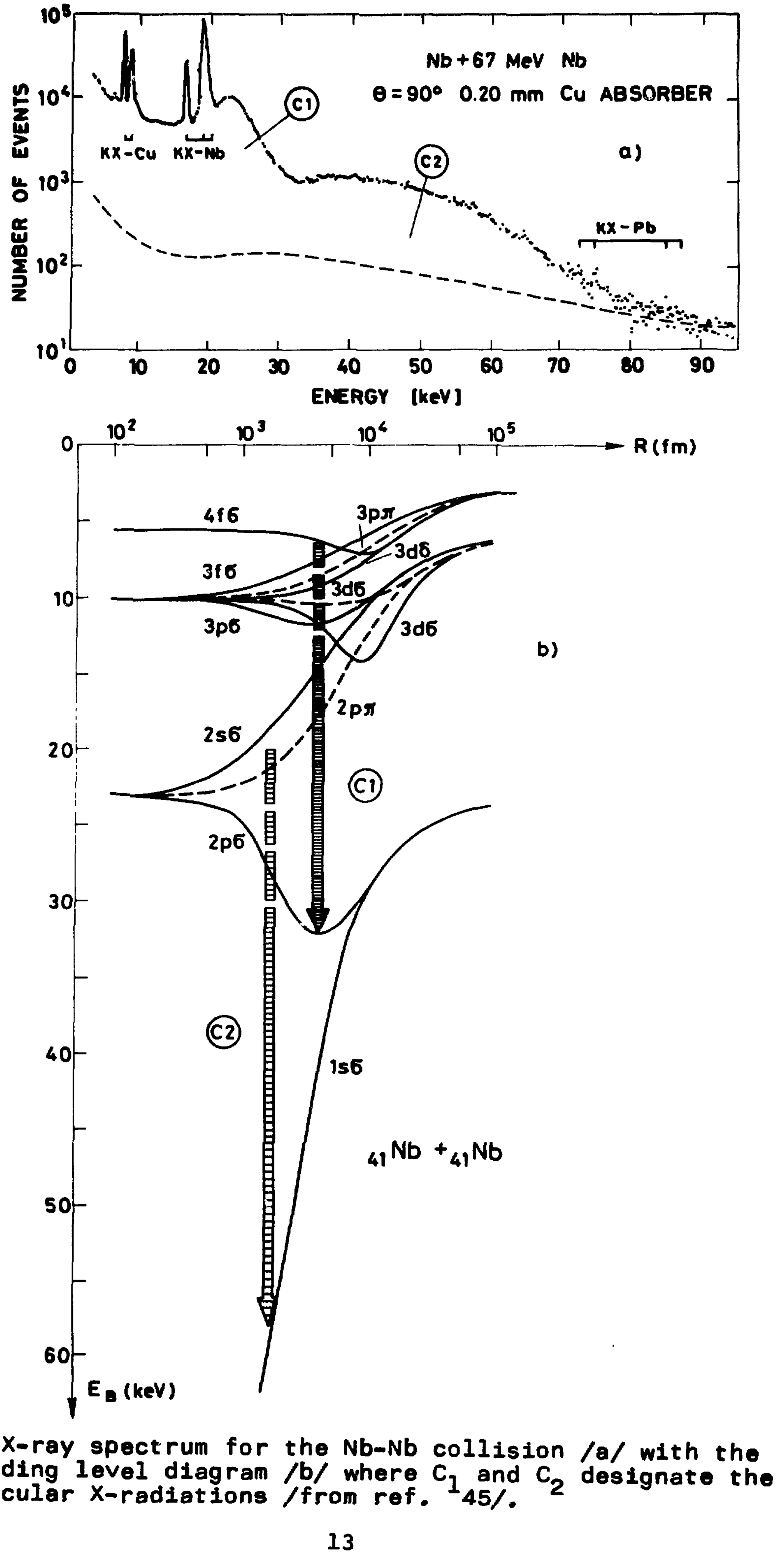

Fig. 15. X-ray spectrum for the Nb-Nb collision /a/ with the corresponding level diagram /b/ where C_1 and C_2 designate the quasimolecular X-radiations /from ref. [1]45/.

3.2. Superheavy quasi-atoms. When the quasi-molecular model is valid for the collision, there is a finite probability for the emission of a quasi-molecular /quasi-atomic/ X-radiation /see. e.g. ref. 22 or 43/. This radiation is not a peak in the spectrum rather a dump because the separation between the quasi-molecular /-atomic/ levels is changing together with the distance between the projectile and the target atom. The first experimental evidence for that was discovered for the Ar+Ar collision[44/]. Fig. 15 shows a nice result from Dubna[45/] where it can be seen how some information on the energy levels of the united atom can be obtained. If, however, the spectrum in question is measured in coincidence with the scattered projectile ion, the impact parameter dependence of the phenomena can be studied.

The above mechanism makes it possible to have information on the level energies and momentum distribution of the superheavy atoms /through quasi-atoms/ if high Z target is bombarded by heavy ion of high energy[46/]. The I-Au system e.g. corresponds to a quasi-atom with $Z_{UA}=132$. In Fig. 16 as an example, the quasi-atomic transition energy is given for different collision system as a function of the atomic number of the united atom /Z_{UA}/.

A recent analysis of the experimental data for systems $Z_{UA}=Z_1+Z_2 \geq 100$ in the bombarding energy region 0.5 - 6 MeV/amu shows that around Z 165 there is an additional coupling of the $p_{1/2}$ and 3s levels of the united superheavy quasi-atom[48/] /see Fig. 17/.

3.3. Positron production in supercritical fields. It is a very puzzling question if what happens to a bound electron in a supercritical electromagnetic field, namely if the Coulomb potential is beyond $Z\alpha = 1$[39,49,50/]. These issues are of fundamental interest because they are strongly connected with the behaviour of quantum electrodinamics beyond the limits of the validity of perturbation theory.

According to the theoretical considerations, if the atomic number of the atom /quasi-atom, collision system/ is higher than certain critical values /where the binding energy exceeds the energy corresponding to $2m_e$ for the individual shell /$1s_{1/2}$, $2p_{1/2}$, $2s_{1/2}$/, at filling the holes in these levels rather positrons than X-rays will be emitted /Fig. 18/. The appearance of this new production mechanism and the intensity of the positron

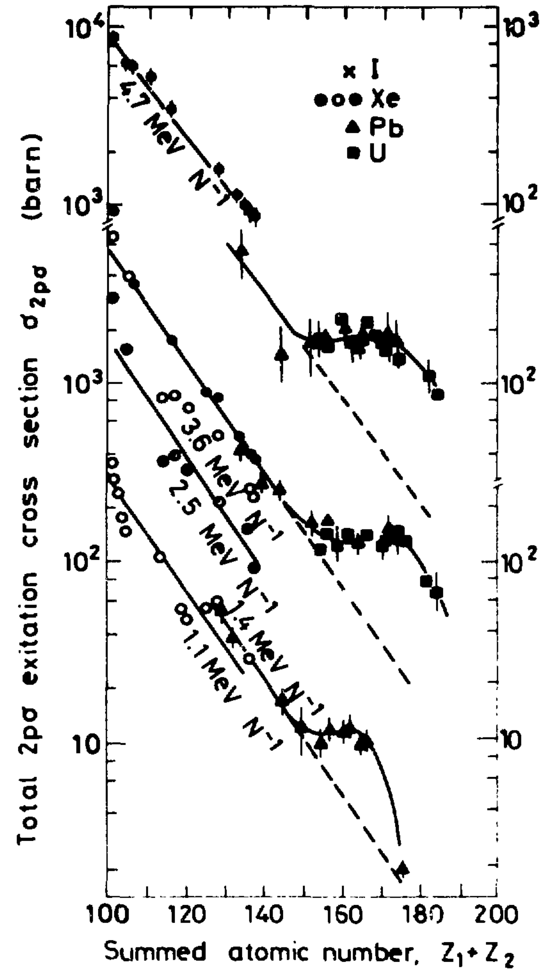

Fig. 17. Total 2p excitation cross section for different superheavy collision systems /after ref. 48/.

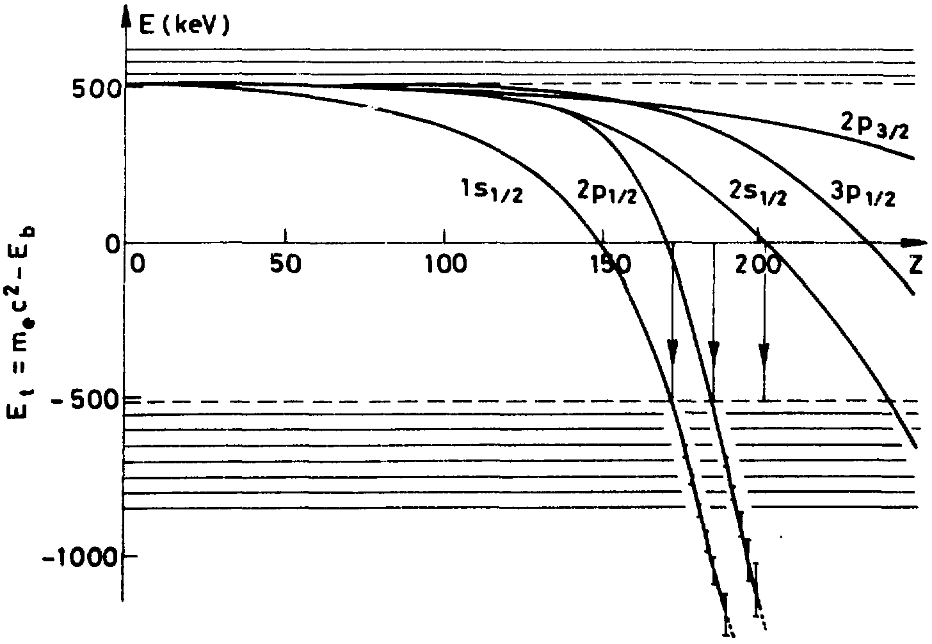

Fig. 18. Binding energies in superheavy nuclei /ref. 49/.

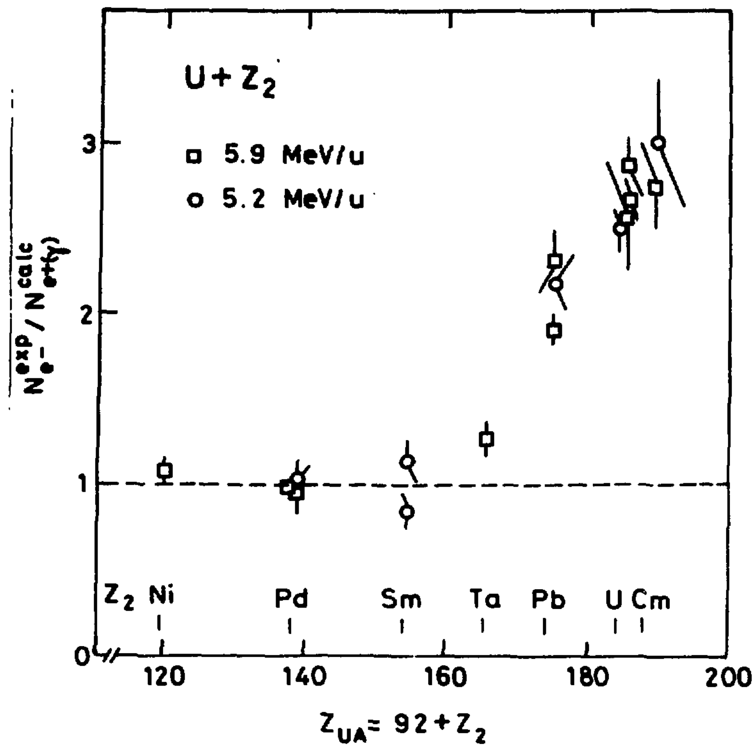

Fig. 19. Ratio of the observed number of positrons and the number of those calculated from gamma ray pair creation /after ref. 51/.

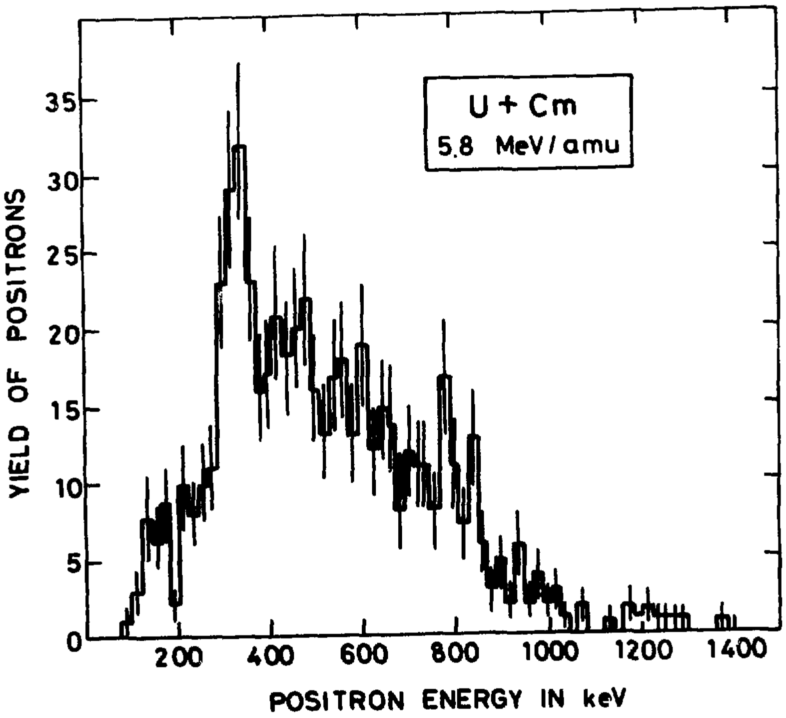

Fig. 20. Positron spectrum from ^{238}U/5.8 MeV/amu/ - ^{248}Cm collision in coincidence with backward scattered projectiles /from ref. 52/.

here are the tests for the relativistic quantum electrodinamical calculations.

A special difficulty in these experiments is that there are several other sources of positrons /nuclear, pair creation etc./ here. Fig. 19 shows, however that relating the observed number of positrons to the number of calculated from pair creation of the gamma rays present in the gamma spectrum, there is a real uprise in the neighbourhood of $Z_{UA}=170$.

During the recent experiments with the heaviest atoms as collision partners, however, a very distinct structure /some individual peaks/ have been found in the positron spectrum[52] /Fig. 20/. The explanation for that is still not clear at all, they might come from superheavy metastable nuclear complexes /Z 180/.

It was a very short and sketchy survey of the very broad and rich field of the high energy heavy ion collisions[53]. A number of interesting issues have not been even mentioned, e.g. the possibility to have information on the molecular structure from molecular projectiles[54] or the study of superheavy quasi-atoms by means of the spectra of δ-rays from the collisions regarded /e.g. in ref. 51/.

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Kiadja a
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Készült az ATOMKI nyomdájában