FROM DEEP INELASTIC TRANSFER REACTIONS TO COMPLETE FUSION OF NUCLEI*

V.V. Volkov

Flerov-Laboratory of Nuclear Reactions
Joint Institute for Nuclear Research
141980 Dubna, Moscow reg., Russia

(Received January 13, 1999)

The Dinuclear System Concept (DNSC) is developed for the description of complete fusion of nuclei. The DNSC is based on the information on the interaction of two nuclei in the deep inelastic collision which have been obtained in the study of deep inelastic transfer reactions. The DNSC revealed the new aspects of complete fusion of massive nuclei: the specific inner fusion barrier $B^*_{\rm fus}$ and the competition between complete fusion and quasi-fusion. The DNSC is used for the analysis of reactions of heavy and superheavy element synthesis.

PACS numbers: 25.70.Jj, 01.30.Cc

1. Introduction

In my talk I would like to discuss the approach to the description of complete fusion of nuclei proposed at Dubna: the Dinuclear System Concept (DNSC) [1]. According to the DNSC the main content of the complete fusion process is the formation and evolution of the Dinuclear System (DNS) which is formed on the capture stage. The DNSC is based on the unique information on the interaction of two nuclei in the deep inelastic collision. The information has been obtained in the study of deep inelastic transfer reactions. The participants of this investigation are G.G. Adamin, E.A. Cherepanov, V.V. Volkov — FLNR, JINR; N.V. Antonenko, A.K. Nasirov — BLTP, JINR, Dubna, Russia; W. Scheid — ITP, Giessen, Germany.

* Presented at the International Conference "Nuclear Physics Close to the Barrier", Warszawa, Poland, June 30–July 4, 1998.

2. The main features of the DNSC

The main idea of the DNSC is the assumption that complete fusion reactions and deep inelastic transfer reactions are similar nuclear processes. Really, both processes are realized in deep inelastic collisions of nuclei with full dissipation of the kinetic energy. In both processes the same forces act between the nuclei. They are the conservative Coulomb, nuclear and centrifugal forces, and dissipative forces of nuclear friction. There is a transitional zone on the angular momentum scale where both complete fusion and deep inelastic transfer reactions are possible.

According to the DNSC the scenario of the complete fusion process may be described as follows [1].

- At the capture stage, after full dissipation of the collision kinetic energy the dinuclear system (DNS) is formed.
- The complete fusion process is the DNS evolution which proceeds via nucleon transfer, shell by shell, from one nucleus to another.
- The DNS nuclei retain their individuality throughout their way to the compound nucleus. This important peculiarity of the DNS evolution is the consequence of the nucleon and shell structure of the atomic nuclei.

Fig. 1 illustrates the compound nucleus formation process within the framework of the popular macroscopic dynamical model of Swiatecki [2] and within the framework of the DNSC. In the MDM, the nuclei quickly lose their individuality as a result of the neck formation. In the DNSC, the fused nuclei retain their individuality until the end of the complete fusion process.

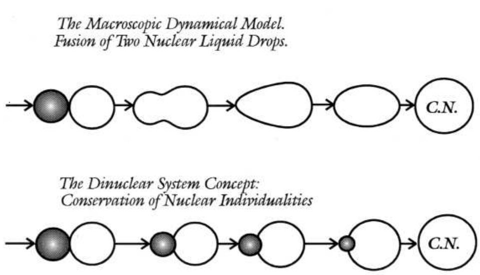

Fig. 1. Schematic illustration of the compound nucleus formation process within the framework of the MDM- and DNS-concept.

3. The new aspects of the complete fusion process

The DNSC reveals two important peculiarities of complete fusion of massive nuclei:

- the appearance of the specific inner fusion barrier — $B^*_{\rm fus}$ and
- the competition between the complete fusion and quasi-fusion channels in the DNS, which is formed on the capture stage.

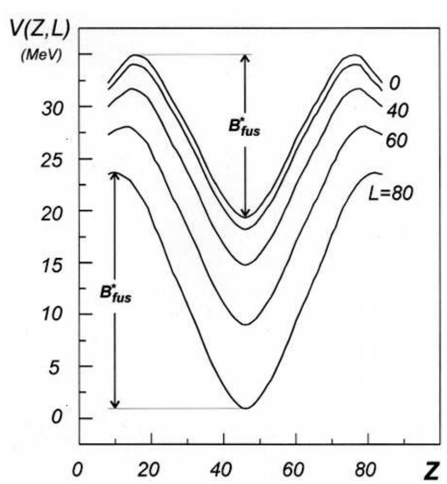

Fig. 2. The inner fusion barrier $B^*_{\rm fus}$ in the ^{110}Pd+^{110}Pd reaction. $V(Z,L)$ is the potential energy of the DNS, Z is the atomic number of the DNS nuclei, L is the angular momentum of collision.

The DNS evolution is determined by the potential energy of the system as a function of charge (mass) asymmetry and the angular momentum of collision. Fig. 2 shows the potential energy of the DNS which is formed in the reaction ^{110}Pd+^{110}Pd. The atomic number of one of the DNS nuclei is indicated on the abscissa axis. The angular momentum of collision is indicated by figures. The initial DNS is situated in the minimum of the potential energy. The complete fusion is realized if the DNS overcomes the potential barrier $B^*_{\rm fus}$. This potential barrier is the result of the endothermic character of the fusion process in the first part of the DNS evolution. The asterisk indicates that the energy for overcoming the inner fusion barrier is taken from the DNS excitation energy.

In asymmetric nuclear reactions there are two ways of the DNS evolution (Fig. 3). The first way brings the DNS to the compound nucleus. This ways requires overcoming the inner fusion barrier $B^*_{\rm fus}$. The other way leads

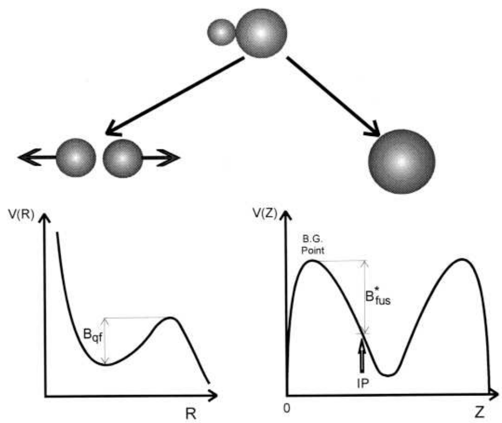

Fig. 3. Two ways of evolution of a massive asymmetric DNS.

to symmetrization of the DNS form. In the symmetric DNS the Coulomb repulsion between nuclei has a maximum value, and the massive DNS decays into two fragments. It means that quasi-fission take place. In this case the DNS must overcome the potential barrier in the nucleus–nucleus interaction potential $V(R)$ — the quasi-fission barrier B_{qf}. The DNS evolution is a statistical process and the competition between the complete fusion channel and the quasi-fission channel arises.

4. The description of experimental data within the framework of the DNSC

As an example of the description of experimental data within the framework of the DNSC I would like to discuss the minimum excitation energy of the compound nucleus in the cold fusion reactions used for the synthesis of transuranium and superheavy elements (TUE and SHE).

The popular models of complete fusion, *i.e.* the macroscopic dynamical model of Swiatecki [2] and the surface friction model of Frobrich [3] predict too high excitation energy of heavy compound nuclei. Fig. 4 [4] demonstrates the difference between the experimental data and the results of calculation within the framework of these models.

According to the DNSC the minimum of the compound nucleus excitation energy is determined by the height of the inner fusion barrier B^*_{fus}, that is by the shape of the potential energy curve (Fig. 5). On the picture I.P. is the injection point of the reaction, E^*_{min} (DNS) is the minimum excitation energy of the DNS, and E^*_{min} (CN) is the minimum excitation energy of the compound nucleus. We have calculated the minimum excitation energy

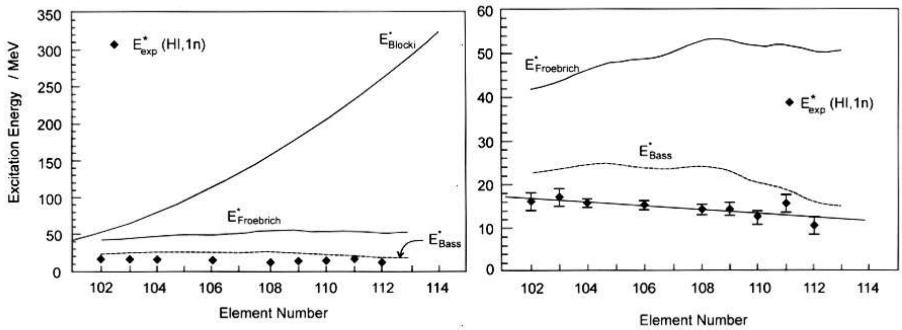

Fig. 4. The minimal excitation energy of the compound nuclei of the 102–112 elements which have been synthesized in cold fusion reactions $(HI,\, 1n)$. ♦ — the experimental data, the solid lines present the results of calculations within the framework of the MDM and the surface friction model, the dashed line indicates the compound nucleus excitation energy in the collision when kinetic energy is equal to the Bass barrier [4].

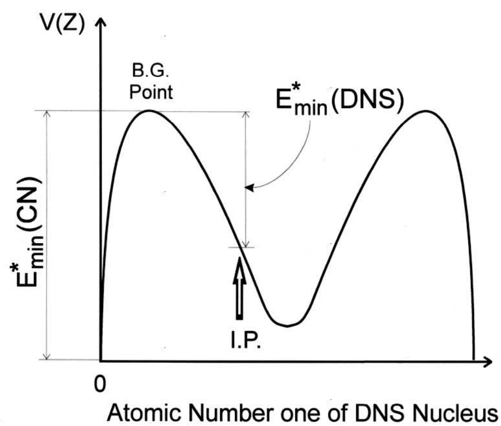

Fig. 5. The minimum of the excitation energy of the DNS and excitation energy of the compound nucleus according to the DNS-concept.

of the compound nucleus of 102–114 elements in the cold fusion reactions $(HI,\, 1n)$. The results of the calculation are shown in Fig. 6(a) [5]. In the calculation of the DNS potential energy the deformation of the heavy nucleus of the DNS was taken into account. The deformation was taken for the ground state. One can see that the calculated values $E^*_{\rm min}$ are close

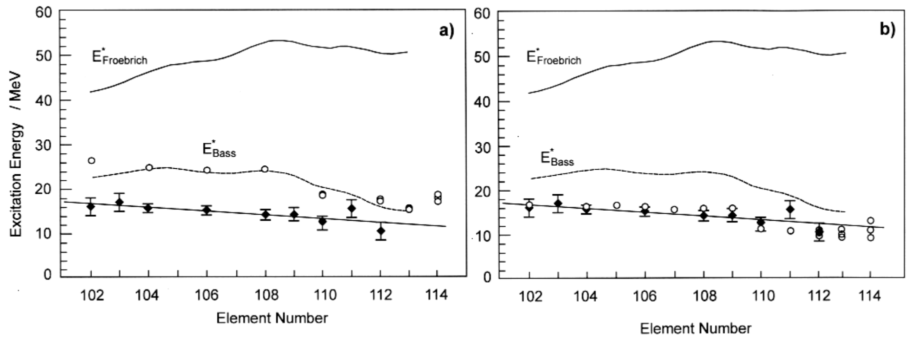

Fig. 6. The minimal excitation energy of the compound nuclei of 102–114 elements in cold fusion reactions (HI, $1n$). ♦ — the experimental data, ∘ — the calculated data according to the DNS-concept: (a) the deformation of the heavy nucleus of the DNS is taken into account, (b) the deformation of the heavy and light nuclei of the DNS is taken into account.

to the experimental data. However, the calculated data turned out to be about 5 MeV higher than the experimental data. The difference disappears if one takes into account the possible deformation of the light nucleus of the DNS in Fig. 6(b) [5]. We put in the deformation of the light nucleus in the excited state 2^+. So the DNSC gives a possibility to estimate the minimum excitation energy of the compound nucleus in the synthesis of the heaviest elements and the optimal value of the bombarding energy.

5. The role of quasi-fission in the reactions of SHE synthesis

During many years fission of excited compound nuclei was considered as the main obstacle in the synthesis of new transuranium and superheavy elements. The increasing of the fission barrier in the region of SHE inspired hopes of reducing this dangerous factor. Fig. 7 shows calculation of the production cross section of elements 104, 108 and 110 which were synthesized in Darmstadt in cold fusion reactions. The calculations were made by Boris Pustylnik [6]within the framework of a statistical model. For element 104 one can see a good agreement between the calculation and the experimental data. Large discrepancy is observed, however, for element 108 and 110. What is the cause of this discrepancy? The existing models of complete fusion do not give an answer.

According to the DNSC the production cross section of heavy nuclei is determined by the following expression:

$$\sigma_{\rm ER} = \sigma_{\rm c} \cdot P_{\rm cn} \cdot W_{\rm sur}\,,$$

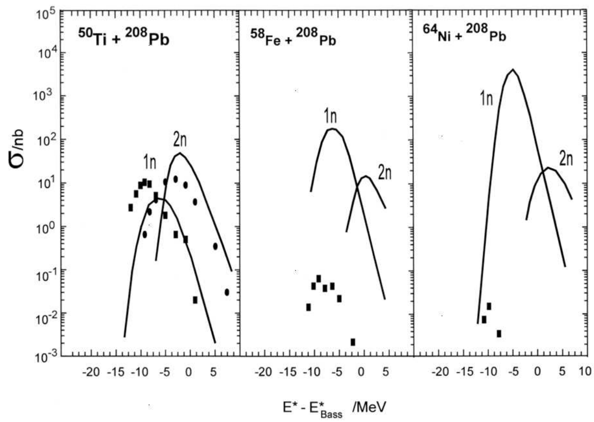

Fig. 7. The production cross section of elements 104, 108, 110 in cold fusion reactions (HI, $1n$). ■ — the experimental data obtained at the GSI, the lines are the results of the calculations within the framework of the statistical model [6].

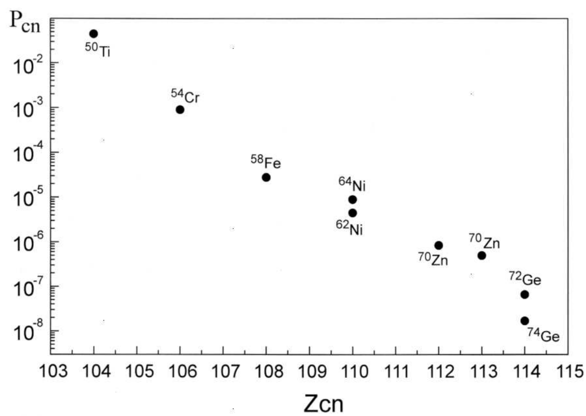

Fig. 8. The probability of complete fusion $P_{\rm cn}$ in the cold fusion reactions (HI, $1n$).

where $\sigma_{\rm c}$ is the capture cross section, $P_{\rm cn}$ is the probability of the compound nucleus formation in the competition with quasi-fission, $W_{\rm sur}$ is the survival probability of the compound during its deexcitation. The value of $\sigma_{\rm c}$ and $W_{\rm sur}$ may be calculated using existing theoretical models. But there is no theoretical model for the calculation of $P_{\rm cn}$.

On the basis of the DNSC two models of the competition between complete fusion and quasi fission were elaborated. In the first model the Monte-Carlo method is used for the calculation of the DNS evolution [7]. In the second model the diffusion equation by Fokker–Planck and the Kramers approach are used to describe the evolution and decay of the DNS [8]. Fig. 8

shows the results of calculation of the probability of compound nucleus formation — $P_{\rm cn}$ in cold fusion reactions [5]. The targets are ^{208}Pb and ^{209}Bi. The bombarding ions are in the range from ^{48}Ti to ^{72,74}Ge. The atomic number of the synthesized element is indicated on the horizontal axis. For element 104 $P_{\rm cn}$ is equal to$\sim 5\cdot 10^{-2}$, but for element 114 $P_{\rm cn}$ drops to 10^{-7}. The DNSC evidences that quasi-fission is the main factor in decreasing the SHE production cross section in the cold fusion reactions. This picture (Fig. 9) demonstrates the situation in the synthesis of superheavy elements after the analysis of this problem within the framework of the DNSC.

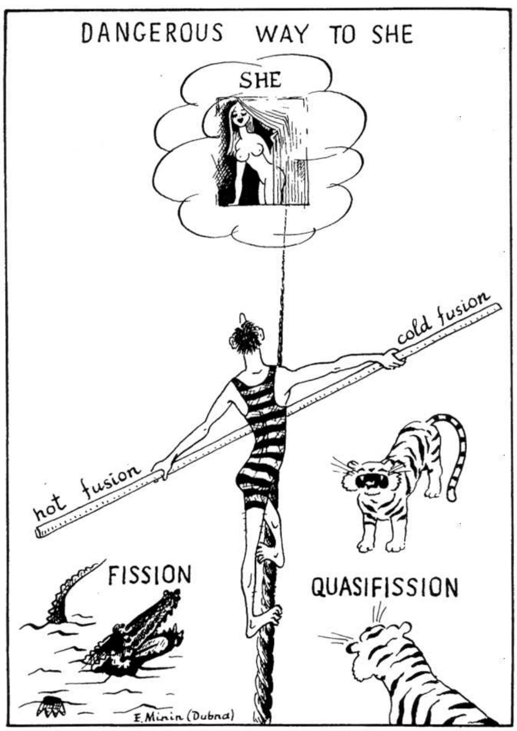

Fig. 9. Dangerous ways to the synthesis of the Superheavy Elements

6. Conclusion

It is possible to say that today the DNSC provides the most realistic picture of the complete fusion process and the mechanism of the compound nucleus formation.

REFERENCES

[1] V.V. Volkov, *Izv. Acad. Nauk SSSR, ser fiz.* **50**, 1879 (1986); N.V. Antonenko, E.A. Cherepanov, A.K. Nasirov, V.P. Permjakov, V.V. Volkov, *Phys. Lett.* **B319**, 425 (1993); *Phys. Rev.* **C51**, 2635 (1995).

[2] W.J. Swiatecki, *Phys. Scripta* **24**, 113 (1981); S. Bjornholm, W.J. Swiatecki, *Nucl. Phys.* **A319**, 471 (1982); J.P. Blocki, H. Feldmeier, W.J. Swiatecki, *Nucl. Phys.* **A459**, 145 (1986).

[3] P. Fröbrich, *Phys. Rep.* **116**, 337 (1984).

[4] A. Popeko *et al.*, Report at Deutsche Physikalische Gesellschaft, 1997.

[5] V.V. Volkov, G.G. Adamian, N.V. Antonenko, E.A. Cherepanov, A.K. Nasirov, Preprint of the Joint Institute for Nuclear Research, E7-97-367, Dubna 1997.

[6] B. Pustylnik, Dynamical Aspects of Nuclear Fission, ed. J. Kliman, B.I. Pustylnik, Dubna 1996, p. 121.

[7] E.A. Cherepanov, V.V. Volkov, N.V. Antonenko, A.K. Nasirov, in *Heavy Ion Physics and Its Applications* ed. Y.X. Luo, G.M. Jin, J.Y. Liu, World Scientific, Singapore 1996, p. 272.

[8] G.G. Adamian, N.V. Antonenko, W. Scheid, V.V. Volkov, *Nucl. Phys.* **A627**, 361 (1997).