# Shell Effects in Heavy Ion Collisions

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The importance of shell effects in the fusion of nuclei was demonstrated experimentally as an enhanced fusion probability when using Pb or Pb-like targets as compared to targets from the transuranic region. In our dynamical approach developed originally [1], we did not include shell effects and therefore we could describe only the average behavior of heavy-ion collisions and not the behavior of specific combinations of target and projectile. We have now included shell effects in our calculations in a phenomenological form proposed by Myers and Swiatecki [2]. In that approach the shell correction $S_0(N,Z)$ to the potential energy is written in the form

$$S_0(N,Z) = (5.8 \text{ MeV}) \left( \frac{F_N + F_Z}{(A/2)^{2/3}} - 0.325 A^{1/3} \right)$$

where

$$F_N = q_N(N - N_{i-1}) - \frac{3}{5}(N^{5/3} - N_{i-1}^{5/3})$$

with

$$q_N = \frac{3}{5} \frac{N_i^{5/3} - N_{i-1}^{5/3}}{N_i - N_{i-1}} .$$

Here $N_{i-1}$ and $N_i$ correspond to the numbers of closed shell neutrons and $N$ is the actual number of neutronsbetween $N_{i-1}$ and $N_i$ for a system of mass $A$. The same formulas for $F_Z$ and $q_Z$ describe the shell effect for protons. For neutron and proton numbers $N$ and $Z$ corresponding to closed shells $N_{i-1}$ and $Z_{i-1}$ the shell effect is strongest and is equal to

$$S_0(N = N_{i-1}, Z = Z_{i-1}) = -(5.8)(0.325)A^{1/3} .$$

For example, in the case of $^{208}$Pb this gives about -11.2 MeV.

The above shell correction $S_0(N,Z)$ refers to spherical shapes. For deformed shapes the shell correction is attenuated according to [2]:

$$S(N,Z) = S_0(N,Z)(1 - 2\frac{\text{dist}^2}{a^2}) \exp(-\frac{\text{dist}^2}{a^2})$$

where

$$\text{dist}^2 = \int \frac{d\Omega}{4\pi} \left(r(\theta,\phi) - R_0\right)^2$$

and $r(\theta,\phi)$ is the radius vector describing the given shape and $R_0$ is the radius of the equivalent sphere.

One problem which remains is how to interpolate in a smooth way between the sum of the shell corrections $S_1$ an $S_2$ of the colliding nuclei in the entrance channel and the shell correction $S_c$ of the compound shape. We adopted an interpolation in terms of the degree of communication between the two nuclei as specified by the "window opening" parameter $\alpha$ of [3],

$$S = (1 - \alpha)(S_1 + S_2) + \alpha S_c .$$

For separated shapes (below the scission line) alpha is equal to zero and we have only $S_1 + S_2$. When the neck loses its concavity at $\alpha = 1$ the shell correction is equal to the compound nucleus shell correction $S_c$, and this is used for convex shapes with $\alpha > 1$.

As a test of our model we have taken the recently measured reaction [4] $^{86}$Kr+$^{126}$Xe for which we have closed neutron shells in both ions. The calculated energy in the center of mass system for which the fusion probability reaches the value one half is equal to 224 MeV, in agreement with experiment. If one makes the same calculations without shell effects the probability of fusion at 224 MeV is practically zero.

[1] J.P. Blocki, H. Feldmeier and W.J. Swiatecki, Nucl. Phys. A459 (1986) 145
[2] W.D. Myers, W.J. Swiatecki, Art. Fys. 36 (1967) 343
[3] J.P. Blocki and W.J. Swiatecki, LBL-12811 (1982)
[4] P. Armbruster, private communication