Influence of proton shell closure on production and identification of new superheavy nuclei

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The problem

- **Synthesis of superheavy nuclei**
  The experiments on complete fusion reactions with ^{48}Ca beam and various actinide targets were successfully carried out at FLNR (Dubna), GSI (Darmstadt), and LBNL (Berkeley) in order to synthesize superheavy nuclei (SHN) with $Z = 112 - 118$.
- **Understanding structure of SHN**
  The found experimental trend of the nuclear properties (Q_α–values and half-lives) and production cross sections of the SHN reveals the increasing stability of nuclei approaching the spherical closed shell.
- **Description of data and prediction of the properties of these nuclei.**

  There is a difference in the predictions of properties of SHN in various models:
- the microscopic-macroscopic models of P. Möller et al. predicts the position of closed proton shell at charge number $Z = 114$;
- the relativistic mean-field model - at $Z = 120$;
- the phenomenological model S. Liran et al. - at $Z = 126$;

We explored the variation of shell structure of SHN, if we modify the microscopic-macroscopic model based on the TCSM for better description of the structure of known heaviest nuclei.

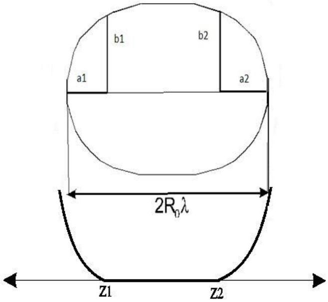
Modification of the two center shell model (TCSM)

$$H = (-\hbar/2m_0)\nabla^2 + V(\rho, z) + V_{\bar{l},\bar{s}}(\bar{r}, \bar{p}, \bar{s}) + V_{l^2}(\bar{r}, \bar{l})$$

In the present work we choose the shape parametrization adopted in the TCSM (J. Maruhn and W. Greiner, Z. Phys. A **251**, 431 (1972)).

- the elongation $\lambda = L/2R_0$,
- the case of deformation $\beta = a/b = \beta_1 = \beta_2$,
- the neck parameter $\varepsilon = E_0/E' = 0$,
- the mass asymmetry $\eta = (A_1 - A_2)/(A_1 + A_2) = 0$;

Other variables are fixed.

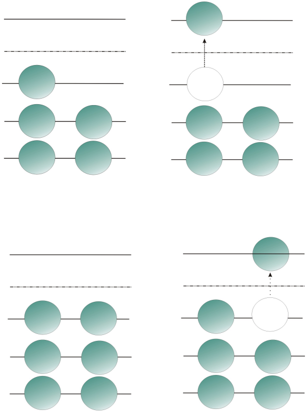


The quasiparticle excitations

We obtain from the TCSM the following data:

1. single-particle states $|\mu>$ with energies ε_μ
2. the pairing-energy gap parameter Δ;
3. the Fermi energy λ_F;

In our calculations we use the BCS approximation.



$$E_{qp} = \sqrt{(\varepsilon\prime_\mu - \lambda_F)^2 + \Delta^2} - \sqrt{(\varepsilon_\mu - \lambda_F)^2 + \Delta^2}$$
$$E_{2qp} = \sqrt{(\varepsilon\prime_\mu - \lambda_F)^2 + \Delta^2} + \sqrt{(\varepsilon_\mu - \lambda_F)^2 + \Delta^2}$$

The calculations

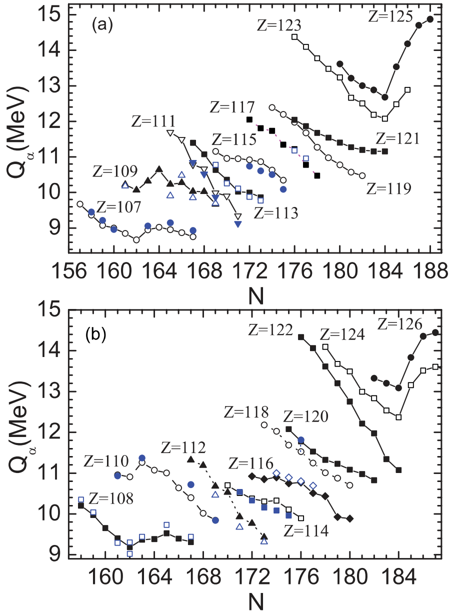
- The potential energy is calculated as
$$U(Z,A,\lambda,\beta) = U_{LDM}(Z,A,\lambda,\beta) + \delta U_{mic}(Z,A,\lambda,\beta)$$
The first term is a macroscopic energy (the Coulomb and surface energies) calculated with the liquid drop model. The second term contains the shell E_{sh} and pairing corrections.
We find the ground state.

- Then we calculated the quasiparticle energies in g.s.

- And the binding energies of α-particles $Q_\alpha = U_A - U_{A-4} - U_\alpha$.

- The evaporation residue cross section in xn evaporation channel is determined as
$$\sigma_{ER}^{xn}(E_{\rm c.m.}) = \sum_J \sigma_c(E_{\rm c.m.},J) P_{CN}(E_{\rm c.m.},J) W_{sur}^{xn}(E_{\rm c.m.},J),$$
where $\sigma_c(E_{\rm c.m.},J)$ is the capture cross section, $P_{CN}(E_{\rm c.m.},J)$ is the probability of complete fusion and W_{sur}^{xn} is survival probability.

The binding energies of α-particles for even-Z (b) and odd-Z (a)

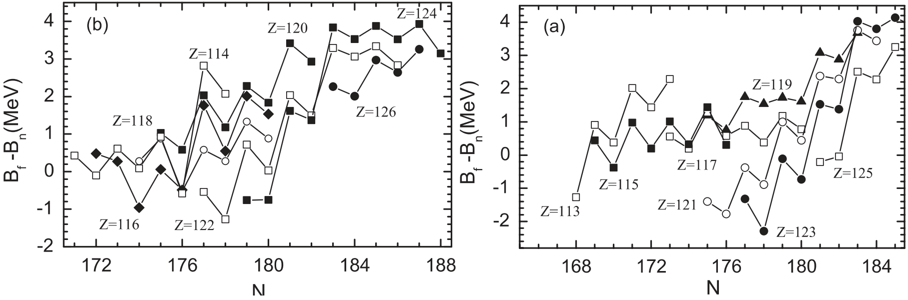


- $Z = 114$, $N = 172 - 176$;
- $N = 184$, $Z = 120 - 126$

The calculated Q_α are in a good, within 0.3 MeV, agreement with the available experimental data.

1. Yu.Ts. Oganessian, J. Phys. G **34**, R165 (2007) / *et al.*, Phys. Rev. Lett. **104**, 142502 (2010);
2. S. Hofmann *et al.*, Eur. Phys. J. A **32**, 251 (2007) / Lec. Notes Phys. **764**, 203 (2009); Radiochim. Acta **99**, 405 (2011);
3. L. Stavsetra *et al.*, Phys. Rev. Lett. **103**, 132502 (2009).

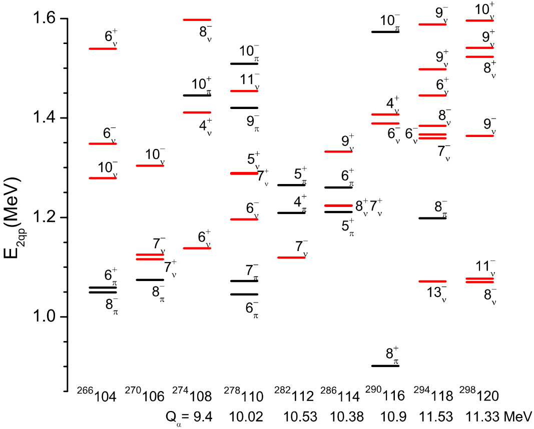
The difference between the height B_f of the fission barrier and the neutron separation energy B_n



Our microscopic-macroscopic approach provides the shell at $Z = 114$. However, **the shell effects at $Z = 120 - 126$ are rather strong**.

The value of survival probability strongly depends on $B_f - B_n$.

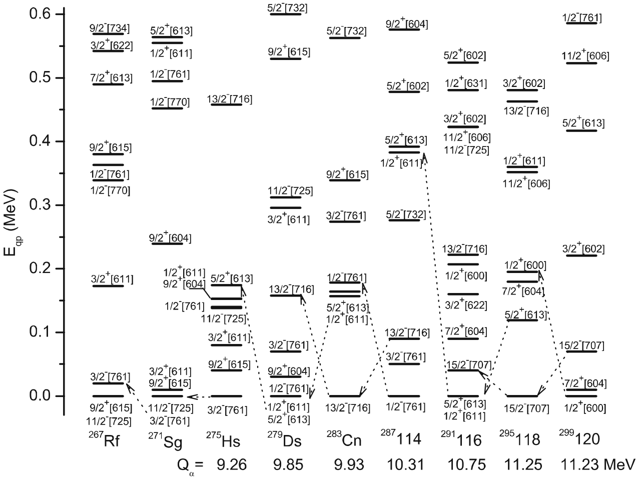
The calculated two-quasiparticle spectra of nuclei of α decay chains of $^{298}120$



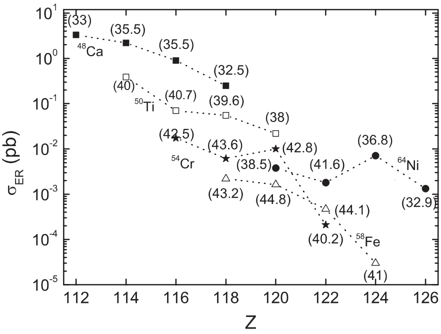
Calculated energies of low-lying two-quasiproton (black signs) and two-quasineutron (red signs) states. The states are marked by the spins and parities. The energy of the first two-quasiproton state is high ⇒ the shell effects.
(Eur. Phys. J. A (2011)47: 145)

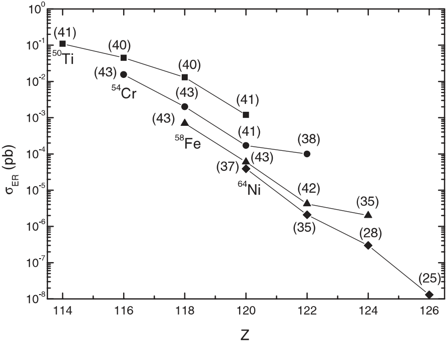
The calculated one-quasiparticle spectra of nuclei of α decay chains of $^{299}120$

The states are marked by the Nilsson asymptotic quantum numbers. The possible α decays are shown by arrows (Eur. Phys. J. A (2011)47: 145).



Evaporation residue cross sections





σ_{ER} were calculated using our predictions (left side) of nuclear properties and predictions from P. Möller et al. (right side) in the reactions:

^{48}Ca,^{50}Ti,^{54}Cr,^{58}Fe,^{64}Ni+^{238}U,^{244}Pu,^{248}Cm,^{249}Cf (Phys. Rev. C 85, 014319 (2012))

The excitation energies of compound nuclei are given in brackets.

1. stronger shell effect revealed here for nuclei with $Z > 118$ result larger survival probabilities and larger values of σ_{ER}.
2. For $Z = 120$: the values of σ_{ER} are about twenty times smaller then in our predictions.

Summary

- The calculations performed with the modified TCSM reveal quite strong shell effects at $Z = 120 - 126$ and $N = 184$. So, our microscopic-macroscopic treatment qualitatively leads to the results close to those in the self-consistent mean-field treatments.

- If our prediction of the structure of heaviest nuclei is correct, then one can expect the production of evaporation residues $Z = 120$ in the reactions ^{50}Ti+^{249}Cf and ^{54}Cr+^{248}Cm with the cross sections 23 and 10 fb, respectively.

- In accordance with our predictions the $Z = 120$ nuclei with $N = 175 - 179$ are expected to have Q_α about 12.1 - 11.2 MeV and lifetimes 1.7 ms - 0.16 s.

- The experimental measurement of Q_α for at least one isotope of $Z = 120$ nucleus would help us to set proper shell model for the SHN with $Z > 118$.