selection for increased variability in egg coloration, making it easier to detect parasitic eggs[5]? A combination of Lyon's incisive field techniques with genetics, and with molecular determination of parasitism and parentage[10,11], seems likely to provide further insights into the cognitive and tactical aspects of brood parasitism and reproductive behaviour. ■

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Nuclear physics

Into the fission valley

Peter Möller and Arnold J. Sierk

Why are new elements difficult to make? Fusion of two nuclei to produce heavy elements seems to be hindered by a competing process of 'quasi-fission'. New work builds a more complete picture.

On Earth, elements heavier than uranium do not exist in easily measurable quantities, because they become increasingly unstable against radioactive decay. Some heavier elements can be artificially created through the collision and fusion of other nuclei, and over the past 60 years about 20 new elements have been added to the periodic table — up to an atomic number of at least 110. But fusion becomes less successful when the projectile and target nuclei are chosen to form a product with nucleon number, A, greater than 220 (more than 90 protons and 130 neutrons). For example, in some experiments[1] only about one out of 10^{18} nuclei incident on a target leads to the creation and detection of the desired new element.

In *Physical Review Letters*, Hinde, Dasgupta and Mukherjee[2] present a detailed analysis of this inhibition of fusion near $A = 220$. They made a careful comparison of fusion cross-sections (or probabilities) from their own experiment on the reaction $^{16}\mathrm{O} + {}^{204}\mathrm{Pb}$ with other experiments on $^{40}\mathrm{Ar} + {}^{180}\mathrm{Hf}$, $^{48}\mathrm{Ca} + {}^{172}\mathrm{Yb}$, $^{82}\mathrm{Se} + {}^{138}\mathrm{Ba}$ and $^{124}\mathrm{Sn} + {}^{96}\mathrm{Zr}$, all of which lead to the same compound system, $^{220}\mathrm{Th}$. The results show that it is much more difficult to make $^{220}\mathrm{Th}$ with more symmetric combinations of target and projectile than with the most asymmetric combination ($^{16}\mathrm{O} + {}^{204}\mathrm{Pb}$) — specifically about ten times more difficult. Hinde *et al.* propose that this is due to competition with the process of 'quasi-fission'. Colliding nuclei form a composite at the onset of the fusion process, but the composite may break up, or undergo fission, before fusion is complete. True fission occurs after the formation of an equilibrated compound nucleus; quasi-fission results from the much faster breakup of a partially fused composite.

Today's theories of heavy-ion collisions are mainly macroscopic; the energy of the colliding system can be written as a sum of the repulsive electrostatic energy and the attractive nuclear energy. After the colliding nuclei touch, these energies must be calculated for the combined system as functions of its shape. The resulting 'energy landscape' (a multi-dimensional potential-energy surface in deformation space) has a strong influence on the dynamics of the fusion process.

In macroscopic models, the energy landscape changes relatively slowly with proton and neutron number and with deformation of the shape of the nucleus away from a simple sphere. But microscopic effects, which arise because the protons and neutrons in the nuclei obey quantum-mechanical laws, vary much more rapidly as the neutron and proton numbers and the shape change, sometimes producing large differences between the behaviour of systems with only slightly different nucleon number. Microscopic effects are not often included in theoretical studies of nuclear collisions, but we believe that they should be considered more carefully. There are other factors, too: how dissipation converts the kinetic energy of the projectile into internal excitation energy of the fusing system; and the effect of the relative orientation of target and projectile if one or both of them are deformed (around 50% of stable nuclei are not spherical).

In their paper, Hinde *et al.*[2] consider various explanations for the inhibition of fusion seen in the data. First, they discuss the idea of the 'extra push' — a colourful misnomer used to describe a dynamical threshold. For heavy compound systems, extra kinetic energy (more than is needed to bring the nuclei into contact after overcoming their electrostatic repulsion) is required for them actually to fuse and form a single nucleus. A good analogy is a skier crossing a mountain range, starting out with some initial energy. For

100 YEARS AGO

Concerning the recently discovered heat emission from radium, it is perhaps worth noting that it appears to be connected with, and is probably an immediate consequence of, the remarkable observation by Rutherford that radium emits massive positively-charged particles, which are probably atoms, with a velocity comparable to one-tenth of the speed of light… Because it is easy to reckon that the emission of a million heavy atoms per second, which is a small quantity barely weighable in a moderate time such as a few weeks (being about the twentieth part of a milligramme per century), with a speed equal to one-tenth that of light, would represent an amount of energy equal to one thousand ergs per second; that is to say, would correspond to heat enough to melt a milligramme of ice every hour. And inasmuch as these atoms are not at all of a penetrating kind, but are easily stopped by obstacles, they would most of them be stopped by a small thickness of air, and their energy would be thus chiefly expended in the immediate proximity of the source, which source would thereby tend to be kept warm.

From *Nature* 2 April 1903.

50 YEARS AGO

Before the War one could make materials artificially radioactive by bombardment in big machines like cyclotrons, or by using relatively weak neutron sources. In the cyclotron, one can generally only use one target at a time and the irradiation is therefore costly. The weak neutron sources induce only weak activities. Therefore only a few research workers profited from the radioisotopes which one could produce in these ways. The situation changed suddenly with the discovery of fission of uranium in 1939. This discovery showed that chain reactions were possible in which more neutrons are created than used. Accelerated by war research, the first chain-reacting atomic pile was working on December 2, 1942, in Chicago… New radioisotopes were quickly discovered and the chart of radioactive isotopes started to expand. To-day, there are more than six hundred radioactive isotopes, of which, however, only some hundred can be made conveniently in an atomic pile. For most elements there is at least one usable radioactive isotope. The only notable exceptions are the two elements nitrogen and oxygen for which no convenient radioactive isotope exists.

From *Nature* 4 April 1953.

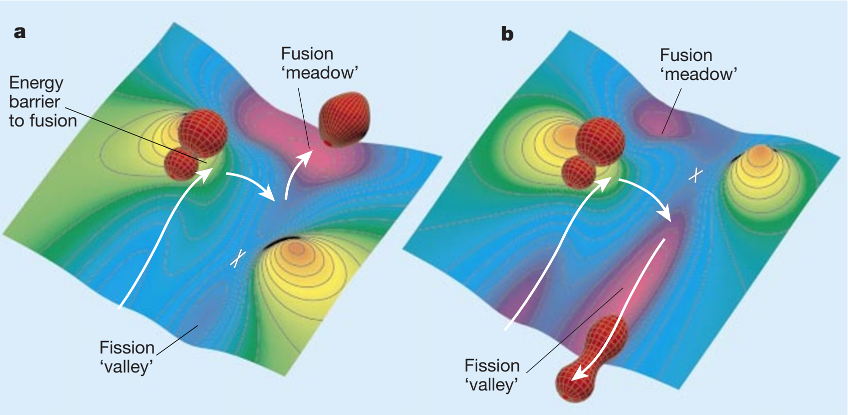

Figure 1 **Schematic energy landscapes for fusing nuclei.** a, **For lighter nuclei, the pair move up the 'fusion valley', opposed by electrostatic repulsion. The maximum in the potential along the initial path ('fusion barrier') occurs near the point where they first touch. If there is only enough initial energy to reach this point, the forces push the system to the right, leading inside the fission saddle point (indicated by a cross). Then the system falls towards the fused ground state (pink area).** b, **For a heavier system, the nuclei pass outside the saddle point, eventually falling down the fission valley — unless they are given sufficient extra initial energy to drive them towards fusion.**

lighter systems (Fig. 1a), the process of fusion corresponds to climbing up to the head of a fusion valley (overcoming electric repulsion) and surmounting a barrier (where the short-range nuclear attraction balances the electric repulsion) to access a meadow beyond (the lower energy of the fused nuclei). After passing over this barrier, the nuclei come into contact, and the system, or skier in our analogy, is on the side of a hill, which is due to the forces trying to deform the nuclei. Once he has surmounted the barrier peak, even with no residual energy, the skier would naturally descend into the depression beyond.

For heavy systems (Fig. 1b), in which the electric forces are relatively stronger, the topography is different. For one thing, the 'fusion meadow' becomes much smaller, and has higher energy. The path to the smaller meadow lies along the side of a slightly steeper hill. So if the skier started up the valley with just enough energy to reach the peak of the barrier, he would find himself pushed sideways, moving away from the meadow down a separate 'fission valley' below his initial path on the side of the hill.

By starting out with additional energy, the skier would arrive at the touching point with residual forward momentum, and could continue along the side of the hill far enough to drop into the meadow. So even in the absence of friction, extra energy above the barrier peak (dynamical threshold energy) is needed for heavy systems to fuse. If there are dissipative processes (such as energy coupling from the motion of the nuclei into internal excitations when they come into close proximity), even more energy is needed for fusion. Calculations in macroscopic models show that a fairly rapid transition occurs between the two situations sketched above, owing to the shift of the fission saddle point, when the target and projectile masses add up to $A \approx 220$. This is why it is relatively easy to make lighter nuclei through fusion and more difficult to make heavier nuclei. Experiments and macroscopic theory seem to agree well on this feature of fusion reactions.

But there are other details to be taken into account for heavy systems. Hinde *et al.*[2] also looked at the effect of the asymmetry of a system on the fusion probability. In very asymmetric systems, the larger body tends to absorb the smaller one, but in more balanced systems there tends to be a transfer of mass from the heavy to the light partner. We would caution against invoking this macroscopic mechanism too strongly, however, as microscopic effects may dominate the gentler macroscopic forces.

Another consideration is that in the quantum world a reaction is more successful if the initial state highly resembles the final state. The final state in this case is a single spherical, or almost spherical, nucleus. A very small projectile touching a very large target more closely resembles this final state than do two nuclei of more similar size. Even in a classical context, less matter needs to be moved in the very asymmetric case.

If the target or the projectile is deformed, the relative orientation of the nuclear symmetry axes should also be considered. Hinde *et al.*[2] argue, as others have done[3], that if an undeformed nucleus hits a (prolately) deformed one at its equator, this compact configuration might be less hindered than other collision orientations, again because of the greater compactness and similarity to the final configuration. Of course, if both target and projectile are deformed, many other intriguing possibilities arise[4].

Microscopic effects should not be overlooked. For example, the cross-section for creating isotopes of 'darmstadtium', the element with atomic number 110, is five times as large for ^{64}Ni + ^{208}Pb as for ^{62}Ni + ^{208}Pb. Such rapid cross-section variations are not predicted in macroscopic models. In another study, Satou *et al.*[5] saw similar differences between the two reactions ^{82}Se + ^{134}Ba and ^{82}Se + ^{138}Ba (leading to ^{216}Th and ^{220}Th, respectively): the second reaction is much more productive than the first. The isotope ^{138}Ba has extra binding energy because the outermost shell of neutrons in its nucleus is full. This extra binding (about 5 MeV) will tend to resist deformations away from the fusion path.

In our skier analogy, the full spherical shell may create a ditch along the side of the hill that the skier traverses, enabling him to follow the fusion path without needing to start with the extra momentum apparently necessary in the ^{134}Ba case. But it is also possible that, if the neutron shell is not full (as in ^{134}Ba), the nucleus would dissipate more energy because there are more low-lying energy levels that could be excited in the early stages of the interaction of the colliding nuclei. Trying to isolate the microscopic potential-energy effects from dissipative dynamics remains a problem in both theory and experiment.

Some of the more efficient reactions for the production of heavy nuclei have involved Pb targets, which also have resistance to deformation because both the proton and neutron shells are full, or almost full[6]. It is conceivable that the higher fusion probability for ^{16}O + ^{204}Pb is not due to the macroscopic 'swallowing-up' effect discussed above, but to the extra binding (10 MeV) of the nearly closed-shell ^{204}Pb nucleus. It is tantalizing that the next-highest cross-section in the ^{220}Th system analysed by Hinde *et al.*[2] involves the ^{82}Se + ^{138}Ba system, which has the most extra binding (5 MeV) of the other, less asymmetric channels studied.

The conclusion from the work of Hinde *et al.* is that the big picture — of valleys, mountains and meadows — is well described by some macroscopic models, but considerable effects arise because of microscopic details. The machinery for calculating these microscopic effects has developed rapidly in recent years, and may soon be used to help understand experimental data, with an eye to predicting promising new reactions to explore. ■

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