Stable Planetary Atom Configurations

A proper description of highly doubly excited atoms or ions is still an outstanding problem of "elementary" quantum mechanics. Current interest both experimentally and theoretically is focused on highly correlated electron motion, where any independent-particle model is inadequate to describe the properties of such states.

In a recent publication[1] Eichmann, Lange, and Sandner reported on the observation of planetary atomic states, where two electrons of a barium atom were both in highly excited states. The authors could reproduce their data quite well within a "frozen-planet approximation" (FPA), where one electron is fixed at some radial distance, whereas the other electron moves in the field of the residual barium ion and of the frozen electron. The remarkable success of their model indicates that there is a dynamical mechanism behind the *ad hoc* assumption of a frozen electron at large radial distances. We will comment on this mechanism and show that indeed there are classically stable configurations, which are close to the frozen-planet configuration of Ref. 1.

Our procedure to solve the classical equations of motion for the general three-body Coulomb problem are described elsewhere.[2] Here we focus on the helium atom with total angular momentum $J=0$. Because of inherent classical scaling properties the results are valid for all (negative) energies.[2] Most of the classical orbits are unstable and ionize, but stable bound motion does also exist. The most stable configuration we found is a collinear one, where both electrons are on the same side of the atom and where both electrons oscillate with the same frequency. The radial extents of these motions are very different and are indicated in Fig. 1(a). The stability of the motion is rather insensitive to variations in initial conditions. This is exemplified in Fig. 1(b), which shows the (regular) motion for slightly different initial conditions. It is obvious from Fig. 1(a) that the *dynamical* configuration of the electrons is very close to the FPA configuration considered in Ref. 1, which explains the success of their model.

It is straightforward to quantize the motion semiclassically.[3] Associated with the regular phase-space volume around the dynamical FPA orbit is a series of resonances converging to the double-ionization threshold. The resonance energies are given by (atomic units)

$$E_{nkl}=-\frac{1/S}{2[n+\frac{1}{2}+(k+\frac{1}{2})\gamma_1+(l+\frac{1}{2})\gamma_2)]^2}, \quad (1)$$

where $S=1.4915$ is the action of the orbit and $\gamma_1=0.4616$, $\gamma_2=0.5677$ are the winding numbers of the trajectory describing the behavior of nearby trajectories. The quantum numbers n,k,l have the meaning of nodal excitations along the orbit (n) and perpendicular to the orbit (k,l), with $\{k,\gamma_1\}$ describing bending motion. n is unlimited, but the upper limits of k,l depend on n. Semiclassically these states are bound, but they can decay quantum mechanically by (dynamical) tunneling. The decay times T for such processes are typically exponentially small, that is $\ln(T)\approx -n$, with n defined above.

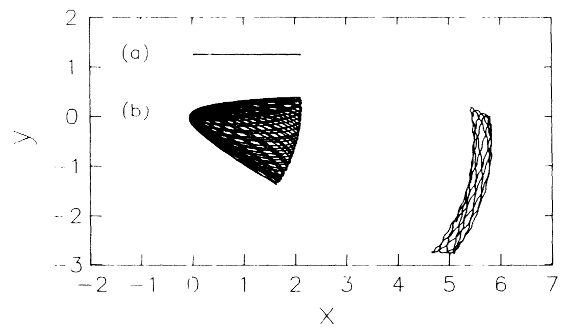

FIG. 1. The radial extents of the electrons for (a) the FPA periodic orbit, and (b) a nonperiodic but regular trajectory in its neighborhood.

The charge distributions of the associated wave functions show a huge gap between the turning point of the inner electron and the localization of the frozen electron. Therefore, laser excitation of such states *must* occur in multiple steps, as has been done in Ref. 1. The states should also show up in experiments using coherent laser excitation of wave packets.[4] In such an experiment the first laser pulse prepares the outer wave packet and a second laser pulse excites the inner one. The time delay between the two laser pulses plays a crucial role: The outer wave packet has to be at its turning point when the second wave packet is excited.

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