δ-electron emission in superheavy quasiatomic systems with total charge $Z_u = 110$ to 171

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(Received 20 August 1985)

δ-electron emission from superheavy quasiatomic systems formed during heavy-ion collisions was studied for several systems with united atomic charge Z_u up to 171. The double differential cross sections $d^2\sigma/dE_e d\Omega_e$ including the cross sections for total electron emission, electron emission from $1s_{1/2}$ and $2p_{1/2}\sigma$ states of the quasiatom, and the electron emission probabilities $P(R_0)$ for total electrons as well as for K-shell electrons are presented. These results are compared with available theoretical results. The results are interpreted in terms of the relativistic localization of the electronic wave functions and the effects due to the increase of the electronic binding energy. Binding-energy differences between K- and L-shell electrons are given for all the systems studied.

I. INTRODUCTION

Over the past several years the inner-shell electron emission process in superheavy quasiatoms has been the subject of several theoretical and experimental studies. Müller *et al.*[1] studied the electron promotion process by solving the two-center Dirac equation and suggested possible coincidence experiments. Then Soff *et al.*[2–4] proposed possible δ-electron spectroscopic experiments to study the superheavy quasiatoms. Because of the strong localization of the system's electronic wave functions[5] with increasing total atomic charge Z_u, the electronic emission cross section increases with the increasing Z_u. The experimental results of Kozhuharov,[6] Güttner *et al.*[7] and Herath Banda *et al.*[8] show evidence that these high-energy δ electrons emitted during heavy-ion collisions stem from the innermost shells of the quasiatoms. Experimental results also show that the emission cross section increases with the increase of the total atomic charge Z_u.[8] In addition these cross sections can be used to estimate the binding energies of the K- and L-shell electrons. While most of these cross sections can be reproduced by the coupled-channel calculations,[8–12] there are several important exceptions.[8,10–12] These discrepancies are not systematic and there are no clear explanations as yet. It is also known that in superheavy quasiatomic systems, electronic wave functions at distances small compared to the shell radius depend on the internuclear distance[5] R_0. This produces a strong increase in the vacancy-production probability of the $1s_{1/2}$ and $2p_{1/2}\sigma$ states with decreasing internuclear distance. Correlation between the strong localization of the wave function and the electron emission probability as a function of internuclear distance is predicted by a scaling law[13–15] derived from first-order perturbation theory. The electron emission probability as a function of internuclear distance provides a measure of wave-function localization and at the same time it allows one to investigate the validity of the scaling law.

In our effort to understand and extend our knowledge of the nature of atomic systems beyond the stable elements, we have been investigating several target and projectile systems with united atomic charge Z_u ranging from 110 [Ni on Pb (Ref. 16)] to 171 (Au on U). In this paper we present the double differential cross sections of the systems I on Pb and U at a beam energy of 3.9 MeV/u and Au on U at beam energies at 3.6 and 3.9 MeV/u. These results are compared with the available theoretical calculations. Impact-parameter dependences of the electron-emission probability for the systems I on Au, Pb, and U are also presented. We have extended our previous measurements and have been able to measure electron energies up to 1 MeV. Results are compared with available theoretical calculations. Binding-energy differences between K- and L-shell electrons are presented for all the systems investigated.

II. EXPERIMENTAL SETUP AND TECHNIQUES

The experiments were performed using the Heidelberg MP tandem Van de Graff in combination with the postaccelerator using beams of I on Au. Except for the system I on Au, the projectile energies were chosen below the

Coulomb barrier to avoid the background due to nuclear excitations. Beam intensity was about 1 pna (particle nanoamperes). Targets were self-supporting Pb, U, and Au foils intensity was about 1 pna. Targets were self-supporting Pb, U, and Au foils with thicknesses of 800, 1000, and 800 $\mu g/cm^2$, respectively. The experimental setup consisted of an achromatic magnetic spectrometer with two Si(Li) detectors to measure electrons, two NaI(Tl) detectors to measure the characteristic x rays of the target and projectile atoms, a parallel-plate avalanche counter to measure the scattered heavy ions and a surface barrier Si(Li) detector to monitor the beam and the target quality. The parallel-plate avalanche counter was able to detect heavy ions scattered between 10° and 58°. A different experimental setup was used to study the systems I on Pb and I on U. Further details on experimental setups and data analysis techniques are found in Refs. 16—20.

When the projectile atom slowly approaches the target atom the inner-shell electrons of both target and projectile have sufficient time to adjust themselves to form common orbits of target and projectile atoms. As the projectile moves closer to the target atom a quasimolecule and, at the closest distance of approach, a quasiatom are formed. During the formation of the quasiatom, the strong time-varying Coulomb field can cause an electronic transition of an inner-shell electron to the positive continuum or to any other empty bound state, leaving a vacancy in an inner shell of the quasiatom. Transient formation of the atom occurs during the passage time, which is about 10^{-20} s (τ_{coll}). In the subsequent process the K vacancy is deexcited. The deexcitation time of a vacancy τ_{de}, is of the order 10^{-17} s, which is much longer than the collision time τ_{coll} of 10^{-20} s. Therefore the deexcitation takes place long after the collision, that is, after the collision partners are well separated. The K vacancy appears either in the target or projectile atom K shell and the deexcitation gives rise to the emission of characteristic K x rays. For very asymmetric systems a K-shell vacancy in the united atom occurs asymptotically in the K shell of the heavier partner.[21] Thus the coincidence measurement between δ electrons and the characteristic K x rays of the target atom isolates the electrons stemming from the K shell of the quasiatom of an asymmetric system. Furthermore, a vacancy in the $2p_{1/2}\sigma$ shell of the quasiatom occurs asymptotically in the K shell of the lighter collision partner and the coincidences between δ electrons and the characteristic K x rays of the lighter collision partner isolate the electrons stemming from the $2p_{1/2}\sigma$ shell of the quasiatom. In addition, by measuring the triple coincidences of δ electrons, K x rays, and heavy ions scattered to a known angle, electrons from a given shell of the quasiatom can be measured as a function of the impact parameter or the internuclear distance. The following results were obtained using the techniques presented above.

III. CROSS SECTIONS

The I on U system was studied with two different beam energies, one of 3.7 MeV/u and the other of 3.9 MeV/u. The data for 3.9 MeV/u are presented in Sec. VI. In this experiment we were able to measure electron energies up to 900 keV. The measurements of electron energies were taken at an angle of 70° with respect to the beam direction. The double differential cross sections for electron singles (total electrons) and electrons in coincidence with uranium-K x rays are shown in Fig. 1. The arrows indi-

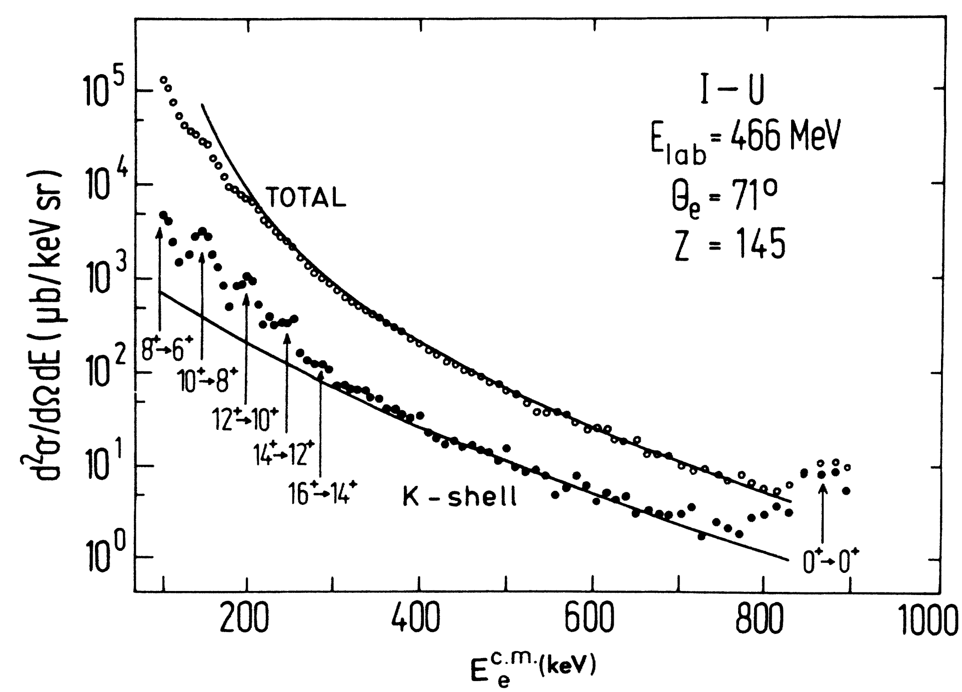

FIG. 1. Double differential cross sections $d^2\sigma/dE_e d\Omega_e$ of total electrons and K-shell electrons of the system I on U measured at beam energy of 3.7 MeV/u and electron angle 71° compared with coupled-channel calculations (Refs. 11 and 12).

cate the conversion lines due to the Coulomb excitation of the ground-state rotational band in ^{238}U. We also observe the conversion line due to the $0^+ \rightarrow 0^+$ transition in U. These lines are Doppler shifted and broadened. The rapid falloff of the cross sections is a characteristic feature common to these and other systems[8] studied. The solid lines shown in Fig. 1 are from the coupled-channel calculations of Mehler *et al.*[11,12] They numerically solve the stationary two-center Dirac equation in the monopole approximation to the two-center potential, including the corrections for the electron-electron interaction in the relativistic Hartree-Fock-Slater approximation, and perform a coupled-channel calculation for the electron-excitation amplitudes. At higher electron energies, these calculations agree rather well with our experimental data. However, at lower electron energies the calculations overestimate the total electron emission. For example, at 150 keV the total electron emission cross section is overestimated by more than a factor of 2. In addition, the measured electron spectrum includes the contribution due to conversion electrons. However, the results in coincidence with K-shell electron emission are very encouraging.

The I on Pb system was studied with a projectile energy of 3.9 MeV/u. The total electron emission for this system was previously reported.[7] Total electron emission as well as electron emission from the K shell are shown in Fig. 2. The solid lines are again the coupled-channel calculations of Mehler *et al.*[11,12] In this case coupled-channel calculations show remarkably good agreement with our data.

The heaviest system studied in our work was Au on U which has a united atomic charge of 171. The cross sections were measured at two-beam energies, one of 3.2 MeV/u and the other of 3.6 MeV/u, both of which are below the Coulomb barrier of the system. The results for 3.2 MeV/u are shown in Fig. 3. The arrows indicate the conversion electron lines in ^{238}U and the solid lines are the coupled-channel calculations of Mehler *et al.*[11,12] The theoretical results for the total electron emission agree fairly well with our data at lower electron energies but at higher electron energies the calculations overestimate the cross sections. In addition, the conversion electrons are not subtracted from the data. The experimental results shown by the lower set of data in Fig. 3 are the electrons measured in coincidence with characteristic K x rays of U. For very heavy systems, coincidence between electrons and K x rays do not directly give the electrons emitted from the K shell of the quasiatom. Particularly in the system Au on U there are two major problems. Since the Au on U system is not very far from symmetry, vacancy sharing[21,22] between the $2p_{1/2}\sigma$ and $1s_{1/2}$ states cannot be neglected. The second problem is the *uncorrelated* events in very heavy collision systems. Corrections to the data must be made for both of these problems. The details of these problems and methods used to correct for them are described in Secs. IV and V. The results in Fig. 3 are not corrected for either uncorrelated events or for the vacancy sharing and therefore the lower set of data represents the cross section of the K-hole production. When the uncorrelated events are subtracted, the contribution of conversion electrons is automatically eliminated from the spectrum. Figure 4 shows the experimental results of the same system with a beam energy of 3.6 MeV/u. In this

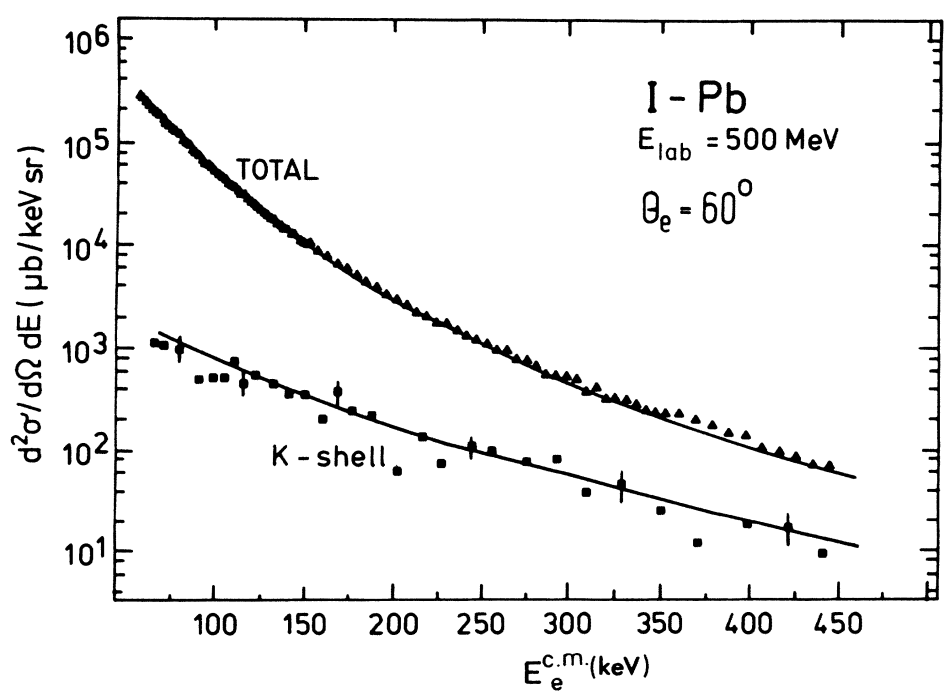

FIG. 2. Double differential cross sections $d^2\sigma/dE_e d\Omega_e$ of total electrons and K-shell electrons of the system I on Pb measured at beam energy of 3.9 MeV/u and electron angle 60° compared with coupled-channel calculations (Refs. 11 and 12).

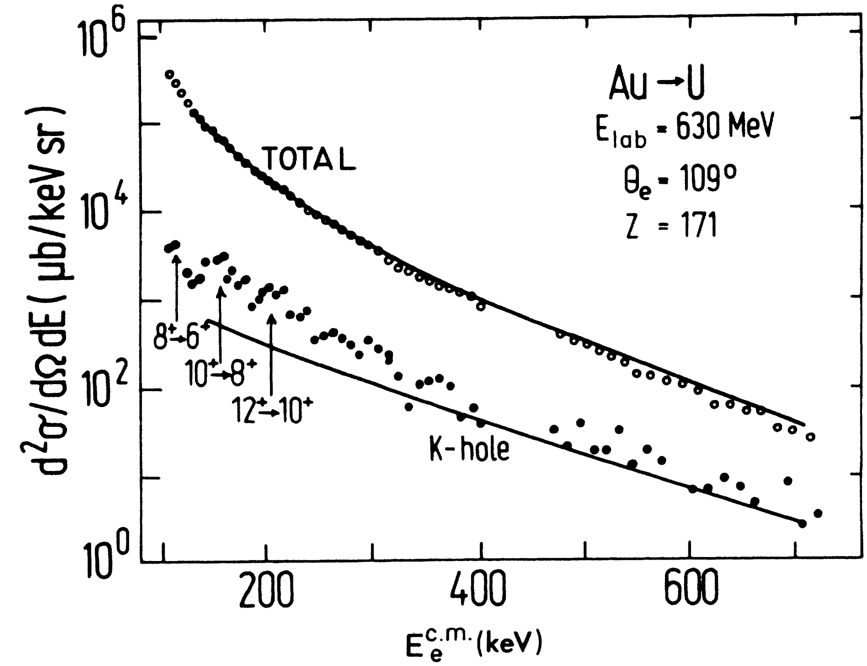

FIG. 3. Double differential cross sections $d^2\sigma/dE_e d\Omega_e$ of total electrons and K-shell electrons of the system Au on U measured at beam energy of 3.2 MeV/u and electron angle 109° compared with coupled-channel calculations (Refs. 11 and 12).

case we were able to measure the electron energies up to 1 MeV, and in addition to the coincidences between electrons and K x rays of the heavier collision partner we measured the coincidences between electrons and the K x rays of the lighter collision partner, in this case Au. The latter gives the electron emission cross section of the $2p_{1/2}\sigma$ state of the quasiatom. The differential cross section for total electron emission, electron emission from

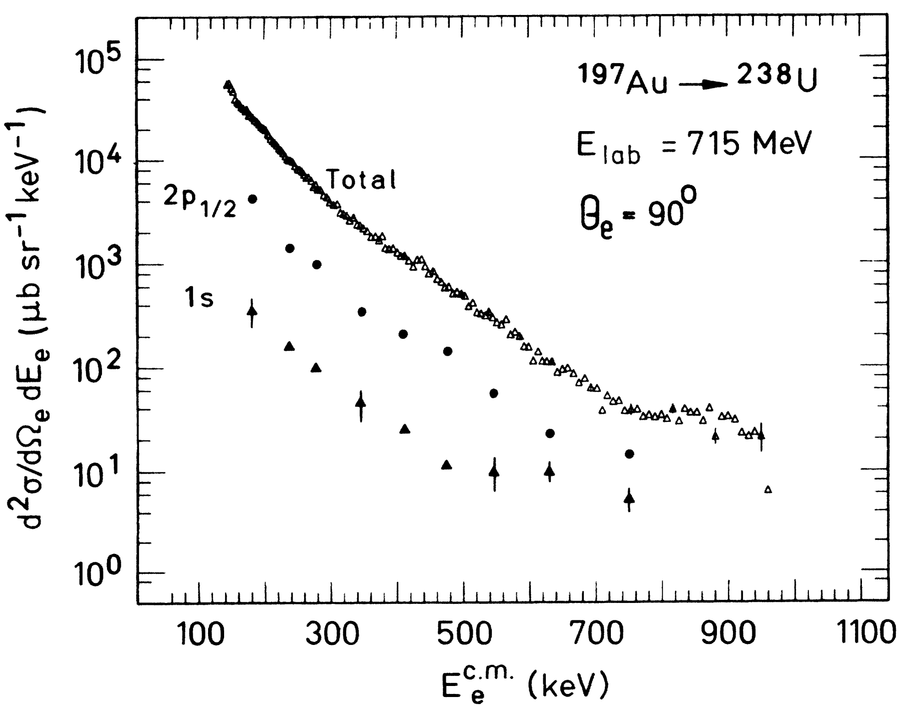

FIG. 4. Double differential cross sections $d^2\sigma/dE_e d\Omega_e$ of total electrons and K-shell electrons of the system Au on U measured at beam energy of 3.6 MeV/u and electron angle 90°.

the $2p_{1/2}\sigma$, and electron emission from the $1s_{1/2}$ shells are shown in Fig. 4. These results have been corrected both for uncorrelated events and for vacancy sharing. Theoretical cross sections for the production of K holes or δ electrons with this beam energy are not available for comparison. As one goes from lighter to heavier systems the major difference in the cross sections is that for heavier systems the difference in order of magnitude of K- and L-shell spectra at lower and higher electron final energies becomes less, compared to that of lighter systems, that is K and L cross sections look nearly parallel to each other. For example, in the Br on Pb system the ratio of L- to K-shell spectra at $E_f = 200$ keV is 100 and at 500 KeV the ratio is less than 2. In the case of Au on U these ratios are 100 and 45, respectively. However, the cross sections increase with the increase of the united atomic charge Z_u. The double differential cross sections of the total electron emission for various systems are shown in Fig. 5. The cross section increases from less than a microbarn for the C on Pb systems to several millibarns for the Pb on U system. This is about a factor of 10^4 increase in cross section as the total atomic charge increases from 94 to 174. The cross sections for the systems C, S, Ni, Br, and Pb on Pb; and Br, Ni, and Pb on U were taken from previous measurements.[7,8,18,23] The electron emission cross sections for the systems C, S, Ni, and Br on Pb were measured at $\theta_e = 30°$. The measurements for the other systems were taken at various other electron angles. However, for these very heavy systems the angular distribution of the electron emission is isotropic.[8,24] As seen in Fig. 5 the increase in cross section slows down at very large unit-

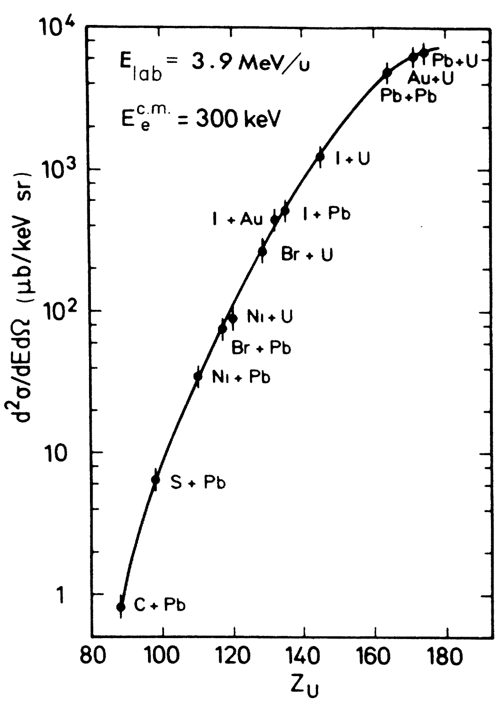

FIG. 5. Double differential cross sections $d^2\sigma/dE_e d\Omega_e$ of total electron emission from various target projectile systems at beam energy of 3.9 MeV/u and electron final energy of 300 keV.

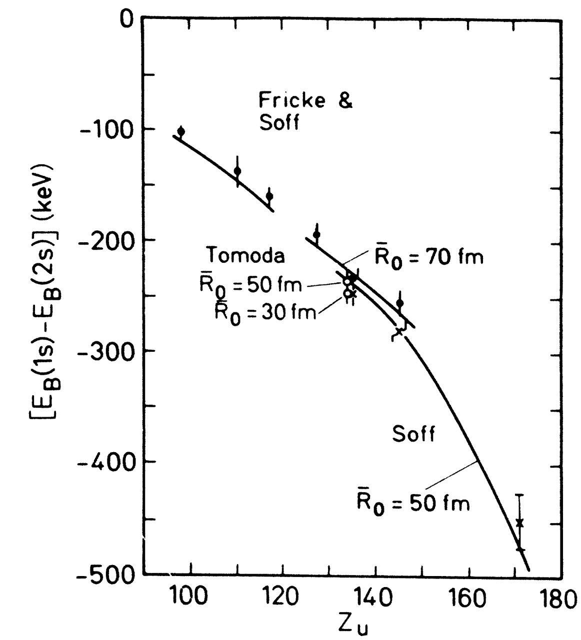

FIG. 6. Binding-energy difference between K- and L-shell electron of quasiatoms compared with the theoretical results (Refs. 24—26).

ed atomic charge. This is partly due to the strong increase in the binding energy and partly due to the tendency of the electron density to decrease at very high charge and nuclear size. The solid line in Fig. 5 is drawn through the experimental points to guide the eye.

The same method which we develop to extract binding energies from the cross sections[8] was used to extract the binding-energy difference between K- and L-shells of all the systems. These experimental binding-energy differences are compared with the theoretical results of Tomoda[25] and Soff *et al.*[26,27] and are shown in Fig. 6. Although the theoretical calculations overestimate the binding energies ΔE_B, within experimental errors these results show reasonably good agreement. The mean internuclear distance R_0 was calculated using the mean impact parameter $\bar{b} = 1/q_0$, where q_0 is the minimum momentum transfer to the electron.

IV. UNCORRELATED EVENTS

In heavy-ion collisions both target and projectile nuclei may be Coulomb excited resulting in the emission of electrons due to the internal conversion. In the subsequent process of deexcitation, characteristic K x rays are produced. In addition to conversion electrons, electrons may be emitted due to a multistep process. During the collision a vacancy created by emitting an electron from an outer shell can be filled by promoting an electron from an inner shell. The vacancy produced by this inner shell may in turn be filled by any other lower shell including the lowest K-shell electrons. These multistep processes are not distinguished by the detectors. An electron stemming from L-shell or a higher shell may be detected by the electron detector and in the same collision an electron emitted from the K shell of the quasiatom may not be detected. However, the x-ray detector may be triggered due to the deexcitation of the K vacancy producing a valid event. These are true x rays and therefore the events produced are true electron—K x-ray coincidence events. However, they are not correlated K x-ray—K electron coincidence events. The number of these uncorrelated events depends on the product of the emission probabilities of K x rays and electrons. This probability can be approximately expressed as

$$P_{\text{uncorr}}(b) \simeq P_{e,\text{tot}}(b) P_{K\text{-}x}(b) ,$$

where $P_{e\text{-tot}}(b)$ is the total electron emission probability and $P_{K\text{-}x}(b)$ is the K x-ray-emission probability as a function of the impact parameter. The differential cross section for the uncorrelated events is given by

$$\frac{d^2\sigma}{dE_e d\Omega_e} = 2\pi \int_0^\infty [P_{\text{uncorr}}(b) b] db .$$

For very heavy systems electron and K x-ray-emission probabilities are larger than for lighter systems. These probabilities also increase with the decreasing internuclear distance. In order to calculate the partial cross section due to uncorrelated events one needs to know the total electron emission probability as a function of the impact parameter, and electron energy and the K x-ray-emission probability as a function of b. The measured x-ray-emission probabilities of the Au on U system are shown in Fig. 7. At 30 fm, the Au K x-ray-emission probability is more than 50% and the U K x-ray-emission probability is more than 25%.

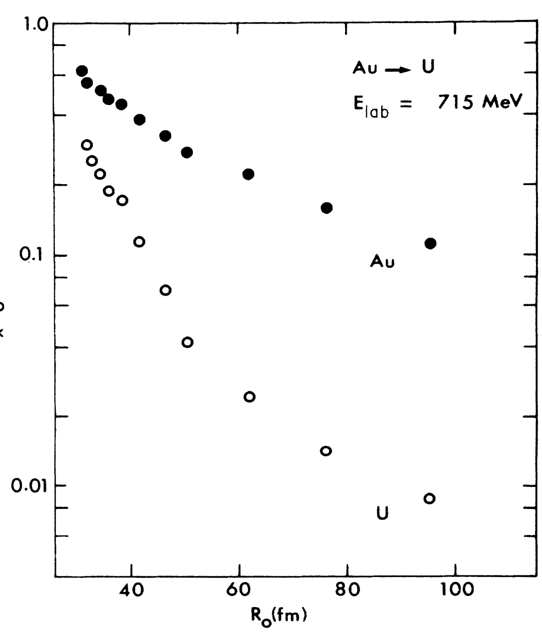

FIG. 7. Probability $P(R_0)$ of K x-ray emission as a function of internuclear distance R_0.

V. VACANCY SHARING

For a system where both the target and the projectile nuclei are the same, it is difficult to distinguish between $1s_{1/2}$ and $2p_{1/2}\sigma$ quasiatomic states and the vacancies in these states. In asymmetric systems the $1s_{1/2}$ and $2p_{1/2}\sigma$ states are well separated whereas, in a system which is not far from symmetry, a vacancy can be shared between these states. The probability of this vacancy sharing[21,22] depends on the asymmetry parameter $\Delta Z = |Z_p - Z_t|$ and is given by

$$P_{\text{vac}} \simeq \exp\left[-\pi\alpha c\frac{\Delta Z}{v_p}\right] .$$

In the case of Au on U the quantity P_{vac} is 3.4%. The vacancy sharing component $P_{\text{vac}}(d^2\sigma/dE_e d\Omega_e)_{2p_{1/2}}$ is subtracted from the $1s_{1/2}$ cross section in Fig. 4. Since the $1s_{1/2}$ emission probability is very small the amount one has to subtract from $2p_{1/2}\sigma$ is negligible.

VI. IMPACT-PARAMETER DEPENDENCE OF THE δ-ELECTRON EMISSION PROBABILITY

The impact-parameter dependence of δ-electron emission probability was measured for several systems. Data for the system Au on U were reported in a previous paper.[28] Figure 8 shows the measured total electron emission probability as a function of internuclear distance R_0 for the system I on Pb. The emission probability for this

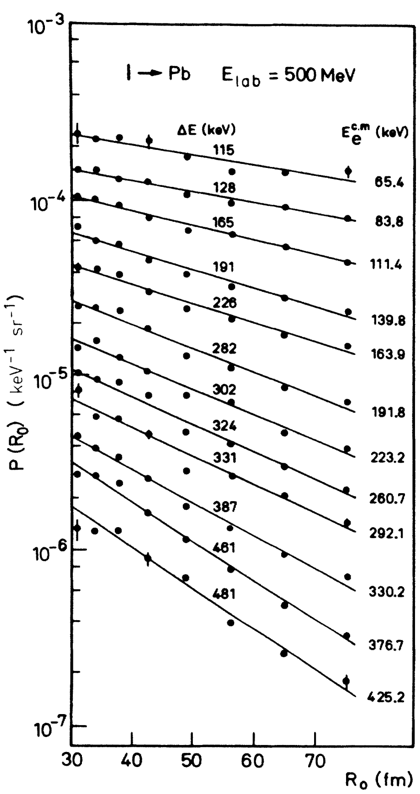

FIG. 8. Probability $P(R_0)$ of total electron emission from the quasiatom I on Pb as a function of R_0 for the electron final energies from 65 to 425 keV.

system was measured for electron energies from 65 to 425 keV and internuclear distances from 80 to 30 fm. The solid lines in the figure are the exponential fit to the data points. These results show a very clear exponential behavior. The steep exponential increase of $P(R_0)$ with decreasing internuclear distance is the dominant feature of all the systems. At larger electronic kinetic energies the $P(R_0)$ increases more rapidly with decrease of the internuclear distance R_0 than for smaller electronic energies. A decrease in the internuclear distance by a factor 2, for example, from 70 to 35 fm leads to an increase of the $P(R_0)$ by a factor of 8 at 425 keV and to a factor of about 1.5 at 65 keV. Total electron emission probabilities for the systems I on U and I on Au are shown in Figs. 9 and 10, respectively. For the I on U system the emission probability was measured for internuclear distances from 30 to 85 fm and electron final energies up to 560 keV. In the case of I on Au system the beam energy was chosen above the Coulomb barrier in order to study other effects.[20,29] As a result of separating the elastic and inelastic events during data analysis[30] we were able to get the emission probability for internuclear distance from 50 to 30 fm. Both systems I on U and I on Au show similar characteristics as compared to the I on Pb system. These and other results[28] show that the electron emission takes place predominantly near the minimum distance of closest approach of the collision partners.

Assuming the general form of the scaling law[13,15] for the electron emission probability in superheavy quasiatoms one can evaluate the slope constant of the emission probability. The emission probability and the coupling matrix element can be written as[13–15]

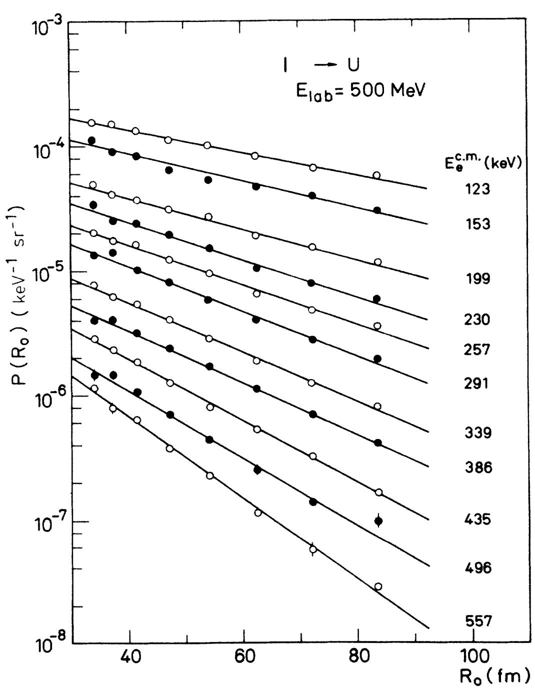

FIG. 9. Probability $P(R_0)$ of total electron emission from the quasiatom I on U as a function of R_0 for the electron final energies from 123 to 557 keV.

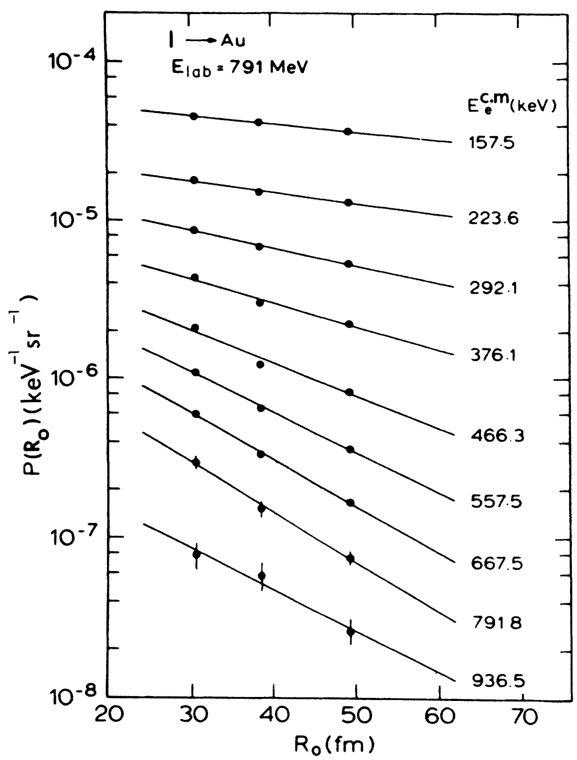

FIG. 10. Probability $P(R_0)$ of total electron emission from the quasiatom I on U as a function of R_0 for the electron final energies from 157 to 937 keV.

$$P(R_0) \sim e^{-mq_0R_0} ,$$

and

$$\left\langle E_f \left| \frac{\partial}{\partial R} \right| E_i \right\rangle \sim \frac{1}{R^{\gamma}} ,$$

respectively, where m and γ are related by $m \simeq 1+\gamma$. Therefore the slope constant m in the scaling law is a measure of the shrinking or the localization of the electronic wave function. Total electron emission probabilities shown in the Figs 8, 9, and 10 are dominated by the electrons emitted from the L shell of the quasiatom.[8] The contribution of the K shell to these is less than 1% (see Figs. 1 and 2) of the total electrons. Therefore the slope constant of these probabilities can be calculated using the theoretical L-shell binding energies[26] to calculate the minimum momentum transfer q_0 to the electron where

$$q_0 = \frac{|E_B| + E_f}{v_p} ,$$

and where E_B and E_f are the electron binding energy and the final energy, respectively. Studies of the electron energy dependence on the slope constant m of the electron emission probability yield average values of the slope constant of 1.70±0.06, 1.93±0.03, and 1.94±0.05 for the systems I on Au, U, and Pb, respectively. The internuclear-distance dependence, R_0, of the electronic

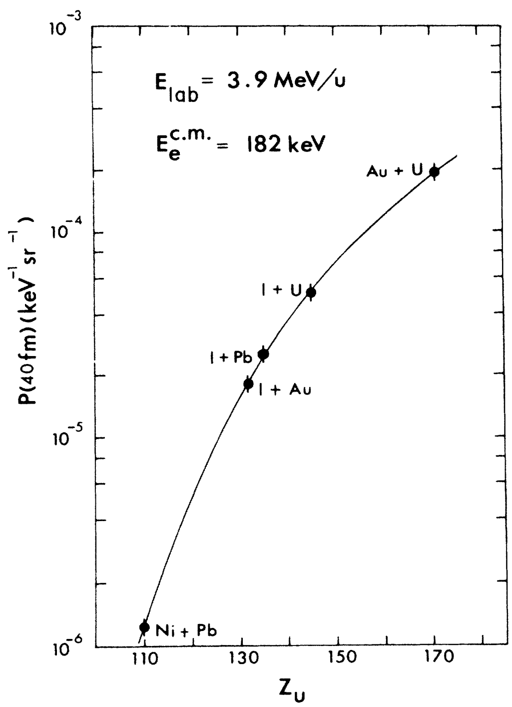

FIG. 11. Total electron emission probability as a function of total nuclear charge Z_u at internuclear distance of 40 fm, beam energy of 3.9 MeV/u and electron final energy of 180 keV.

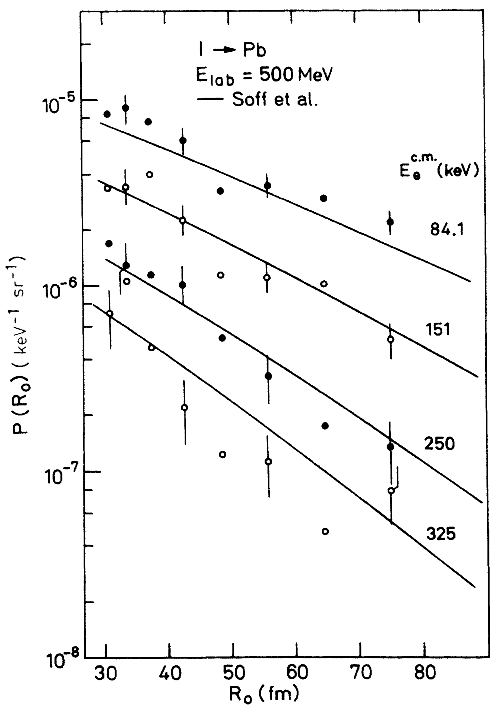

FIG. 12. Probability $P(R_0)$ of total electron emission from the $1s_{1/2}\sigma$ shell of the quasiatom I on Pb as a function of R_0 for the electron final energies from 84 to 325 keV.

transition matrix elements was calculated[25] and average values of γ were obtained by fitting the data to a power law in R_0. The theoretical slope constants obtained from these γ's are 1.7, 1.8, and 1.8, respectively, for the above three systems. The theoretical slope constant obtained for I on Au agrees well with our data and the slope constants for the systems I on U and Pb are not far off from our experimental values. Total electron emission probability at 40 fm and electron energy of 182 KeV is plotted against the total nuclear charge in Fig. 11. Again the increase of the probability for increasing Z_u indicate the relativistic localization of the electronic wave functions. The solid line in Fig. 11 is drawn to guide the eye.

The measured triple coincidences of electrons, scattered heavy ions, and the characteristic K x rays of Pb for the system I on Pb are shown in Fig. 12. The results are shown for the electron energies of 84, 157, 250, and 325 keV. Because of the poor statistics the data points do not show a clear exponential behavior as in the case of total electron emission. The solid lines which are in good agreement with our data shown in the figure are the coupled-channel calculations of Soff *et al.*[31] While one might think that the fluctuations in the data are due to interference effects in deep inelastic reactions,[3] this is highly unlikely due to the fact that our beam energy was below the Coulomb barrier. In addition, any real fluctuations in the data would not be visible due to the large statistical errors. The increase in the $P(R_0)$ with the decrease of the internuclear distance R_0 is much steeper than that of total electrons emission. For example, at 330 keV, the decrease of R_0 from 70 to 35 fm gives rise to an increase of emission probability by a factor of 3 for the total electrons and by a factor of 7 for K-shell electrons. The emission probability for the K shell of the system I on Au is shown in Fig. 13. The slope constants obtained for the $1s_{1/2}$ state

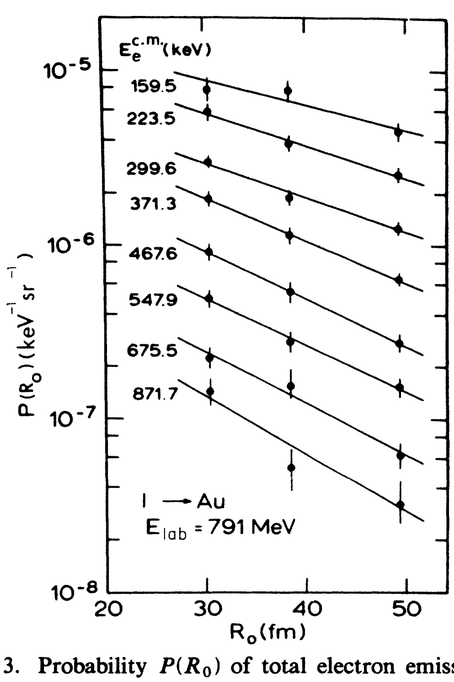

FIG. 13. Probability $P(R_0)$ of total electron emission from the $1s_{1/2}\sigma$ shell of the quasiatom I on Au as a function of the R_0 for the electron final energies from 160 to 872 keV.

of the systems I on Pb and I on Au are 1.90 ± 0.09 and 1.75 ± 0.11, respectively. The corresponding theoretical slope constants we obtained were 1.8 and 1.6, respectively. Again these values are not far off from our data.

VII. DISCUSSION

In this paper we have presented our data for the superheavy quasiatomic systems I on Au, Pb, and U, and Au on U. The δ-electron emission cross sections are compared with the available theoretical results. At higher beam energies the theoretical calculations can overestimate or underestimate the cross sections. The results presented here and other results[8,10,32,33] show that these discrepancies are not systematic. Since there are as yet no explanations for these discrepancies, it is difficult to understand the collision process completely. However, for many of the cases agreement between theory and experiment is extremely good. The experimentally observed increase of the electron emission cross section and probability with Z_u is a signature of the relativistic localization of the electronic wave functions. As we have seen, this increase of the cross section slows down at very heavy systems. This is partly due to the strong increase of the binding energies and partly due to the tendency of the electron density to decrease at very high charge and nuclear size. We have presented binding-energy differences between the K and L shells of the quasiatomic systems and compared them with the theory. The theoretical results agree reasonably well with our data. Impact-parameter (or internuclear distance) dependence of the electron emission probability show a clear exponential behavior. The K-shell electron emission probability of the system I on Pb can be reproduced by the coupled-channel calculations. Similar calculations are not yet available for the other systems. However, it is known that coupled-channel calculations overestimate the emission probability for the system Xe on Pb.[32] The scaling-law approximations discussed in this paper are valid only for the lighter systems. For very heavy systems they are known to produce incorrect results.[28,33] To understand the electron emission process, the transient atomic structure, and the nuclear interactions, more experimental data as well as theoretical studies are required. Although future studies are limited by the available long-lived beams and targets, heavier systems such as U on Cm with united atomic charge in the range of 110 to 188 can be studied. According to the recent results of positron spectroscopy[34] it is also clear that more theoretical and experimental studies on superheavy quasiatoms are essential to understand the reaction mechanism and the emission of electrons, positrons, and other particles.

ACKNOWLEDGMENTS

The research of Dr. M. A. Herath Banda was supported by Max-Planck-Gesellshaft zur Förderung der wissenschaften e.V. The research at Space Astronony Laboratory is supported by U. S. Department of Energy Contract No. DE-FG05-84ER10410. We are grateful to G. Soff, T. de Reus, G. Mehler, B. Müller, and W. Greiner for providing us with their theoretical calculations.

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