89-567

объединенный
институт
ядерных
исследований
дубна

E4-89-567

N.V.Antonenko*, R.V.Jolos

THE COULOMB EFFECTS IN THE MICROSCOPIC THEORY OF MULTINUCLEON TRANSFER REACTIONS

Submitted to "Ядерная физика"

* Nuclear Physics Institute, Tomsk

1989

1. Introduction

There are some experimental data which demonstrate the influence of the shell structure on the multinucleon transfer process in the heavy-ion reactions at projecile energies up to 10 MeV/nucleon. The charge and mass distributions of the reaction products are characterized by local maxima corresponding to double even nuclei with the closed shells or subshells /1-3/. The strongly enhanced production cross-sections for very light nuclei ^{4}He, ^{12}C, ^{15}N and ^{16}O in the heavy-ion deep inelastic collisions contradict the diffusion model predictions /1,4/.At the same time it is not always possible to predict the evolution direction of a dinuclear system using the standard calculation method based on the potential energy surfaces /3/. These and other experimental results stimulate working out of the theoretical approaches based on the microscopic nuclear model.

In /5/ various approaches to calculate the coefficients of the transport equation describing the process of multinucleon transfers have been analysed and shell effects have been taken into account. The expressions for the transport coefficients including influence of the shell structure on the system evolution have been obtained in this work. It was noted that it is nessesary to consider the mutual influence of the mean fields of fragments on the single-particle energies, as small changes of the relative positions of the Fermi levels of fragments can strongly influence the evolution direction of the system. The relative displacement of the single-particle levels of fragments is very essential in the very asymmetric configuration since this effect can be important for the light nuclei production in the heavy-ion collision.

In the next section we consider the changes of the single-particle energies of fragments, stimulated by the mean field of the conjugated nucleus.

2. Influence of the dinuclear mean field on the nucleons trasfer process

Consider dinuclear system after the complete kinetic energy damping assuming that the thermal equilibrium is established. It is convenient to use as the single-particle basis the wave vectors of the single-particle states of the noninteracting nuclei i.e. $|P\rangle$ and $|T\rangle$ for a projectile and a target, respectively. However, the vectors $|P\rangle$ and $|T\rangle$ are not orthogonal, so their direct application can lead to some mistakes when the matrix elements of the nucleon transfer between nuclei are calculated. We will then use the wave vectors:

$$|\tilde{P}\rangle = |P\rangle - \frac{1}{2}\sum_T |T\rangle\langle T|P\rangle$$

and

$$|\tilde{T}\rangle = |T\rangle - \frac{1}{2}\sum_P |P\rangle\langle P|T\rangle$$

which form an orthonormalized set with the accuracy up to the second order in the overlapping integral $\langle P|T\rangle$.

The single-particle Hamiltonian of a dinuclear system is chosen in the form:

$$H = -\frac{\hbar^2}{2m}\,\Delta + U_P(\vec{r}-\vec{R}) + U_T(\vec{r}), \qquad (1)$$

where m is the nucleon mass, R is the distance between fragment centers. The mean single-particle potentials $U_{P,T}$ include both the nuclear and Coulomb fields. In the second quantization form the Hamiltonian (1) is written as

$$H = \sum_{P,P'} \langle\tilde{P}|H|\tilde{P}'\rangle a^+_P a_{P'} + \sum_{T,T'} \langle\tilde{T}|H|\tilde{T}'\rangle a^+_T a_{T'} + \sum_{P,T} (\langle\tilde{P}|H|\tilde{T}\rangle a^+_P a_T + \text{h.c.}), \qquad (2)$$

where with the accuracy up to the second order in $\langle P|T\rangle$

$$\langle\tilde{P}|H|\tilde{P}'\rangle = E_P\delta_{PP'} + \langle P|U_T|P'\rangle ,$$

$$\langle\tilde{T}|H|\tilde{T}'\rangle = E_T\delta_{TT'} + \langle T|U_P|T'\rangle , \qquad (3)$$

$$\langle\tilde{P}|H|\tilde{T}\rangle = \frac{1}{2}\langle P|U_P+U_T|T\rangle .$$

In expressions (3) E_P and E_T are the single-particle energies of noninteracting nuclei. In the further consideration we will take into account only diagonal matrix elements $\langle P|U_T|P\rangle$ and $\langle T|U_P|T\rangle$, characterizing energy shifts of the single-particle levels caused by the nuclei interaction. Corresponding nondiagonal matrix elements excite the nucleon transitions between the single-particle levels in the same nucleus. This leads to the Fermi surface dissolution. This effect is assumed to be included in the Fermi surface dissolution, which is described by phenomenological temperature occupation numbers $n_P(\tau)$, $n_T(\tau)$. The temperature τ is determined by the system excitation energy.

Because of the long range character the Coulomb interaction gives a main contribution to the energy shift of the proton single-particle levels. Approximately for protons:

$$\langle\tilde{P}|H|\tilde{P}\rangle = E_P + \frac{z_T e^2}{2R} \equiv \hat{E}_P ,$$

$$\langle\tilde{T}|H|\tilde{T}\rangle = E_T + \frac{z_P e^2}{2R} \equiv \hat{E}_T , \qquad (4)$$

where $z_{P,T}$ are the charges of the corresponding fragments. The factor 1/2 in eqs. (4) takes into account mutual influence of the Coulomb fields on the proton different fragments. This allows us to avoid the double counting of the Coulomb interection.

Let $P_z(t)$ be a probability to find the system at the moment t in the state with the charge asymmetry z. It is defined by the following equation:

$$\frac{d}{dt}P_z = \Delta^{(-)}_{z+1} P_{z+1} + \Delta^{(+)}_{z-1} P_{z-1} - (\Delta^{(-)}_z + \Delta^{(+)}_z) P_z , \qquad (5)$$

with transport coefficients /5/

$$\Delta^{(-)}_z = \frac{1}{\Delta t}\sum_{P,T} |\langle\tilde{P}|H|\tilde{T}\rangle|^2 n^z_P(\tau)(1-n^z_T(\tau)) \frac{\sin^2(\frac{\Delta t}{2\hbar}(\hat{E}^z_P - \hat{E}^z_T))}{\frac{1}{4}(\hat{E}^z_P-\hat{E}^z_T)^2} , \qquad (6a)$$

$$\Delta^{(+)}_z = \frac{1}{\Delta t}\sum_{P,T} |\langle\tilde{P}|H|\tilde{T}\rangle|^2 n^z_T(\tau)(1-n^z_P(\tau)) \frac{\sin^2(\frac{\Delta t}{2\hbar}(\hat{E}^z_P - \hat{E}^z_T))}{\frac{1}{4}(\hat{E}^z_P-\hat{E}^z_T)^2} . \qquad (6b)$$

The mutual influence of the fragment average fields leads to the following renormalization of the single-particle energy differences

$$E_P-E_T \longrightarrow \tilde{E}_P-\tilde{E}_T=E_P-E_T+\frac{(z_T-z_P)e^2}{2R}. \qquad (7)$$

In the very asymmetric configurations due to the Coulomb interaction the single-particle proton levels of a light fragment are shifted in energy relatively to the single-particle levels of a heavy fragment, i.e. the Fermi surface of the light fragment becomes to be higher in energy than in the heavy fragment. This fact is confirmed in the transfer reaction experiments. When a projectile is much lighter than a target, measured cross-sections of a proton stripping from the light nucleus is significantly larger than for a neutron /6/. This result can be easily explained by the shifts of the single-particle proton levels.

The following effect is connected with the Coulomb interaction too. There is a possibility of the appearance of an additional isovector nuclear density component. Althought the isovector nuclear density component can appear as the system response to the action of the nuclear potential of the other fragment, one can expect it to be less important than the contribution from the Coulomb interaction. The value of the isovector nuclear density component can be defined by minimizing the sum of the Coulomb and symmetry energies. It indicates the impoverishment of the overlapping region of the nuclei by protons and its enrichment by neutrons. As a result, the single-particle wave functions are changed and the matrix elements of the dipole component of the Coulomb field of the conjugated fragment are not equal to zero. The estimations show that their value does not exceed 0.25 MeV. It is significantly less than the Coulomb corrections included in eqs. (4).

3. The calculation results

We have investigated the charge distributions of the reaction products in the collisions ^{52}Cr(378 MeV)+^{181}Ta, ^{51}V(447 MeV)+^{197}Au and ^{20}Ne(175 MeV)+^{197}Au. For the calculation of the transtion probabilities $\Delta_z^{(\pm)}$ the realistic scheme of the single-particle levels has been used. The scale of the single-particle energies was fixed so that the energy of the last occupied level coincided with the experimental nucleon separation energy /7/. As in the paper /5/ the matrix elements g_{PT} have

been parametrised in the following way

$$g_{PT}=\langle\tilde{P}|H|\tilde{T}\rangle=g_0\exp\left(-\frac{|\tilde{E}_P-\tilde{E}_T|}{\Delta}\right), \qquad (8)$$

where $\Delta \simeq 8\div10$ MeV,

$$g_0=\int d^3x\left(\frac{\rho_P^z(x)}{z_P}\right)^{1/2}\frac{1}{2}(U_T(x)+U_P(x))\left(\frac{\rho_T^z(x)}{z_T}\right)^{1/2},$$

ρ_P^z, ρ_T^z are the nuclear charge densities and U_T, U_P are potentials of the single-particle fragments chosen in the Saxon-Woods form. We fixed Δt to be equal to 10^{-22}s. It corresponds to the relaxation time of the nuclear averaged field. The system temperature was determined by the excitation energy. It is necessary to remark that $\rho_{P,T}^z(x)$ differ from their asymtotic values due to the isovector density component created by the Coulomb interaction of fragments. Energy differences $\tilde{E}_P-\tilde{E}_T$ in eq. (8) have been determinated according to eq. (7).

The calculation results for $\Delta_z^{(\pm)}$ in the reaction ^{52}Cr+^{181}Ta are shown in fig.1 for two temperatures τ=0.5 MeV and τ=2.0 MeV corresponding to larger and smaller impact parameters. The oscillating character of the dependence of $\Delta_z^{(\pm)}$ on z reflects the influence of the shell structure. The transition probabilities $\Delta_z^{(\pm)}$ have local minima at z=2,8 corresponding to magic nuclei.

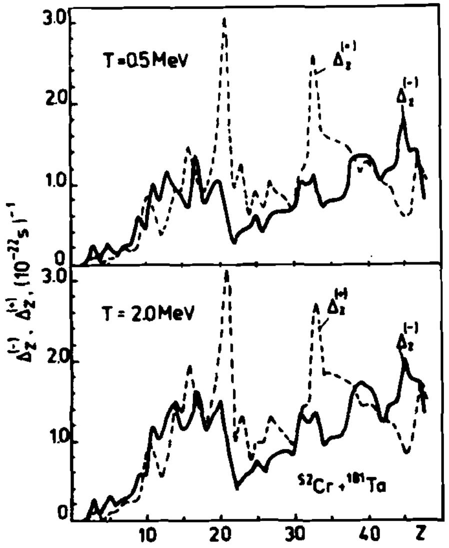

Fig.1. Transition probabilities $\Delta_z^{(\pm)}$ for the reaction ^{52}Cr+^{181}Ta calculated for two temperatures: τ=0.5 MeV (upper part) and τ=2.0 MeV (lower part). $\Delta_z^{(-)}$- solid line, $\Delta_z^{(+)}$- dashed line.

At other magic numbers the local minima are absent. This fact can be explained by the structure of the conjugated fragments and by the influence of the neutron system. The system stability with charge asymmetry z' is determined not only by the existence of the local minima in $\Delta_{z'}^{(\pm)}$, but also by the following conditions: $\Delta_z^{(+)}>\Delta_z^{(-)}$ for $z<z'$ and $\Delta_z^{(+)}<\Delta_z^{(-)}$ for $z>z'$. These conditions are fulfilled at $z'=40$ (a conjugated fragment has N=82) and $z'=48$ (the system is near the symmetric configuration and to $z=50$).

The influence of the shell effects on the nucleon transfer process decreases with increasing temperature. This means some decrease of the amplitudes of the $\Delta_z^{(\pm)}$ oscillations with z when the temperature increases (fig.1). The transition probabilities $\Delta_z^{(\pm)}$ depend on the temperature only through the Fermi occupation numbers, eqs.(6a,b). For examples, we analyse the dependence of $(\Delta_z^{(-)}-\Delta_{z+1}^{(-)})$ on τ:

$$\Delta_z^{(-)}-\Delta_{z+1}^{(-)}=\sum_{P,T} F_{PT}\,[n_P^z(\tau)(1-n_T^z(\tau))-n_P^{z+1}(\tau)(1-n_T^{z+1}(\tau))]\ , \qquad (9)$$

where $F_{P,T}$ is the product of quantities independent on τ. In eq.(9) we have neglected the single-particle energy changes in the transition $z\longrightarrow z+1$.

For very asymmetric configurations the interval between the single-particle levels in the light fragment is larger than the temperature τ in the considered region of the excitation energies. It means that deviation of $n_P^z(\tau)$ from 1 or 0 is small and the shell effects are manifested more clearly. For the configurations close to symmetric forms the changes of the fragment Fermi energies $\Delta E_F^{P,T}$ are smaller than τ in the transition $z\longrightarrow z+1$, so the expression in the square brackets of eq.(9) can be rewritten approximetely in the following way

$$n_P^z(1-n_T^z)-n_P^{z+1}(1-n_T^{z+1})\approx\frac{1}{\tau}\,n_P^z(1-n_T^z)[n_T^z\,\Delta E_F^T-(1-n_P^z)\Delta E_F^P]\ .$$

The main contribution to the sum (9) comes from the terms with $n_P^z(\tau)\approx n_T^z(\tau)\approx 1/2$, i.e. $(\Delta E_F^P\approx -\Delta E_F^T)$

$$\Delta_z^{(-)}-\Delta_{z+1}^{(-)}\approx\frac{1}{\tau}\,\frac{\Delta E_F^T}{4}\sum_{P,T}F_{PT}. \qquad (10)$$

One can make the conclusion from eq.(10) that the weakening of shell effects in the nucleon transfer process with increasing τ is slower than the exponential decrease of the shell corrections to the nuclear binding energies. The same conclusion follows from the consideration of the difference $(\Delta_z^{(-)}-\Delta_{z+1}^{(-)})$.

The calculation results for P_z corresponding to different interaction times and temperatures are shown in figs. 2 and 3 for the collision $^{52}Cr+^{181}Ta$. The results obtained for the interaction time $t_{int}=10^{-21}$s and τ=1.5 MeV are shown in fig.2. For comparison the experimental values of σ_z [8] for deep inelastic transfer products are given. It is seen from fig. 2 that inclusion of the Coulomb interaction in the calculation improves the agreement between the theoretical and experimental data. Also we can see that the Coulomb effects increase the production of light nuclei. The large difference between the theoretical and experimental results for z<8 is probably connected with the increased decay probability of the dinuclear system with a large charge asymmetry. The experimental data on the multiplicity of the γ- rays [8] show that for z<9 the collisions with $l<l_{crit}$ give an essential contribution to the reaction cross-section, i.e. the additional mechanism of the light nuclei production exists. This mechanism was not included in our calculations.

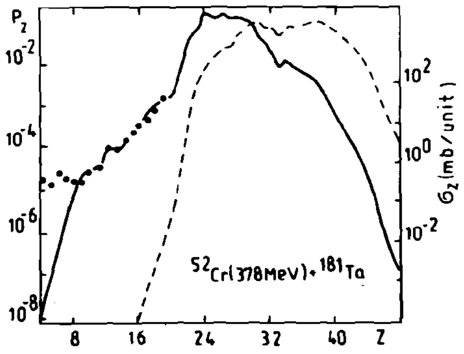

Fig.2. Charge distribution P_z of the deep inelastic collision reaction products for ^{52}Cr(378 Mev)+ ^{181}Ta, calculated with the parameters τ=1.5 MeV and $t_{int}=10^{-21}$s. The results obtained with the Coulomb correction to the single-particle energies are represented with a solid line and without Coulomb correction with a dashed line. The dots mark the experimental data σ_z [8].

In the reaction $^{52}Cr+^{181}Ta$ there was measured also the charge distribution of the products characterized by the angular distribution symmetric in the c.m.s. These experimental data [8] are compared in fig. 3 with the theoretical results obtained for the τ=2.0 MeV and $t_{int}=5\ 10^{-21}$s. This corresponds approximately to the collision with l≈

$l_{B_f=0}$. It is seen that there is a qualitative agreement between the theoretical and experimental results. For comparison, we presented also, in fig. 3, the results of calculations based on the liquid drop model /9/. We can conclude that the shell effects are needed for the explanation of the light nuclei production cross-section.

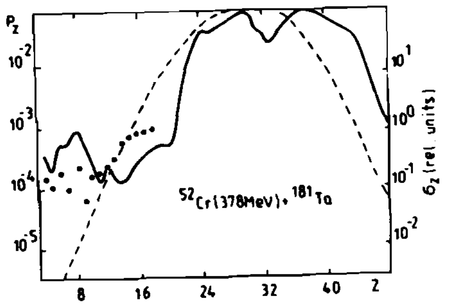

Fig.3. Charge distribution of the products with the angular distribution symmetric in the c.m.s. for the reaction $^{52}Cr(378\ MeV)+\ ^{181}Ta$. A solid line is the results for P_z calculated with the parameters $\tau=2.0$ MeV and $t_{int}=5\ 10^{-21}s$. The prediction of the model /9/ is represented with a dashed line. Dots mark the experimental data σ_z /8/.

The results presented above have been obtained under the assumption that the N/Z equilibration is established before multinucleon transfer.

The theoretical results together with experimental data for the reaction $^{51}V+^{197}Au$ are presented in fig.4. The experimental charge distriburion /10/ is integrated over the measured angular and final total kinetic energy ranges ($20^\circ \le \theta_{cm} \le 90^\circ$, 100 MeV $\le E \le$ 340 MeV). So, the quasielastic processes contribute to the experimental cross-section near z=23. Probably, it is the reason of a disagreement between the theoretical and experimental results near z=23. The broad tail of the charge distribution for large z is due to the quasifission process.

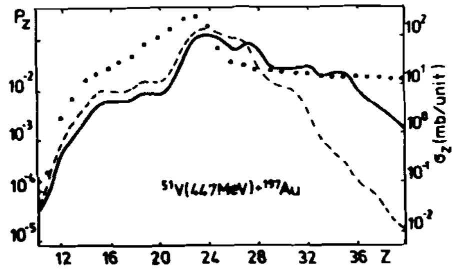

Fig.4. Charge distribution of the products for the reaction $^{51}V(447\ MeV)+\ ^{197}Au$. Solid and dashed lines are the results for P_z calculated at $\tau=2.0$ MeV and $t_{int}=10^{-21}s$ with and without the assumption of N/Z equilibration. Dots mark the experimental data σ_z /10/.

The theoretical charge distribution obtained without the requirement of the N/Z equilibration is shown for comparison in fig. 4. It is seen that there is a large disagreement between the theoretical and experimental results for large z in this case. So, the assumption of the N/Z equilibration is important for a theoretical analysis of the charge distribution in the multinucleon transfer reactions.

A satisfactory qualitative agreement has been obtained also for the charge distribution in the reaction $^{20}Ne+^{197}Au$ /11/ (fig.5). We put $\tau=1.0$ MeV, $t_{int}=10^{-21}s$.

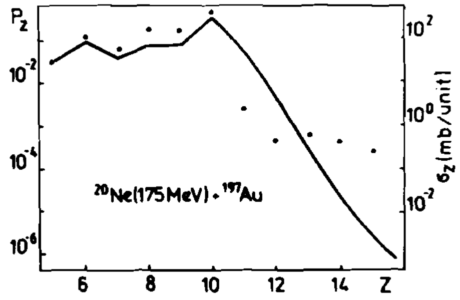

Fig.5. The charge distribution P_z of the deep inelastic collision products in the reaction $^{20}Ne(175\ MeV)+\ ^{197}Au$ calculated with the parameters $\tau=1.0$ MeV and $t_{int}=10^{-21}s$. Dots mark the experimental data σ_z /11/.

4. Summary

We have investigated the influence of the fragment interaction on their single-particle energies. This effect has been taken into account in the calculations of the charge distributions of some heavy-ion reaction products. The theoretical results describe satisfactory the structure of the charge distributions.

Because of the Coulomb interaction for very asymmetric configurations the differences between the shifts of the single-particle energy spectra in the light and heavy fragments achieve significant values. It leads to a strong enhancement of the light nuclei production.

It has been shown that the calculation results for the charge distributions are sensitive to the isotopic composition of interacting fragments, so the assumption about the N/Z equilibration is important for a theoretical investigation of the multinucleon transfer reactions.

Acknowledgement

The active attention of Dr. V.V.Volkov and his comments are gratefully acknowledged.

References

1. Volkov V.V.-In: Proc. Intern. Conf. on Clustering Aspects of Nuclear Structure and Nuclear Reactions, Winnipeg, 1978, 352.
2. Gippner P. et al.- Z. Phys., 1986, v.A325, 335.
3. Bohne W. et al.- Z. Phys., 1983, v.A313, 19.
4. Volkov V.V.- Izvestia AN SSSR (ser. fiz.), 1986, v.50, 1879.
5. Antonenko N.V., Jolos R.V.- Yad. Fiz., 1989, v.50, 98.
6. Volkov V.V.- Part. Nucl., 1971, v.2, 285.
7. Wapstra A.M., Audi G.- Nucl. Phys., 1985, v.A432, 1.
8. Mezentsev A.N. et al.- 5th Intern. Conf. on Clustering Aspects in Nuclear and Subnuclear Systems, Kyoto, 1988, 214 & 216.
9. Moretto L.G., Sventek J.S.- Phys. Lett., 1975, v.58B, 26.
10. Schmider L.M. et al.- Phys. Rev., 1988, v.C37, 139.
11. Mathews G.J. et al.- Phys. Rev., 1982, v.C25, 300.

Received by Publishing Department
on July 27. 1989.

Антоненко Н.В., Джолос Р.В. E4-89-567

Кулоновские эффекты в микроскопической теории реакций многонуклонных передач

Исследовано влияние перенормировки одночастичных энергий, вызванной кулоновским взаимодействием, на зарядовые распределения продуктов реакций многонуклонных передач. Показано, что учет кулоновского взаимодействия в двойной ядерной системе увеличивает вероятность образования сильно асимметричных конфигураций. На основе модели, учитывающей явно эффекты оболочечной структуры, с использованием реалистических одночастичных схем уровней рассчитаны зарядовые распределения продуктов реакций $^{52}Cr + {}^{181}Ta$, $^{51}V + {}^{197}Au$ и $^{20}Ne + {}^{197}Au$. Показана чувствительность результатов расчета к предположению об установлении N/Z равновесия в системе. Рассмотрена зависимость влияния оболочечных эффектов на процесс передачи нуклонов от температуры.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1989

Antonenko N.V., Jolos R.V. E4-89-567

The Coulomb Effects in the Microscopic Theory of Multinucleon Transfer Reactions

Influence of the Coulomb renormalization of the single-particle energies on the charge distributions of the multinucleon transfer reaction products is investigated. It is shown that the Coulomb interaction increases the formation probability for very asymmetric configurations. In the framework of the model with the realistic single-particle scheme of levels, which includes shell effects directly, the charge distributions of the reaction products in the collisions $^{52}Cr + {}^{181}Ta$, $^{51}V + {}^{197}Au$ and $^{20}Ne + {}^{197}Au$ have been calculated. It is shown that the calculation results are sensitive to the assumption of the N/Z equilibration in dinuclear system. The dependence of the shell effects on the temperature of the dinuclear system are considered.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna 1989