The Impact Parameter Dependence of the K MO X-Ray Emission in $^{208}$Pb+$^{208}$Pb Collisions

1$s\sigma$- and $2p_{1/2}\sigma$-Excitation Probabilities in Symmetric, Superheavy Collision Molecules*

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The emission probabilities for quasimolecular K-x-radiation (K-MOR) have been measured in $^{208}$Pb+$^{208}$Pb collisions at 4.3 MeV/u and 4.8 MeV/u as a function of the scattering angle using the particle-photon-coincidence technique. The probabilities exhibit a superposition of two exponential slopes with different fall-off constants. We identify the sharp fall off at very small impact parameters (<60 fm) with the K-MOR contribution from the decay of 1$s\sigma$-vacancies. The flatter slope for impact parameters larger than 60 fm is attributed to the radiative decay of holes in $2p_{1/2}\sigma$ molecular states. In this way, experimental "$1s\sigma$-MOR-emission probabilities" could be extracted and compared with theory. For 4.3 MeV/u the $1s\sigma$- and $2p_{1/2}\sigma$-excitation probabilities could also be determined and have been compared to coupled-channel calculations and to a scaling law for $1s\sigma$- excitation.

1. Introduction

In this article we report on measurements of the emission probabilities for K-MO-x-rays from the collision system $^{208}$Pb+$^{208}$Pb, at incident energies of 4.3 MeV/u and 4.8 MeV/u, performed at the Universal Linear Accelerator (UNILAC) of the Gesellschaft für Schwerionenforschung in Darmstadt, FRG. The transient formation of quasimolecular electron orbitals during these encounters leads to the creation of atomic states, whose binding energies can approach or exceed twice the rest mass energy of the electron. Experiments with these "superheavy" collision systems therefore offer the unique opportunity to test the physics predicted by quantum electrodynamics in regions of extreme electric and magnetic field strength associated with overcritical binding. A

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large number of relevant theoretical [1-5] and experimental work [6-21] has been published during the last decade. We give here only a very short introduction to the theory and its experimental verification, addressing points particularly useful to the understanding of this measurement.

For collisions between ions and atoms with similar or equal nuclear charge at velocities small compared to the electron velocities, the "quasimolecular" (MO) description is appropriate. Here the dynamical behaviour of the electron cloud is separated from the motion of the nuclei (Born-Oppenheimer approximation) and the evolution of atomic states is, expressed in a "quasiadiabatic" way by solving the two centre Dirac equation at the varying internuclear distances $R(t)$ [21]. The dynamical couplings between molecular states during the collision enter the calculations via the time derivative operator $\partial/\partial t$. At collision energies below the Coulomb barrier, $R(t)$ is completely described by the Rutherford trajectory. A unique correspondence between $R(t)$, scattering angle $\theta_{CM}$ and impact parameter $b$ exists, where $R_0(\theta_{CM})$, the distance of closest approach for a given scattering angle:

$$R_0(\theta_{CM}) = a \left( \frac{1}{\sin(\theta_{CM}/2)} + 1 \right),$$

has turned out to play a particularly important role (see below). $2a$ is the distance of closest approach in a head on collision ($b = 0$):

$$a = Z_1 Z_2 e^2/(2E_{CM}).$$

$Z_1$ and $Z_2$ stand for projectile and target nuclear charge, respectively, and $E_{CM}$ is the collision energy in the centre-of-mass system. According to the nomenclature of the nonrelativistic MO-model the "innermost" electrons are denoted as $1s_{1/2}\sigma$- (or $1s\sigma$-) electrons. In this paper we will mainly deal with these $1s\sigma$-electrons and those from the next orbital, the $2p_{1/2}\sigma$-electrons. The binding energies for these and some of the higher lying orbitals are shown in Fig. 1 as a function of $R$. This correlation diagram represents relativistic Hartree Fock calculations [23]. A typically relativistic feature of the two levels of interest is the strong increase in binding energy even at very small $R$ (note the doubly logarithmic representation of Fig. 1), which is absent for nonrelativistic systems.

In all measurements of $1s\sigma$-excitation probabilities $P_{1s\sigma}$ as a function of the distance of closest approach $R_0(\theta)$, or likewise of the impact parameter $b(\theta)$, a strong exponential increase of $P_{1s\sigma}(b)$ towards small $R_0(b)$ is manifested [8, 9, 20, 21]. This behaviour has also been expressed in terms of a scaling law resulting from a simplified analytical treatment of $1s\sigma$-excitation [24, 25]. Most frequently it is used in the form [9]:

$$P_{1s\sigma}(b) = 1/2 D(Z) \exp (-2R_0(b) \cdot q_0(b)), $$

where $D(Z)$ is a factor varying only with $Z_{UA}$; $q_0$ is given as $q_0 = E_{1s\sigma}(R_0)/\hbar v_{ion}$, with $v_{ion}$ being the impact velocity and $E_{1s\sigma}(R_0)$ the $1s\sigma$ binding energy at $R_0$.

A large number of experiments has been performed, to test the validity of the above described theoretical picture, by seeking to provide spectroscopic data about the quasimolecular levels. The observation channels open to experimental investigation are:

i) x-ray spectroscopy [6]

a) characteristic K-x radiation [7-9]