A rotating α -chain in the nucleus ^{12}C

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Because of the strong nuclear force among protons and neutrons, α -particles form a stable configuration not only in free space, but also in very light nuclei. Even in unstable configurations of heavy and super-heavy nuclei, α -decay is often observed. Obviously there is a high probability for the formation of an α -particle in such systems, which tunnels through the Coulomb barrier as a combined particle. There were many attempts in the past to describe nuclei in terms of localized α -clusters [1]. However, it turned out that, for the ground states, this picture applies only for very light systems. Already in ^{12}C and even more in all heavier nuclei, the ground state is no longer formed by localized α -clusters but rather by configurations where the protons and neutrons form a correlated Fermi liquid, filling up a self-consistent mean field up to the Fermi surface.

Nonetheless, configurations of α -clusters have been predicted and found in excited states. In ^{12}C , the Hoyle state at an excitation energy 7.65 MeV plays an important role in the $3\alpha \rightarrow ^{12}\text{C}$ reaction, most important for nucleosynthesis in the early universe. Already more than 60 years ago it has been interpreted by Morinaga [2] as a linear chain of three α -particles, but later it turned out to have a gas-like structure forming a kind of α -condensate [3]. So far this linear chain structure has not been observed in ^{12}C . It turns out to be unstable by bending modes leading through triangular configurations to the spherical ground state. However it can be stabilized by the Coriolis force in a rotational motion. Of course, if the angular velocity is too high the α -chain will

break and one expects fission.

In a recent work, Ren et al. [4] investigate the stability of this rotating linear α -chain configuration in the framework of cranked covariant density functional theory [5]. This method presents an optimal tool for such an investigation, because density functional theory is a mapping of the complicated nuclear many-body problem onto a relatively simple one-body problem which is applied with great success not only in nuclear, but also in molecular and condensed matter physics. The energy density functionals used for this purpose are universal. They depend only on the underlying force, but not on a specific region of the periodic chart. In nuclear physics, so far, such functionals cannot be derived *ab-initio*, i.e., from the nucleon-nucleon force. After fifty years of intensive investigations, one has, however, a number of very successful phenomenological functionals.

Covariant density functionals [6] are particularly interesting in nuclear physics because Lorentz invariance is a basic symmetry of QCD. A relativistic description not only includes the spin-orbit coupling in a consistent way, but also puts stringent restrictions on the number of phenomenological parameters without reducing the quality of the agreement with experimental data. Lorentz invariance guarantees that the time odd parts of the functionals are completely determined from the time-even parts. This is particularly important for calculations at finite angular velocity, where time-reversal symmetry is broken.

In ref. [4], the authors use the density functional DD-ME2 [7], based on a Lagrangian with meson exchange and density dependent coupling constants. DD-ME2 has been

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used with great success in many nuclear applications in the past. They assume that the α -chain along the z -axis rotates with constant angular velocity around the y -axis. They find a stable rotation for angular velocities in the interval $2 \text{ MeV} < \hbar\omega < 3.5 \text{ MeV}$. For smaller angular velocities unstable bending modes lead to a transition to the ground state and for larger angular velocities one observes fission. In experiment, so far, excited states corresponding to such a stable rotation of a linear chain of α -particles have not been found in ^{12}C . This work gives a hint where to look for in the future.

The paper is particularly interesting because of the modern numerical techniques used here. The authors had to overcome several problems. Most of the applications of covariant density functional theory in the rotating frame have been carried out, so far, in a 3D oscillator basis [5], leading to rather large matrices and a limited possibility to describe fission. This is the first cranked relativistic calculation carried out on a 3D lattice in r -space. Unphysical admixtures of the Dirac-sea (*variational collapse*) are avoided by the *inverse Hamiltonian method* [8] and the Fermion doubling problem is solved by the Fourier spectral method [9]. During the calculation an additional problem is encountered through the admixture of

spurious components in the continuum with very large angular momentum. They drive the system to fission very soon. The authors were able to avoid this problem by introducing an exponential damping of the Coriolis field in the unphysical region of the continuum. Based on these modern techniques this new method will definitely find many useful applications in the future.

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