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THE DRAGON GUARDING THE ISLAND OF SUPERHEAVY NUCLEI HAS DROPPED HIS SHIELD*

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The unexpectedly large cross-section reported for the reaction $^{86}\mathrm{Kr} + {}^{208}\mathrm{Pb} = {}^{293}118 + n$ may be due to the lowering of the Coulomb barrier (measured with reference to the energy of the compound nucleus). Some consequences of this "unshielding" phenomenon are discussed.

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It is a great pleasure to contribute this talk on the occasion of Kasimir Grotowski's 70th jubilee. Three score and ten seems to most people like an appropriate retirement age, but this does not take account of the twin paradox in special relativity, which says that if you travel frequently and far — as Kasimir has done — you age more slowly. I believe that tunneling effects may also have contributed to Kasimir's looking suspiciously younger than 70. As many of you know, Kasimir has done a lot of tunneling at one time, as described in a book on the exploits of Polish spelunkers in the fifties. (P. Burchard, "Z Wypraw Grotołazów", Warsaw 1957.) Now, tunneling effects are related to so called instantons, for which time stands still. It is true that this is only the case for quantal tunneling, but some of the photographs in Burchard's book have convinced me that the tunneling must have been quantal in the tightest passages attempted. In any case, taking both relativity and quantum mechanics into account, we are well justified in not really believing that Kasimir is seventy years old.

Figure 1 provides the justification for the title of my talk about the dragon lowering his shield. The shield in question is the Coulomb barrier that guards the compound nucleus against a direct attack in a heavy-ion reaction. The upper part of Fig. 1 (based on [1]) shows the exponentially

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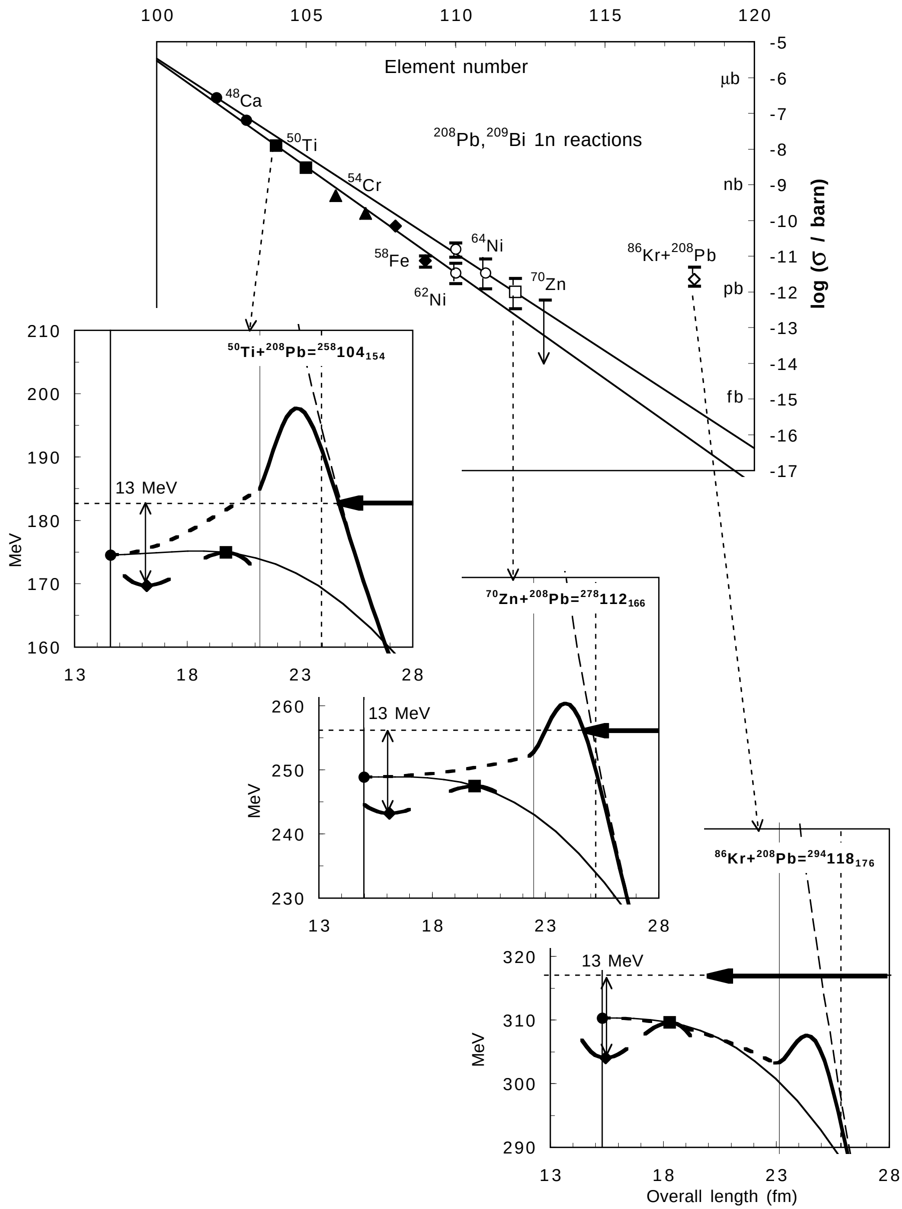

Fig. 1. The upper part shows the cross-sections for forming very heavy nuclei with element numbers between 104 and 118. The lower figures illustrate the energies along the fusion and fission valleys as functions of the overall length of the configuration in question. (See text.)

decreasing cross-sections for making heavy elements in bombardments of ^{208}Pb and ^{209}Bi with progressively heavier projectiles, from ^{48}Ca through ^{70}Zn to ^{86}Kr. The bombarding energies were always such that the excitation energy of the compound nucleus was around 13 MeV, the optimum for emitting just one neutron. The startling feature of the plot is the break in the systematics in going from ^{70}Zn to ^{86}Kr. The cross section for the latter reaction was about 2.2 pb [2], some four orders of magnitude higher than a simple extrapolation would have suggested. The big question is, what happened between ^{70}Zn and ^{86}Kr?

The lower part of Fig. 1 shows the position of the dragon's Coulomb barrier shield (the thick curve, followed by a dashed interpolation) in relation to the center-of-mass bombarding energy (thick horizontal arrow) as one goes through the sequence of the above reactions. The barrier shown is the sum of the electrostatic repulsion (dashed curve) and the nuclear proximity attraction [3], calculated for frozen density distributions of the colliding partners. The plots are against the overall elongation of the configuration in question. This means the distance between the outer tips of the approaching spheres before contact, and the major axis of the fusing system after contact. The diameter of the spherical configuration is indicated by the medium-weight vertical line. "Firm contact", *i.e.*, contact of the two half-density profiles, corresponds to the thin vertical line. "Gentle contact", *i.e.*, contact between the density tails, is indicated by the dashed vertical line. It is the distance at which for the first time the most energetic nucleons can be exchanged between the nuclei without quantal penetration. (At "firm contact" nucleons with any energy can be exchanged for the first time. According to a Thomas–Fermi model of the nuclear surface, "gentle contact" is about 2.74 fm outside "firm contact" [3].) The medium-weight curve shows the energy along the "fission valley" of the disintegrating compound nucleus, as calculated using the Thomas–Fermi model without shell effects. The ground-state shell effect (as estimated using Fig. 3) produces a deformed ground state (the deformation is small for ^{294}118). Also shown is the estimated location of the saddle-point defining the fission barrier that guards the compound nucleus against disintegration [4].

The striking feature of Fig. 1 is the dipping of the Coulomb shield below the $1n$ bombarding energy between ^{70}Zn and ^{86}Kr. Is this responsible for the break in the cross-section systematics? It is difficult to be sure, since there does not exist an adequate theoretical understanding of the observed miniscule cross-sections: theories of fusion dynamics and of the subsequent competition between particle emission and fission have not reached a sufficiently quantitative stage. (A semi-empirical treatment can be found in [5].) Regarding entrance channel fusion dynamics, the relatively abrupt appearance of a hindrance factor for compound-nucleus formation when target-projectile combinations exceed a certain size may, indeed, be correlated with the relative degrees of compactness of the tangent-sphere and the saddle-point configurations [6]. The trend of this relative compactness can be seen in the plots in Fig. 1, where for ^{50}Ti + ^{208}Pb the firm contact configuration is only some 1.5 fm outside the saddle, the difference growing to 2.6 fm for ^{70}Zn and 4.8 fm for ^{86}Kr. One expects that somewhere between gentle contact and firm contact a tendency to heal the neck region between the two nuclei would set in (unless this is resisted by the shell and "congruence" energies — see later). This is bad for fusion, because with increasing neck the system slides down — gets injected — into the fission valley, where the driving force is towards re-separation. As can be seen from Fig. 1, this driving force, as well as the distance between a likely injection point and the saddle, grows with increasing Z. This is the "extra push" phenomenon that may be contributing to the rapid decrease of cross-sections in Fig. 1. But, somewhere between ^{70}Zn and ^{86}Kr, one may expect a qualitative change. The Coulomb shield no longer stops the approach of the nuclei, and the system may fight its way towards a more compact configuration, delaying the near fatal injection into the fission valley. But one should remember that in going from ^{70}Zn to ^{86}Kr three things actually happen. In addition to the favourable lowering of the shield, two unfavourable changes take place: the firm contact configuration has moved up from 22.5 fm to 23.1 fm, and the saddle has moved back from 19.9 fm to 18.3 fm (the ground state of element 118 is almost spherical, and the saddle is correspondingly more compact). Perhaps this increase by 2.2 fm in the distance from the contact configuration to the saddle is responsible for the fact that, despite the lowering of the Coulomb shield, the cross section to make element 118 has remained at the picobarn level.

Is there a way of testing the hypothesis that the break in the trend of cross-sections in Fig. 1 is associated with the lowering of the Coulomb shield? It turns out that this should actually be relatively easy. Fig. 2 shows how. Element 108 was made at GSI with a peak cross-section close to 70 pb in the reaction ^{58}Fe + ^{208}Pb = ^{266}108, and this, as you can see, is a reaction shielded by the Coulomb barrier. The same isotope can be reached by ^{128}Te + ^{138}Ba = ^{266}108, which is unshielded (but with a contact configuration that moved up by 1.0 fm). In these two reactions the compound nucleus is the same, with the same excitation energy, so the only difference is in the entrance channel. If the observed cross-section turns out to be more than 70 pb, this will be a strong indication that unshielding offers definite advantages. The same test can be carried out in the case of element 112, produced at GSI with a picobarn cross-section in the shielded reaction ^{70}Zn + ^{208}Pb = ^{278}112. Again, the same isotope can be reached by the unshielded ^{136}Xe + ^{142}Ce. Will the cross-section be 10 pb, 100 pb, perhaps more?

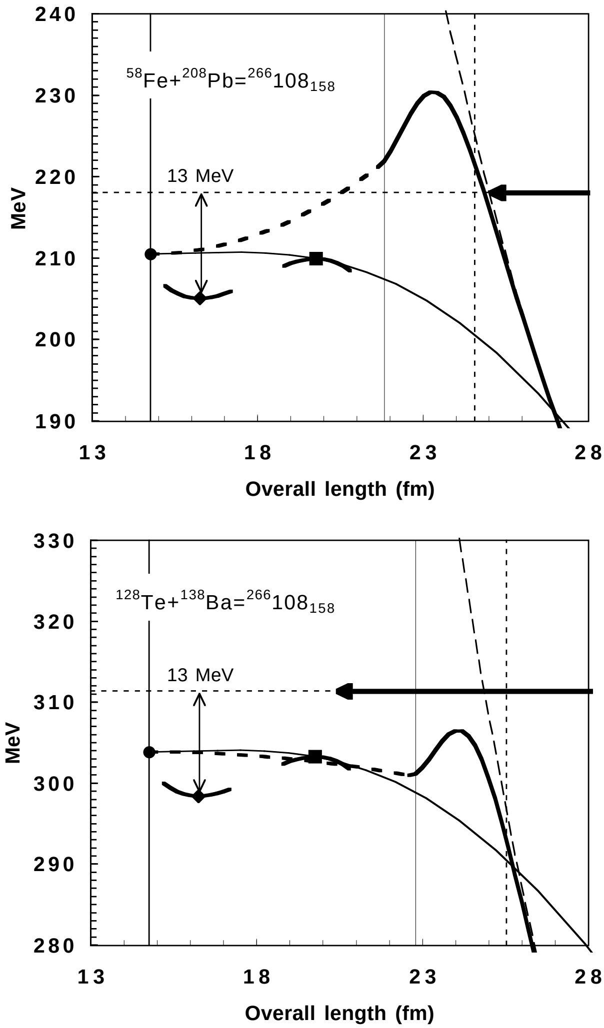

Fig. 2. The fusion and fission valleys for shielded and unshielded reactions leading to ^{266}108. (For the meaning of the lines and curves refer to the text.)

The reason why unshielded reactions make their appearance only with very heavy target-projectile combinations is elementary. The energy needed to deform a compound nucleus into two tangent fragments is resisted by the surface energy and favoured by the electrostatic energy. Hence the greater the charge on the compound nucleus, the lower the Coulomb barrier (as measured with respect to the ground-state energy) until, above a critical charge, the Coulomb barrier sinks below this energy (or this energy augmented by some constant, like the 13 MeV in the examples above). This happens first for deformations into two equal pieces, where the Coulomb energy relief is greatest. For even higher charges there opens up a range of asymmetries for which unshielding is achieved. (Negative shell effects in the target and projectile pieces will enhance the unshielding by lowering the energy of the tangent configuration.)

Unshielded reactions that use more nearly symmetric target-projectile combinations have two disadvantages: the above mentioned loss of compactness of the contact configuration, and (often) the loss of the advantages associated with targets near the doubly magic ^{208}Pb. The advantage of using (doubly) magic targets has long been recognized as lowering the Coulomb shield. But the other, less obvious advantage is that the magicity of target and/or projectile delays the injection into the fission valley. This is because the shell energy resists for as long as possible the growth of the neck that destroys this extra binding energy. In this connection it may be noted that the shape-dependent "congruence energy" of [7], related to the "Wigner term" in nuclear mass formulae, acts like a shell effect: it also resists the transformation of two nuclei into one. (The negative congruence energy is approximately halved after fusion.) As an illustration, in the reaction ^{58}Fe+^{208}Pb, the initial total shell effect is 0.40 MeV −13.41 MeV = −13.01 MeV, and the change in congruence energy in going from the compound nucleus to the two fragments is −6.05 MeV, for a total extra binding that resists neck formation of −19.06 MeV. (All these estimates are made using [8].) In the unshielded reaction ^{128}Te+^{138}Ba the corresponding numbers are: total shell −6.68 MeV, change in congruence energy −4.54 MeV, for a final total of −11.22 MeV. This change from −19.06 MeV to −11.22 MeV represents a significant loss of resistance against neck formation. In the case of the two reactions mentioned above that lead to ^{278}112, the corresponding "figures of merit" are nearly equal: −15.77 MeV (shielded) and −12.52 MeV (unshielded).

Unshielded reactions, if proved beneficial, might open a broad avenue for making heavy elements, in particular for reaching the island of superheavy nuclei around $N = 184$ and $Z = 114$–126. Fig. 3 illustrates what the future might bring. The contour lines are based on calculated shell effects in MeV taken from [9]. The diamonds represent known nuclei, including the heavy elements from $Z = 106$ to 112, laboriously created in the past 25 years in shielded reactions, whose cross-sections peter out ominously at the picobarn level for $Z = 112$. The circles refer to $Z = 118$ and its alpha decay products, resulting from last year's unshielded reaction carried out in Berkeley [2]. If it is confirmed that also $Z = 108$ and $Z = 112$ can be produced with increased cross-sections in unshielded reactions, then the way seems open to eventually creating dozens of new isotopes for $Z > 105$, up to perhaps $Z = 120$, or even beyond. In Fig. 3 we have shown only two additional candidate reac-

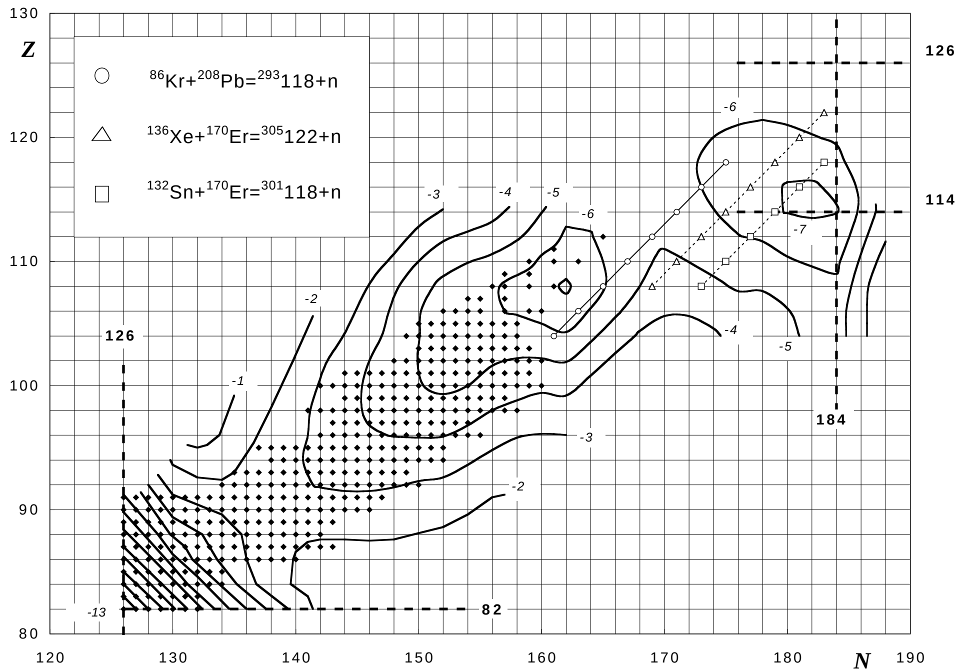

Fig. 3. Contour lines, in MeV, of the calculated shell effect as a function of N and Z. Diamonds refer to known nuclei. The three α-decay chains shown are discussed in the text.

tions. The combination $^{136}\mathrm{Xe} + {}^{170}\mathrm{Er} = {}^{305}122 + n$ is especially interesting because its decay products would overlap the decay chain of $^{289}114$, suggested last year by the Dubna–Livermore collaboration as the result of the reaction $^{48}\mathrm{Ca} + {}^{244}\mathrm{Pu} = {}^{289}114 + 3n$ [10]. These reactions may represent the closest approach to the center of the magic island delineated in Fig. 3 that can be achieved with non-radioactive beams. (Recent estimates suggest that this island may actually be stretched out or even shifted towards $Z = 120$ [11]. In that case the Xe+Er reaction might already be close to ideal.) The squares in Fig. 3 refer to the reaction $^{132}\mathrm{Sn}(\text{radioactive}) + {}^{170}\mathrm{Er} = {}^{301}118 + n$, which samples the deepest part of the island of stability in Fig. 3. Provided sufficiently intense radioactive beams can be produced, the nucleus $^{132}\mathrm{Sn}$, with its huge shell effect of -11.75 MeV, would represent a worthy replacement for the workhorse $^{208}\mathrm{Pb}$ in the regime of unshielded, more symmetric reactions.

The above qualitative discussion of some of the simplest aspects of heavy ion collision dynamics raises interesting perspectives for the future. But it is the experimental progress in the coming year or two that will decide the feasibility of realizing these hopes.

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