SCIENTIFIC REPORT

Implementation of the project IDEI 42/05.10.2011
january – december 2012

Binary nuclear systems

Objective: *Influence of the pairing interaction in binary nuclear systems*

The maccroscopic-microscopic method has been applied to calculate the deformation energy and penetrability for fusion-like nuclear configurations. The deformation space is formed by four independent variables: the target and projectile nucleus semiaxis ratios, the projectile small semiaxis and the distance between the two centers. Within this space we calculate the shell corrections, the pairing energy, which is the subject of this phase, and the charged liquid drop part (macroscopy). Our configuration is formed by two intersected spheroids, with cylindrical symmetry. The microscopic part of the total deformation energy has, as a starting point, the two center Hamiltonian, fit for binary systems:

$$H = -\frac{\hbar}{2m_0}\Delta + V(\rho, z) + V_{\Omega s} + V_{\Omega^2} \tag{1}$$

where the potentials are deformation dependent. The deformed two-center oscillator potential for target and projectile regions v_T and v_P reads:

$$V(\rho, z) = \begin{cases} V_T(\rho, z) = & \frac{1}{2}m_0\omega_{\rho T}^2\rho^2 + \frac{1}{2}m_0\omega_{zT}^2(z+z_T)^2 \quad , for \;\; v_T \\ V_P(\rho, z) = & \frac{1}{2}m_0\omega_{\rho P}^2\rho^2 + \frac{1}{2}m_0\omega_{zP}^2(z-z_P)^2 \quad , for \;\; v_P \end{cases} \tag{2}$$

where z_T and z_P are the centers of the target and projectile. Angular momentum dependent potentials, $V_{\Omega s}$ and V_{Ω^2} are constructed to comply to the $V(\rho, z)$ - dependence and hermiticicity of the operators, so that:

$$V_{so} = \begin{cases} -\left\{\frac{\hbar}{m_0\omega_{0T}}\kappa_T(\rho, z), (\nabla V^{(r)} \times \mathbf{p})\mathbf{s}\right\} & , v_T - region \\ -\left\{\frac{\hbar}{m_0\omega_{0P}}\kappa_P(\rho, z), (\nabla V^{(r)} \times \mathbf{p})\mathbf{s}\right\} & , v_P - region \end{cases} \tag{3}$$

and similarly for the l^2 term. Each potential is centered in the middle of the target and projectile respectively. The spin-orbit potentials also depend on the deformation apropriate to each reaction partner. As a result of the Hamiltonian diagonalization we obtained the corresponding level schemes for two intersected spheroids, for different distances between centers and all possible fragment deformations. The single particle level sequence has been obtained for a regioncovering the distance between the touching pont and total overlapping of the two partners and compound nucleus.

The single particle levels are input data for the shell and pairing correction calculation. The algorithm is repeated for protons and neutrons separately, and the results are added. The shell corrections have been calculated by the Strutinsky method. The final value of this energy is obtained as the difference between the sum of the single particle levels and the energy corresponding to a smoothed distribution:

$$\delta E_{shell} = \sum_i E_i - \tilde{U} \tag{4}$$

where the summation is performed for all occupied levels, where $\tilde{U}$ is calculated with a smearing procedure. For the pairing energy we used the BCS equation method. As a major point, one conserves the number of particles and solve the gap parameter equation. The gap parameter $\Delta = |G| \sum_k u_k v_k$ and the Fermi energy with pairing corellations λ (both in units of $\hbar\omega_0^0$) are obtained as solutions of a nonlinear system of two BCS equations :

$$n' - n = \sum_{k=k_i}^{k_f} \frac{\epsilon_k - \lambda}{\sqrt{(\epsilon_k - \lambda)^2 + \Delta^2}} \tag{5}$$

$$\frac{2}{G} = \sum_{k=k_i}^{k_f} \frac{1}{\sqrt{(\epsilon_k - \lambda)^2 + \Delta^2}} \tag{6}$$

where $k_i = Z/2 - n + 1$; $k_f = Z/2 + n'$. As a consequence of pairing introduction, the levels bellow the Fermi one are only partially occupied, since the one sabove are partially empty. The occupation probability for each level, for one quasiparticle, is:

$$v_k^2 = \frac{1}{2}\left[1 - \frac{\epsilon_k - \lambda}{\sqrt{(\epsilon_k - \lambda)^2 + \Delta^2}}\right] \tag{7}$$

or a hole

$$u_k^2 = 1 - v_k^2 \tag{8}$$

Only the ones in the vicinity of the Fermi level (a width of a few MeV) are influenced by the pairing interaction. This is why one takes an energy cutoff parameter close to the gap value. The binary character is present in the input of single particle levels obtained from the two center shell model.

The shell and pairing corrections are calculated separately for protons and neutrons and the results are added, forming the total microscopic effect in the fusion process.

The total energy is the sum of the microscopic corrections and the Yukawa-plus-exponential energy, obtained in the hypothesis of a two intersected spheroids. The potential energy surfaces are obtained as a result of the variation of all deformation parameters. We applied the method developed along this contract phase of the project to the synthesis of superheavy nuclei $^{294}118$ and $^{290}118$. The fusion channels are obtained by the minimization of the action integral. The pairing energy is in antiphase with the shell corrections. Due to this fact the proton and neutron magicities are diminished. The penetrabilities are calculated with the WKB tunneling approximation. For $^{294}118$ we obtained $logP$ values of -7.5. The pairing energy in this case is up to 6 MeV in absolute value. Symmetric reactions are also favored by the macroscopic energy, which decreases toward equal mass and charge splitting. Such sub-barrier fusion reactions have a very low cross-section compared to the ones with kinetic energy above the Coulomb threshold. However the sub-barrier reactions produce a final nucleus in a much more stable state, close to the ground state. In this way it is possible for the nucleus to live longer against alpha decay.

For the $^{290}118$ nucleus we obtained, as a result of action integral minimization, two favorable channels: ^{120}Cd and ^{140}Nd. Penetrabilities are higher, around $logP$=-5.5. One mentions the proton magicity influence for Cd, (Z=48) around Z=50. Along with these results we performed alpha decay calculations using an analytic model for the halflife.

The results obtained in this phase of the project have been published in ISI reviews:
ISI articles:

1. D. N. Poenaru, R. A. Gherghescu, W. Greiner
   J. Phys. G39, 015105 (2012).
2. D. N. Poenaru, R. A. Gherghescu, W. Greiner
   Phys. Rev. C85, 034615 (2012).
3. D. N. Poenaru, R. A. Gherghescu, W. Greiner
   Int. J. Mod. Phys. E21, 1250022 (2012).54

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