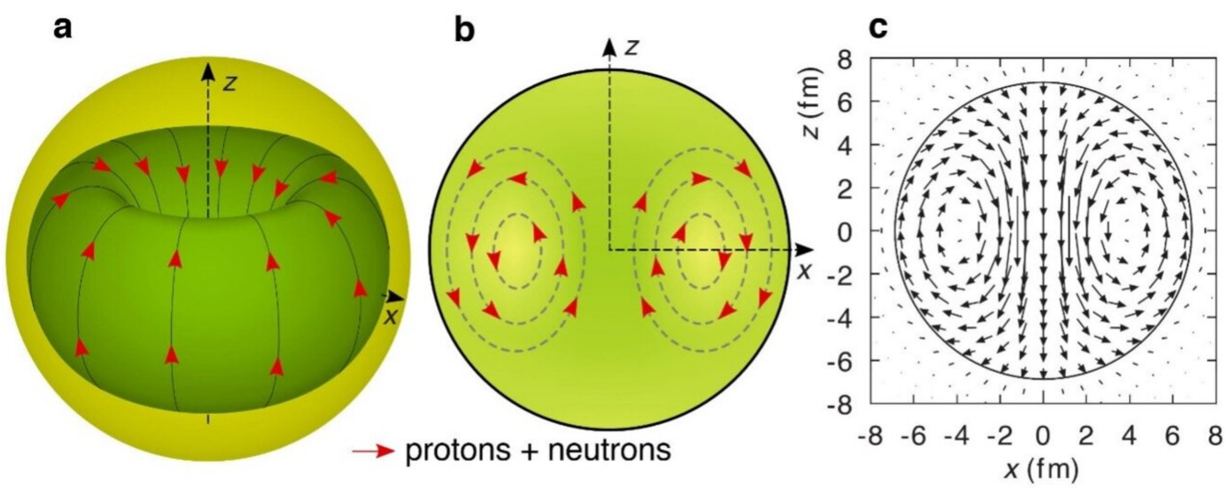
Nickel-58 nucleus may host elusive toroidal dipole excitations

January 7 2025, by Ingrid Fadelli



a) schematic 3D view of currents on the surface of a torus. b) 2D cut of a. in the x-z plane. c) Theoretical prediction of the current distribution of the toroidal electric dipole mode in a nucleus. Credit: *Physical Review Letters* (2024). DOI: 10.1103/PhysRevLett.133.232502

Dipole toroidal modes are a unique set of excitations that are predicted to occur in various physical systems, ranging from atomic nuclei to metamaterials. What characterizes these excitations, or modes, is a toroidal distribution of currents, which results in the formation of vortex-like structures.

A classic example is smoke rings, the characteristic "rings" of smoke produced when puffs of smoke are released into the air through a narrow opening. Physics theories have also predicted the existence of toroidal dipole excitations in atomic nuclei, yet observing these modes has so far proved challenging.

Researchers at Technische Universitat Darmstadt, the Joint Institute for Nuclear Research, and other institutes recently identified candidates for toroidal dipole excitations in the nucleus ^{58}Ni for the very first time. Their paper, published in *Physical Review Letters*, opens new possibilities for the experimental observations of these elusive modes in heavy nuclei .

"Toroidal flow appears in a wide variety of physics fields, including solid-state physics, metamaterials, metaphotonics, heavy-ion collisions and more," Peter von Neumann-Cosel and Valentin O. Nesterenko, co-authors of the paper, told Phys.org. "This flow looks like a vortex ring produced by a current circulating on the surface of a torus. The toroidal motion naturally appears due to turbulence in a variety of classical fluids and gases."

The vortex rings that become visible when smoke is passing through narrow passages or blown out of a person's mouth are actually invisibly produced by people at all times as they breathe out air. Smoke rings are simply one example of how these rings can become visible.

Smoke rings, an example of toroidal excitations in classical physics. Credit: Max Kleinen, Unsplash.com

"Building on this example, it is natural to expect the toroidal flow in atomic nuclei as well," said von Neumann-Cosel and Nesterenko. "During the last 50 years, the toroidal mode was indeed predicted in nuclei within various theoretical models. Moreover, tentative signatures of the toroidal dipole resonance were discussed in inelastic scattering of a-particles."

The experimental observation of these exotic modes during other nuclear reactions has so far been challenging, primarily due to a lack of reliable methods to look for and detect them. Recent studies have tried to evaluate low-energy dipole states in nuclei using high-precision photon, electron and proton scattering techniques.

"These studies have shown that some dipole states, which were previously thought to be of magnetic dipole (M1) character, are actually dipole electric (E1) but with rather unusual properties, resembling the toroidal ones," explained von Neumann-Cosel and Nesterenko. "That's why we started to think about what the peculiar nature of these states might be."

The study by von Neumann-Cosel, Nesterenko and their colleagues builds on recent research efforts studying toroidal excitations in nuclei. By comparing scattering experiments with photons, electrons and photons in the nucleus ^{58}Ni, the researchers identified candidates for excitations in this particular nucleus.

"All three types of experiments (i.e., photon, electron and proton scattering) are sensitive to dipole excitations and capable of distinguishing whether they are of electric and magnetic character," said von Neumann-Cosel and Nesterenko. "Of utmost importance was that all had high energy resolution sufficient to resolve the relevant excitations in each experiment."

The researchers compared theoretical predictions with electron scattering experiments. They found that the scattering under backward angles relative to the beam provides robust signatures of the toroidal mode.

"There are two well-established collective electric dipole excitation modes in nuclei," explained von Neumann-Cosel and Nesterenko. "One corresponds to a counter oscillation of all protons against all neutrons, the other one to an in-phase oscillation leading to a variation of the density in the nuclear interior.

"The toroidal mode is a third class of electric dipole excitations. Like the other two, it is a generic mode that should also appear in all nuclei and thus is important for the general understanding of nuclear structure."

The recent paper by von Neumann-Cosel, Nesterenko and their colleagues could have valuable implications for further research. Specifically, it could help researchers better understand a phenomenon observed in heavy nuclei, in which the number of neutrons is typically larger than that of protons, as the binding of protons is reduced due to the strong Coulomb repulsion between them.

"In these nuclei one finds at low energies a resonance-like structure of electric dipole strength, whose exact features impact on astrophysical reaction network calculations trying to model the nucleosynthesis of heavy elements," said von Neumann-Cosel and Nesterenko. "Our new results indicate that these may be toroidal excitations contrary to the presently favored model of an oscillation of the excess neutrons (which sit on the surface of the nuclei) against an inner core with about equal proton and neutron numbers."

The recent work by this research team could contribute to a better understanding of toroidal excitations in nuclei. Von Neumann-Cosel and Nesterenko are now planning a new experiment for 2025, which will be carried out at the S-DALINAC electron accelerator, situated at the Institute of Nuclear Physics, Technical University Darmstadt.

"Our work has demonstrated that electron scattering provides the clearest signature for toroidal excitations," added von Neumann-Cosel and Nesterenko. "In our next experiment, we will study a heavy nucleus with neutron excess to prove (or disprove) our claim that the low-energy structure mentioned above is due to toroidal electric dipole excitations and measure in coincidence the gamma decay to the ground state.

"The theoretical work performed for the interpretation of the ^{58}Ni experiments in the present paper indicates that this type of measurement provides additional unique signatures of toroidal excitations."

More information: P. von Neumann-Cosel et al, Candidate Toroidal Electric Dipole Mode in the Spherical Nucleus ^{58}Ni, *Physical Review Letters* (2024). DOI: 10.1103/PhysRevLett.133.232502. On *arXiv*: DOI: 10.48550/arxiv.2310.04736

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