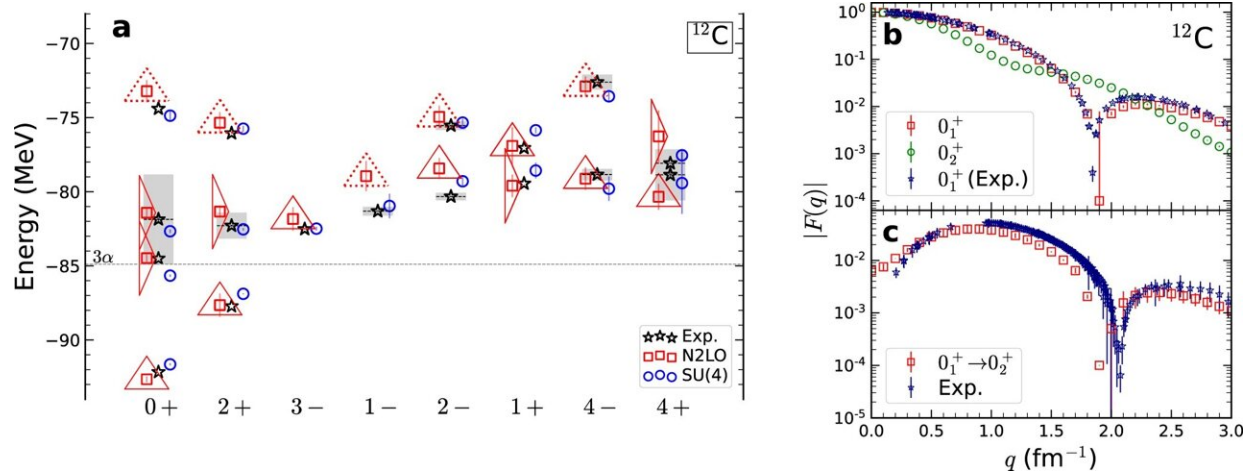


# Simulation provides images from the carbon nucleus

May 15 2023, by Johannes Seiler



Spectrum of  $^{12}\text{C}$  and charge form factors. **a** Spectrum of  $^{12}\text{C}$  using N2LO interaction (red squares) and SU(4) interaction (blue circles) in comparison with experimental data (black stars). The error bars correspond to one standard deviation errors. The gray shaded regions indicate decay widths for cases where it has been measured. The triangular shapes indicate the intrinsic shape of each nuclear state, either equilateral or obtuse triangle arrangements of alpha clusters. The dotted lines for some equilateral triangles indicate significant distortions or large-amplitude displacements of the alpha clusters. **b**, **c** Absolute value of the charge form factor  $F(q)$  using the SU(4) interaction. **b** The ground state (red squares) and Hoyle state (green circles), and **c** the transition from the ground state to the Hoyle state (red squares). The error bars correspond to one standard deviation errors. Experimental data (purple stars) are shown for comparison. Credit: *Nature Communications* (2023). DOI: 10.1038/s41467-023-38391-y

What does the inside of a carbon atom's nucleus look like? A new study by Forschungszentrum Jülich, Michigan State University and the University of Bonn provides the first comprehensive answer to this question. In the study, the researchers simulated all known energy states of the nucleus.

These include the puzzling Hoyle state. If it did not exist, carbon and oxygen would only be present in the universe in tiny traces. Ultimately, we therefore also owe it our own existence. The study has now been published in the journal *Nature Communications*.

The nucleus of a carbon atom normally consists of six protons and six neutrons. But how exactly are they arranged? And how does their configuration change when the nucleus is bombarded with high-energy radiation? For decades, science has been searching for answers to these questions. Not least because they could provide the key to a mystery that has long puzzled physicists: Why is there a significant amount of carbon in space at all—an atom without which there would be no life on Earth?

After all, shortly after the Big Bang, there was only hydrogen and helium. The hydrogen nucleus consists of a single proton, that of helium of two protons and two neutrons. All heavier elements were only created many billions of years later by aging stars. In them, helium nuclei fused into carbon nuclei at immense pressure and extremely high temperatures. This requires three helium nuclei to fuse together.

"But it's actually very unlikely for this to happen," explains Prof. Dr. Ulf Meißner of the Helmholtz Institute of Radiation and Nuclear Physics at the University of Bonn and the Institute for Advanced Simulation at Forschungszentrum Jülich. The reason: The helium nuclei together have a much higher energy than a carbon nucleus. However, this does not mean that they fuse particularly readily—on the contrary, it is as if three people wanted to jump onto a merry-go-round. But since they run much

faster than the merry-go-round turns, they do not succeed.

## **Simulation on the supercomputer**

As early as the 1950s, the British astronomer Fred Hoyle therefore postulated that the three helium nuclei first come together to form a kind of transition state. This "Hoyle state" has a very similar energy to the helium nuclei. To stay in the picture: It is a faster-spinning version of the merry-go-round, which the three passengers can therefore easily jump onto.

When that happens, the carousel slows down to its normal speed. "Only by taking a detour via the Hoyle state can stars create carbon at all in any appreciable quantity," says Meißner, who is also a member of the Transdisciplinary Research Areas "Modeling" and "Matter" of the University of Bonn.

About ten years ago, together with colleagues from the U.S., Forschungszentrum Jülich and Ruhr-Universität Bochum, he succeeded in simulating this Hoyle state for the first time. "We already had an idea then of how the protons and neutrons of the carbon nucleus are arranged in this state," he explains. "However, we were not able to prove with certainty that this assumption was true."

With the help of an advanced method, the researchers have now succeeded. This is essentially based on confinement: In reality, the protons and neutrons—the nucleons—can be located anywhere in space. For their calculations, however, the team restricted this freedom: "We arranged our nuclear particles on the nodes of a three-dimensional lattice," Meißner explains. "So we allowed them only certain strictly defined positions."

## Computing time: 5 million processor hours

Thanks to this restriction, it was possible to calculate the motion of nucleons. Since nuclear particles affect each other differently depending on their distance from each other, this task is very complex. The researchers also ran their simulation several million times with slightly different starting conditions.

This allowed them to see where the protons and neutrons were most likely to be. "We performed these calculations for all known energy states of the carbon nucleus," Meißner says. The calculations were performed on the JEWELS supercomputer at Forschungszentrum Jülich. They required a total of about 5 million processor hours, with many thousands of processors working simultaneously.

The results effectively provide images from the carbon nucleus. They prove that the nuclear particles do not exist independently of each other. "Instead, they are clustered into groups of two neutrons and two protons each," the physicist explains. This means that the three [helium](#) nuclei can still be detected after they have fused to form the carbon nucleus.

Depending on the energy state, they are present in different spatial formations—either arranged into an isosceles triangle or like a slightly bent arm, with the shoulder, [elbow joint](#) and wrist each occupied by a cluster.

The study not only allows researchers to better understand the physics of the [carbon nucleus](#), but also, as Meißner concludes, "The methods we have developed can easily be used to simulate other [nuclei](#) and will certainly lead to entirely new insights."

**More information:** Shihang Shen et al, Emergent geometry and duality in the carbon nucleus, *Nature Communications* (2023). [DOI](#):

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