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Mechanisms Suppressing Superheavy Element Yields in Cold Fusion Reactions

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Superheavy elements are formed in fusion reactions which are hindered by fast nonequilibrium processes. To quantify these, mass-angle distributions and cross sections have been measured, at beam energies from below-barrier to 25% above, for the reactions of ^{48}Ca, ^{50}Ti, and ^{54}Cr with ^{208}Pb. Moving from ^{48}Ca to ^{54}Cr leads to a drastic fall in the symmetric fission yield, which is reflected in the measured mass-angle distribution by the presence of competing fast nonequilibrium deep inelastic and quasifission processes. These are responsible for reduction of the compound nucleus formation probablity P_{CN} (as measured by the symmetric-peaked fission cross section), by a factor of 2.5 for ^{50}Ti and 15 for ^{54}Cr in comparison to ^{48}Ca. The energy dependence of P_{CN} indicates that cold fusion reactions (involving ^{208}Pb) are not driven by a diffusion process.

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The development of the shell model of nuclear structure resulted in the prediction [1–3] in the 1960s of an "island" of enhanced stability for nuclei up to 30% more massive than the heaviest naturally occurring elements. The predicted existence of these superheavy elements (SHE) results from closed shells of protons and/or neutrons (so-called magic numbers) that provide increased nuclear stability—analogous to that of noble gases in chemistry. Different models predict the island may be centred at proton numbers $Z = 114$, 120, or 126 [1–4]. The synthesis of all SHE up to $Z = 118$, and their long half-lives (up to seconds), indicate the existence of the island [5], but its center and extent are not yet known. Defining the properties of SHE, and the location of the boundary to the existence of the chemical elements, are major goals in physics and chemistry.

SHE are created in the laboratory through the fusion of two lighter nuclei. This has required impressive experimental advances due to the extremely small production cross sections in the order of 10^{-36} cm^2. Fundamentally these result from the Coulomb repulsion between the large number of protons that must be packed together in the SHE nucleus. Even with sufficient kinetic energy to bring the surfaces of the colliding nuclei into contact, fast nonequilibrium deep-inelastic (DIC) [6,7] and quasifission (QF) [8] processes can cause the system to reseparate so quickly ($<10^{-20}$ s) that a compact superheavy nucleus is not formed, thus suppressing fusion. Even if the two nuclei fuse and form a compact compound nucleus (CN), the heavy element is unlikely to survive, since the CN usually splits (fissions) in $<10^{-16}$ s into two similar-sized fragments (fusion fission [FF]).

The most successful fusion reactions have used projectile and/or target nuclei that have magic numbers of protons (Z) and/or neutrons (N), particularly ^{48}Ca ($Z = 20$, $N = 28$) and ^{208}Pb ($Z = 82$, $N = 126$). Their use, rather than nearby nuclei, results in lower excitation energy of the fused system, reducing the probability of fission. For this reason, fusion of heavy nuclei with ^{208}Pb is known as cold fusion. Recent experiments [9–12] have indicated that collisions of nuclei having several magic numbers not only decreases the probability of fission after fusion, but also increases the probability of fusion itself.

The heaviest element Oganesson ($Z = 118$) was formed by fusing accelerated ^{48}Ca nuclei with radioactive ^{249}Cf target nuclei [13]. To form even heavier elements, projectiles with more protons than ^{48}Ca must be used because of the near impossibility of creating enough target material of elements heavier than Cf [14]. Their use results in lower SHE yield, as demonstrated by the unsuccessful attempts to synthesize element $Z = 120$ [15] with ^{50}Ti, ^{54}Cr [16], ^{58}Fe [17], and ^{64}Ni [18] beams. It is vital to understand the reaction dynamics in order to choose the best reactions to produce new SHE.

Because of the different timescales of the three stages of SHE synthesis, namely contact, fusion, and fusion fission,

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