Physics

Physics **1**, 12 (2008)

Viewpoint

How stable are the heaviest nuclei?

By Joseph B. Natowitz

Published August 11, 2008

Heavy nuclei formed by fusion reactions often decay rapidly by fissioning into two fragments. Understanding how these decays occur and over what time scale provides a means to locate the superheavy "island of stability."

Subject Areas: **Nuclear Physics**

A Viewpoint on:
Fission Time Measurements: A New Probe into Superheavy Element Stability
M. Morjean, D. Jacquet, J. L. Charvet, A. L'Hoir, M. Laget, M. Parlog, A. Chbihi, M. Chevallier, C. Cohen, D. Dauvergne, R. Dayras, A. Drouart, C. Escano-Rodriguez, J. D. Frankland, R. Kirsch, P. Lautesse, L. Nalpas, C. Ray, C. Schmitt, C. Stodel, L. Tassan-Got, E. Testa and C. Volant
Phys. Rev. Lett. **101**, 072701 (2008) – Published August 11, 2008

Protons and neutrons form shell structures in a nucleus similar in some ways to those observed in the filling of electron energy levels in an atom; in particular, as shells fill up and become closed, the nucleus becomes more stable (yielding a "magic number" of nucleons). For heavy nuclei, shell effects play an important role in determining fusion reaction probabilities and fission fragmentation patterns as long as the excitation energy is not too high. Driven by theoretical predictions of new nuclear shell closures in the atomic number range of $Z = 114$ to 126 (depending upon model) researchers in heavy-ion physics and chemistry have made great progress in recent years [1]. Accelerator production techniques have now extended the periodic table to $Z = 118$[2]. In companion studies, "one atom at a time" chemistry is being employed to establish the chemical families for new elements and explore relativistic effects in atomic structure. For the heaviest elements, electrons moving with relativistic velocities can modify the level structure and chemical behavior of an element.

However, for the synthesis technique that is commonly used (fusion of a heavy target nucleus with a heavy-ion projectile) the net production probability decreases approximately one order of magnitude for each two units of increase in atomic number as the overwhelming bulk of the nuclei produced fission into much lighter products. For the nuclei of atomic number 118 that survive fission, the cross section is $\sim$ 1 pb (picobarn). This corresponds to a nuclear reaction probability $\sim 10^{-12}$ that of normal nuclear reaction probabilities and means that with present accelerator capabilities, weeks or months of accelerator time are required to produce a few atoms. Understanding fission decay processes in these heavy nuclei can provide new guidance for fusion-based synthesis of heavier and heavier elements in the periodic table.

Now, Maurice Morjean and his collaborators at GANIL in France report in *Physical Review Letters* very precise crystal blocking experiments (Fig. 1) to measure fission decay lifetimes for nuclei in the $Z = 114$ to 124 range [3]. The authors observed fission deexcitation of excited compound nuclei formed in fusion reactions involving $^{208}\mathrm{Pb} + \mathrm{Ge}$, $^{238}\mathrm{U} + \mathrm{Ni}$, and $^{238}\mathrm{U} + \mathrm{Ge}$. Their experiment combines a fission-fragment channeling measurement with a careful characterization of reaction mechanisms using the GANIL detector system INDRA that collects emitted light particles and fragments over 4π[4]. Long tails on the decay time distributions, extending well beyond 10^{-18} s (1 attosecond), indicate long fission delays resulting from relatively high fission barriers in the region of atomic number 120 and 124. Furthermore, the fission is asymmetric, reflecting the restoration of significant shell effects as the excited compound nuclei formed in the fusion reaction cool down. These results provide very strong evidence for shell closure in the $Z = 120, 124$ region, a feature seen in full microscopic calculations [5]. In contrast, for $Z = 114$, the delay times are much shorter close to or below the sensitivity limit of the experiment, suggesting that shells are not being closed.

The blocking technique requires a precise measurement of the fragment angular distribution relative to the crystal axis (Fig. 1, left). Coupling this with a 4π detector such as INDRA provides high statistics and, more importantly, allows selection of fragments from complete fusion reactions. Blocking in the atomic plane leads to shadowing of a detector oriented perpendicular to the crystal axis. Channeling between crystal planes allows the fragments to escape the crystal with very small energy losses. In the shadow realm a characteristic blocking dip (Fig. 1, right) is observed with a minimum precisely in the direction of the crystal axis. Due to its geometrical origin this dip would reach its mini-

DOI: 10.1103/Physics.1.12
URL: http://link.aps.org/doi/10.1103/Physics.1.12

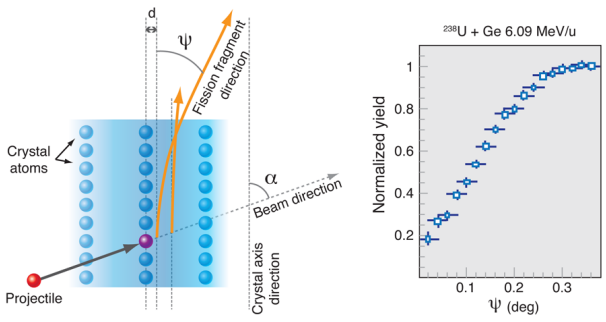

FIG. 1: (Left) Principle of the crystal blocking technique. Heavy ions bombard a single-crystal target at an angle α relative to the crystal planes, causing a projectile nucleus and crystal nucleus to fuse. Fission fragments from very short lived nuclei ($< 10^{-18}$ s) are emitted in the plane of the target atoms (that is, the angle of emission relative to the crystal axis $\psi = 0$) and are thus blocked from reaching the detector. Fragments emitted from nuclei that survive long enough to move into a channel between the crystal planes (e.g., at a distance d from a plane) are detected with little energy loss. Thermal vibrations in the crystal determine the lower time limit for blocking. (Right) The blocking dip observed for $Z = 124$ for $^{238}\mathrm{U} + \mathrm{Ge}$ reactions (at 6.09 MeV per nucleon collision energy) and fragments in the range of $67 < Z < 85$. The width of the dip depends on atomic number and kinetic energy of the fragment. ((Left) Alan Stonebraker/`stonebrakerdesignworks.com` (adapted from [6]); (Right) From Morjean *et al.*[3].)

mum possible value for perfect crystals and experimental conditions. In practice the dips are filled and broadened due to crystal defects and radiation damage or to experimental conditions such as beam size, determination of the axis direction of the crystal, and so forth. The GANIL group has carried out extensive Monte Carlo simulations to evaluate the consequences of these effects. The minimum time which can be measured in this technique is determined by the thermal vibrations in the crystal and is $\sim 10^{-18}$ s. Fission times much longer than this are expected only if the (shell induced) fission barriers in these very heavy nuclei are relatively large. The derivation of more detail on the time distributions is possible but has some model dependence.

Extension of these studies over a broader range of atomic number, neutron number, and temperature should provide a wealth of new information on the shell gaps in the super-heavy element region and pinpoint the location of both spherical and possibly deformed shell closures. In addition, the relative slowness of the fission process for these very heavy nuclei may allow even modestly heated nuclei to assume exotic equilibrium shapes that manifest the nature of the underlying potential energy surface. A number of macroscopic and microscopic models suggest that nuclei in this mass range may assume very exotic Coulomb driven forms, i.e., extended linear, toroidal, or bubble-like shapes. Several calculations indicate that the nucleus $Z = 120$, $N = 172$ is doubly magic and has a semibubble character. The deexcitation of such nuclei may also be quite exotic, for example, fragmentation into multiple, possibly similar-mass, pieces reflecting Raleigh instabilities. Some calculations also suggest that nuclei of $A \sim 300$ to 476 with low excitation energies may exist for very long times.

References

[1] P. Armbruster, *Rep. Prog. Phys.* **62**, 465.
[2] Y. T. Oganessian *et al.*, *Phys. Rev. C* **74**, 044602 (2006).
[3] M. Morjean *et al.*, *Phys. Rev. Lett.* **101**, 072701 (2008).
[4] Website for GANIL and the INDRA detector: `http://infodan.in2p3.fr/indra/`.
[5] M. Bender, K. Rutz, P-G. Reinhard, J. A. Maruhn, and W. Greiner, *Phys. Rev. C* **60**, 034304 (1999).
[6] M. Morjean *et al.*, *Eur. Phys. J. D* **45**, 27 (2007).

About the Author

Joseph B. Natowitz

Joseph B. Natowitz is holder of the Bright Chair in Nuclear Science at Texas A&M University, and conducts research in nuclear reaction dynamics and the properties of very highly excited nuclei. His research has been recognized by election as a Fellow of the American Physical Society (1981), with the American Chemical Society's Award in Nuclear Chemistry (1995) and Southwest Regional Award (2000), as well as by an Alexander von Humboldt Senior Scientist Award (1978) and an Association of Former Students Research award from Texas A&M University (1988). He has been a Visiting Professor at the Université de Caen and the Université Claude Bernard in France, the University of Tokyo, Japan, and the Université Catholique de Louvain, Belgium. He has been Visiting Senior Scientist at the Max Planck Institute in Heidelberg, Germany and the Centre d'Etudes Nucléaires, Saclay, France.

DOI: `10.1103/Physics.1.12`
URL: `http://link.aps.org/doi/10.1103/Physics.1.12`