

Nobelium-254 Forms High-Spin Rotational States

Why should elements beyond, say, atomic number $Z = 100$ exist at all? One might think that the Coulomb repulsion of so many protons ought to make such nuclei fission. But elements with a Z as high as 112 have been created,¹ and they prefer to decay by alpha emission instead of fission. So it's widely believed that the relative stability of these high- Z nuclei is a striking example of nuclear shell structure, which lowers the energy of the ground state, thereby creating a fission barrier. Without the shell-correction energy, the heaviest nuclei wouldn't be stable.

Thirty years ago, using shell model ideas, many nuclear physicists believed that an "island" of stable super-heavy elements would exist, when doubly magic nuclei would be produced, with closed shells of neutrons and closed shells of protons. Those super-heavy nuclei were expected to be spherical. Subsequently, theorists have explained the observed stability of transfermium nuclei ($Z > 100$) as being caused by the ability of the nucleus to deform, not only with quadrupole moments but also with higher multipole moments.

A remarkable experimental tour de force involving element 102 has just been reported in the 18 January issue of *Physical Review Letters* by a group of experimenters from Argonne National Laboratory, the University of Liverpool, Rutgers University, Florida State University, Saclay, the University of Jyväskylä, Lawrence Berkeley Laboratory and the University of Oslo.² Working at Argonne, the team studied nobelium-254 ($Z=102$), which was known to be a relatively stable nucleus (with a half-life of 55 s), near the

▶ An experiment at the limit of feasibility finds that instead of decaying by fission or emission of alphas, an excited nucleus of element 102 stays together and rotates in an elongated shape.

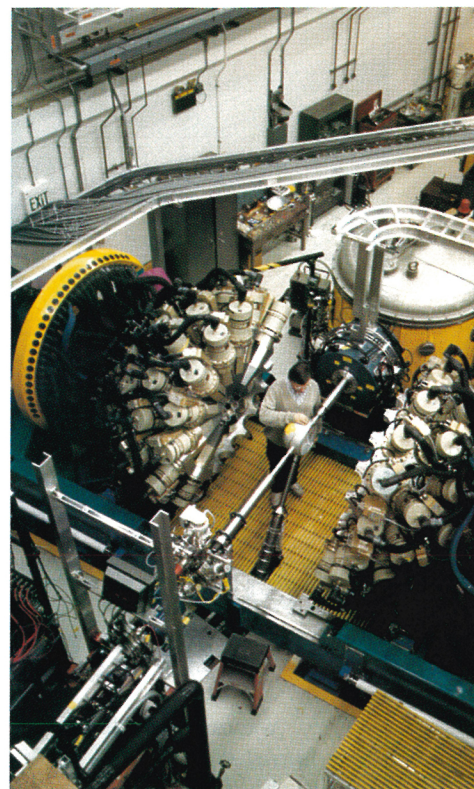
frontier of nuclei that can be reached through heavy-ion-induced compound reactions. For these very heavy nuclei, usually only the ground states have been observed, by measuring the alpha-decay chains. "But nature was kind," says Jolie Cizewski of Rutgers, "and we were able to make high spin states up to $14\hbar$."

The signature for the rotational band observed by the Argonne group is like a picket fence, says Argonne's Robert Janssens, with equally spaced gamma-ray energies marking changes of two units in angular momentum, I , from 14^+ to 12^+ , and so on. From the level spacing, one can estimate I , and with that value, one can deduce the moment of inertia and the deformation, although this calculation is somewhat model dependent. Teng Lek Khoo of Argonne explains that because the rotating nucleus stays intact up to spin $14\hbar$, "This tells us that the shell effect, which is largely responsible for the fission barrier, is robust against rotation." Says Janssens, "The amount of angular momentum transferred is important. You can fuse two nuclei with different impact parameters. In heavy nuclei, you never get very high angular momentum because they'll fission if you spin them too fast." For the heavy-ion experimenters at the Laboratory for Heavy Ion Research (GSI) in Germany, seeking to make elements 114 or 116, the Argonne results offer a clue as to what spin input is needed.

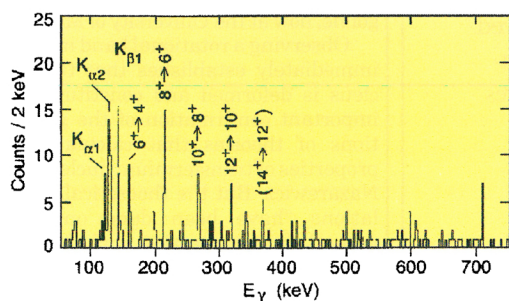
"²⁵⁴No is the heaviest nucleus to be studied by gamma spectroscopy," says theorist Witold Nazarewicz (University of Tennessee and Oak Ridge National Laboratory). "It is probably the most elongated system in its ground state above ²⁰⁸Pb."

Experimental setup

To create ²⁵⁴No, the team takes a beam of ⁴⁸Ca, produced by ATLAS, the Argonne superconducting linear accelerator, and shoots the beam at a thin layer of ²⁰⁸Pb. "You choose the bombard-



THE GAMMASPHERE ARRAY AND THE FRAGMENT MASS ANALYZER (FMA) at the Argonne ATLAS accelerator. The Gammasphere array is open in this photo, to allow the experimenter access to the target chamber. Behind the target location parts of the FMA are visible, including a quadrupole magnet (blue) and two electric dipoles (contained in yellow cylindrical tanks). (Photo courtesy of Robert Janssens, Argonne.)



GAMMA SPECTRUM corresponding to the ground-state rotational band of ²⁵⁴No obtained by a group working at Argonne with the Gammasphere and the Fragment Mass Analyzer. In addition to the energy peaks from transitions within the ground-state band, the K_α and K_β x rays characteristic of nobelium are visible. (Figure courtesy of Teng Lek Khoo, Argonne.)

ing energy and momentum to be just above the Coulomb barrier," says Janssens. "The compound nucleus ²⁵⁶No is produced, can boil off two neutrons and will then fly out of the target in less than 10^{-14} seconds as ²⁵⁴No." The cross section for producing the ²⁵⁴No is about 3 microbarns at the beam energy used. Once produced, the excited ²⁵⁴No decays by gamma emission from its high spin states.

The gamma rays are detected using the Gammasphere (see the photo above), a multidetector array once housed at Lawrence Berkeley that has 101 germanium detectors, surrounded by bismuth germanate Compton suppressors (see PHYSICS TODAY, October 1991, page 21). To identify the rotation band gammas from ²⁵⁴No in a background of over 10^4 times more intense

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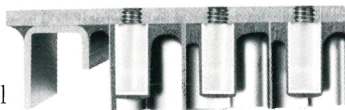
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fission gamma rays, the experimenters required coincidences with evaporation residues—that is, the gamma flash had to be in coincidence with detection of a mass of 254. To do that, the group used the Fragment Mass Analyzer (FMA), an 8 m long device located 10 m away from the Gammasphere. At the back of the FMA, at the focal plane, the particles are dispersed according to the ratio of their mass to the atomic charge state, and the device detects the position at which the mass 254 particle enters. Since the alpha-decay energy of ^{254}No was already known, the group could link the gamma flash with the characteristic alpha-decay energy and with its mass, thus ensuring that the observed particle was indeed ^{254}No .

Because the Gammasphere is a 4π detector and has very good efficiency (10% instead of the 1% efficiency typical of previous arrays of germanium detectors), it will find more than one gamma, as the nucleus loses angular momentum, according to Cizewski. Janssens elaborates: "We must see what gamma is in coincidence with another gamma and establish that there is a rotational cascade. Even though the production cross section is four orders of magnitude lower than the fission cross section, by using the FMA and doing coincidence, we can pick out these precious few events."

Experimental results

The figure on page 21 shows the gamma spectrum obtained using the coincidence gates. The observed transitions within the ground-state rotational band of ^{254}No are marked. In addition, one can also see some gammas above about 500 keV, which are presumed to be from excited bands. "The gamma rays from the rotational band have also been observed in a later experiment in Jyväskylä, Finland," according to Peter Reiter (formerly at Argonne, now at the University of Munich).

Observing a rotational band in ^{254}No immediately establishes that the nucleus is deformed and constitutes an important confirmation of the predictions of theories that calculate the properties of transfermium nuclei, says Nazarewicz. But the theoretical calculations "have been done only for ground-state properties, and the survival (against fission) of high-spin states and their moments of inertia provide new tests for theory," according to Khoo.

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Reference

1. S. Hofmann *et al.*, Z. Phys. A **354**, 229 (1996).
- 2.. P. Reiter *et al.*, Phys. Rev. Lett. **82**, 509 (1999). ■