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THE APPLICABILITY OF THE Q_{gg}-SYSTEMATICS TO THE DESCRIPTION OF CROSS SECTIONS FOR MULTINUCLEON TRANSFER REACTIONS INDUCED BY ^{40}Ar, ^{86}Kr, AND ^{136}Xe IONS

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THE APPLICABILITY OF THE Q_{gg}-SYSTEMATICS TO THE DESCRIPTION OF CROSS SECTIONS FOR MULTINUCLEON TRANSFER REACTIONS INDUCED BY ^{40}Ar, ^{86}Kr, AND ^{136}Xe IONS

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О применимости Q_{gg}-систематики для описания сечений многонуклонных передач с ионами ^{40}Ar, ^{86}Kr, ^{136}Xe

Проведены расчеты относительных сечений образования изотопов золота с массовыми числами 190-199 в системах: ^{181}Ta+^{40}Ar (290 МэВ ЛС), ^{181}Ta+^{86}Kr (550 МэВ ЛС) и ^{181}Ta+^{136}Xe(840 МэВ ЛС). Предполагалось, что изотопы золота образуются за счет многонуклонных передач и последующего испарения нейтронов. Выход первичных изотопов золота рассчитывался по Q_{gg}-систематике, где $Q_{gg}=(M_1+M_2)-(M_3+M_4)$- разность масс начальных и конечных ядер. Процесс испарения нейтронов - по модели Джексона. Параметрами расчета были: средний входной угловой момент $\bar{\ell}$, температура T и r_0 для выходных каналов реакций. При реалистических значениях указанных параметров достигнуто хорошее согласие с экспериментальными данными, полученными ранее. Это свидетельствует о применимости Q_{gg}-систематики к описанию сечений многонуклонных передач и в реакциях с наиболее тяжелыми ионами.

Работа выполнена в Лаборатории ядерных реакций ОИЯИ.

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The Applicability of the Q_{gg}-Systematics to the Description of Cross Sections for Multinucleon Transfer Reactions Induced by ^{40}Ar, ^{86}Kr, and ^{136}Xe Ions

Relative cross sections have been calculated for the production of gold isotopes with mass numbers lying in the range 190-199 in the systems ^{181}Ta+^{40}Ar, ^{181}Ta+^{86}Kr and ^{181}Ta+^{136}Xe at laboratory bombarding energies of 290, 550 and 840 MeV, respectively. It was assumed that gold isotopes were produced as a result of multinucleon transfers followed by neutron evaporation. The yield of primary gold isotopes was found using the Q_{gg}-systematics, whereas the neutron evaporation process was calculated within the framework of the Jackson model. The parameters used in the calculation are the average entrance angular momentum $\bar{\ell}$, temperature T and the nuclear parameter r_0 of exit reaction channels. For realistic values of the parameters indicated one has obtained a good agreement with the experimental data obtained previously [1]. This provides evidence for the applicability of the Q_{gg}-systematics to the description of multinucleon transfer reactions induced by very heavy ions.

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1. INTRODUCTION

In recent years, studies of the interaction of heavy ions with nuclei have led to the discovery of a new type of reaction between complex nuclei, namely, deep inelastic transfers (DIT) (see refs. [2-7] for the latest relevant reviews). A peculiar feature of the DIT mechanism is the combination of the properties of two opposite processes: direct reactions and the decay of an excited compound nucleus. This peculiarity is associated with the formation in deep inelastic nuclear collisions of a short-lived nuclear complex termed as a double nuclear system (the DNS).

The charge and mass distributions of the DIT products have a considerable dispersion. In experiments one has observed products corresponding to the transfer of several dozens of nucleons from one nucleus to the other. A study of the regularities involved in the DNS decay, i.e., regularities in the cross sections of the DIT exit channels, are of considerable interest for the understanding of the reaction mechanism itself and for the estimation of the yield of exotic nuclei formed in multinucleon transfer reactions.

In refs. [8,9] it was shown that cross sections for the production of different isotopes in DIT obey the following relation

$$d\sigma/d\Omega \sim \exp\left(\frac{Q_{gg}+\Delta E_c+\Delta E_{rot}-\delta(n)-\delta(p)}{T}\right), \qquad (1)$$

where $Q_{gg}=(M_1+M_2)-(M_3+M_4)$ is the mass difference between the initial and final nuclei, ΔE_c is a charge in the Coulomb energy of the DNS in the case of proton transfer, ΔE_{rot} is a change in the DNS rotational energy due to a change in its moment of inertia, $\delta(p)$ and $\delta(n)$ are the so-called corrections for non-pairing for the transferred protons and neutrons, respectively. Deep inelastic transfers involve a high excitation of the interacting nuclei. The nucleons transferred from the donor nucleus to the acceptor one, as a rule, go to excited states and appear to be unpaired. However, this circumstance has not been taken into account in the Q_{gg} factor since Q_{gg} characterizes the energy consumption due to the transfer of nucleons from the donor ground state to the acceptor ground state. The neglect of non-pairing corrections in calculating the thermal excitation energy of the DNS after nucleon transfer will lead to an over-estimated value. The parameter T can be interpreted as the temperature of the partial statistical equilibrium[10] of the DNS.

Relation (1) is based on the following assumptions: (i) the decay of the DNS is a statistical process; (ii) the DNS has time enough to establish a partial statistical equilibrium with respect to the exchange of thermal energy and excited and loosely bound nucleons between the nuclei, and (iii) the density of the DNS levels is related to the system excitation energy by an exponential dependence.

The basis of relation (1) does not include any specific assumptions concerning the properties of the nuclei incorporated in the DNS. Therefore one may expect that the relation (1) will be applicable to the decay of any DNS irrespective of the A and Z of the initial nuclei. In fact, the experiments performed have shown that the Q_{gg}-systematics hold for various targets and projectiles ranging from ^{11}B to ^{22}Ne (refs.[2,8,9,11,12]). The first attempt, however, to obtain them for heavier ions has been no success. In particular, by bombarding a ^{232}Th target with 295 *MeV* ^{40}Ar ions the Orsay group has separated isotopes of elements from Cl to Mg at emission angles of 40° and 18° (ref.[13]). At an emission angle of 18° the maxima of the energy spectra of all isotopes were

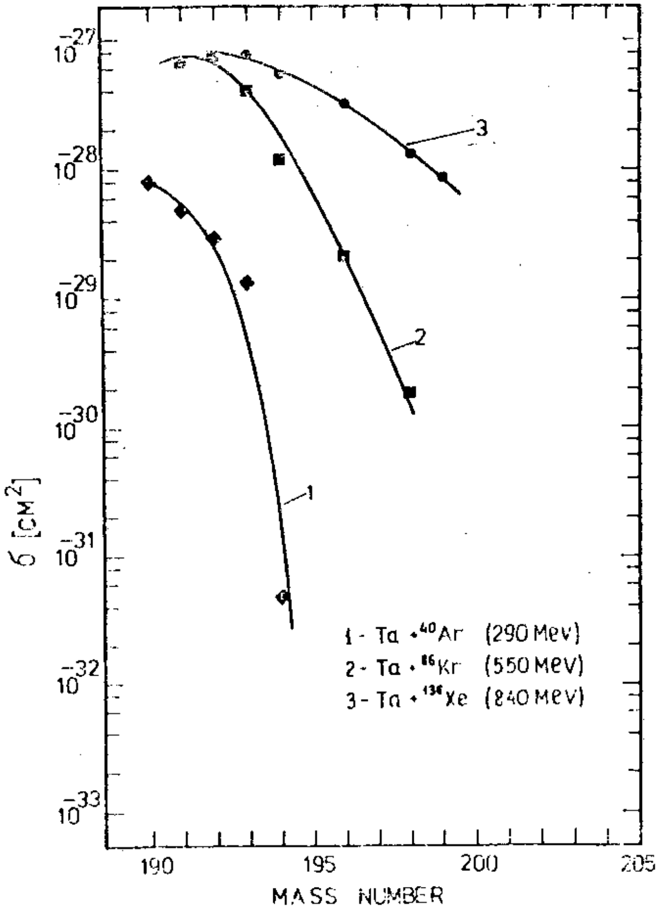


Fig. 1. Cross section for the production of gold isotopes, obtained in ref.[1] *by bombarding* ^{181}Ta *with* ^{40}Ar, ^{86}Kr *and* ^{136}Xe *ions at 290, 550 and 840 MeV, respectively.*

close to the exit Coulomb barriers. This implied that the isotopes were produced in deep inelastic transfer reactions. However, their production cross sections did not satisfy the Q_{gg}-systematics. In our opinion, the violation of the Q_{gg}-systematics in ref.[13] is due to the effect of secondary nuclear processes such as the evaporation of neutrons and α-particles from an excited light fragment. As the ion mass increases, the excitation

energy of the light fragments increases and the effect of secondary processes cannot be neglected.

The problem of the validity of the Q_{gg} -systematics for the DIT products in bombardment with the heaviest ions is of special interest since for these very heavy ions the DIT is a dominant nuclear process contributing mostly to the reaction cross section.

In the present paper an attempt is made to check the validity of the Q_{gg} -systematics for multinucleon transfers induced by such heavy ions as ^{40}Ar, ^{86}Kr, and ^{136}Xe ones. The yield of gold isotopes in the bombardment of ^{181}Ta with these ions was calculated on the basis of these systematics taking into account secondary evaporation processes, and then compared with the experimental data presented in ref. /1/. In this work, thick ^{181}Ta targets were bombarded with ^{40}Ar, ^{86}Kr and ^{136}Xe ions at energies of 290, 550 and 840 *MeV*, respectively. The gold fraction was separated using radiochemical methods. The determination of cross sections for the formation of radioactive gold isotopes with mass from 190 to 199 was performed by measuring γ-ray spectra and half-lives. The data obtained in ref. /1/ are summarized in *fig. 1*.

2. CALCULATION SCHEME

2.1. Assumptions concerning the mechanism of nuclear reactions leading to the production of gold isotopes

The authors of ref. /1/ assumed that the main contribution to the cross section for the production of gold isotopes with mass A > 194 in the reaction ^{181}Ta+^{136}Xe comes from the asymmetric fission of the compound nucleus or composite system.

We shall suppose that the gold isotopes separated in the work /1/ were produced due to the two nuclear processes: the transfer of nucleons to the target nucleus and the subsequent evaporation of nucleons from the excited heavy fragments. The recently obtained experimental data on the interaction of Ar, Kr and Xe ions with heavy nuclei /14-24/ favour this supposition.

The formation of gold isotopes with mass numbers from 190 to 199 requires the transfer to the ^{181}Ta nucleus of a considerable number of nucleons including not less than 6 protons. These typical multinucleon transfer reactions are known to occur in deep inelastic collisions followed by the formation of a short-lived $(10^{-20}-10^{-21}s)$ double nuclear system.

There are some grounds to beleive that the lifetime of the DNS is long enough for the establishment of equilibrium in the distribution of thermal excitation energy each of the two fragments formed in deep inelastic collisions obtained an excitation energy proportional to its mass.

Collisions with angular momentum ℓ lying between ℓ_{cr} and $\ell_{cr} + \Delta\ell$ make a contribution to the cross section for deep inelastic transfers. The magnitude of ℓ_{cr} is a function of the atomic and mass numbers of the initial nuclei and kinetic energy. At present there is some experimental information about the values of ℓ_{cr} for different target-projectile combinations. However, the dependence of $\Delta\ell$ on Z and A of the initial nuclei and on kinetic energy has not been investigated.

In the bombardment of heavy nuclei with Ar, Kr and Xe ions the yield of the transfer reaction products decreases as the Z of the products moves away from the Z of the initial nuclei. The gold nuclei and neighbouring heavy elements de-excite mainly by emitting neutrons and γ-rays. The proton and α-particle emissions are suppressed to a great extent by high Coulomb barriers. This allows one to restrict the set of possible nuclear reactions leading to the formation of gold isotopes. The main contribution to the gold isotope production cross section was assumed to come from reactions involving the transfer to the ^{181}Ta nucleus of six protons and different numbers of neutrons, and the subsequent neutron evaporation.

2.2. The scheme of calculation

The scheme of calculation is shown in *fig. 2.* Deep inelastic collisions of ^{40}Ar, ^{86}Kr and ^{136}Xe ions with ^{181}Ta nuclei produce a double nuclear system. The intense exchange of energy and nucleons between the nuclei bears a variety of possible ways and, consequently, products of the DNS decay. These products may incorporate different gold isotopes. The ratio of cross sections for the production of primary gold isotopes is defined by equation (1), in which the term ΔE_c can be considered to be constant since the Coulomb energy of the interaction between two fragments varies slightly for the isotopes of a given element. The variation of the term ΔE_{rot} with isotopic mass number is very small and can be neglected. The value of $\delta(p)$ is the same for all gold isotopes. Thus the relative yield of different gold isotopes will be determined mostly by two factors, Q_{gg} and $\delta(n)$. The values of these quantities for different gold isotopes were calculated from data on nuclide masses[25].

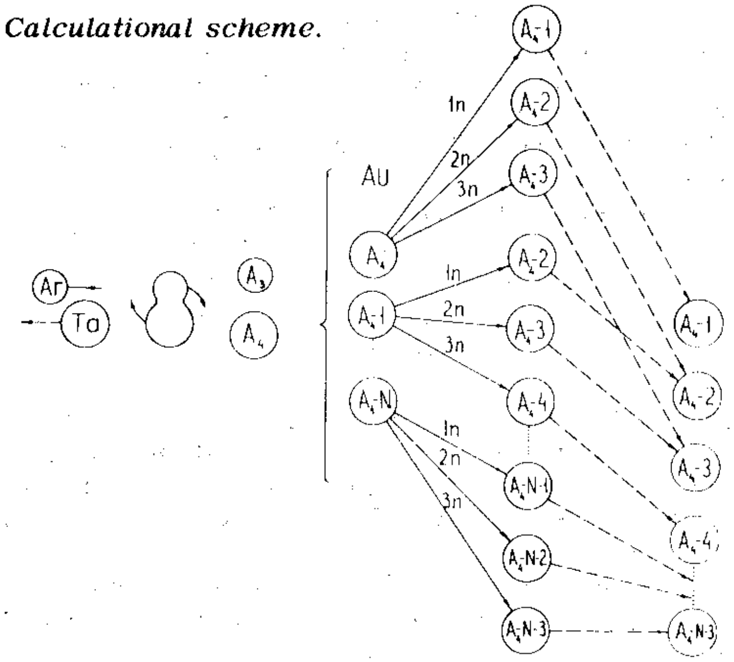
In ref.[1] thick ^{181}Ta targets were used. This implies that the DNS excitation energy varied as a function of the location of the target layer in which the reaction occured. Estimates show that the average dispersion of the DNS excitation energy does not exceed several tens of *MeV*. The parameter T of eq. (1) varies inconsiderably as the DNS excitation energy changes[2]. In our calculation we assumed it to be constant. A specific value of T was chosen in such a way as to provide the best fit to the experimental data.

The total excitation energy of a pair of transfer reaction fragments, E^*, was calculated using the formula

$$E^* = E_0 - B_{cf} - E^f_{rot} + Q_{gg}, \qquad (2)$$

where E_0 is the initial kinetic energy in the c.m. system, B_{cf} is the exit Coulomb barrier, E^f_{rot} is the exit rotational energy of the DNS, defined by the following relations

Fig. 2. Calculational scheme.



$$E^f_{rot} = \frac{\hbar^2 \ell(\ell + 1)}{2J},$$

$$J = J_3 + J_4 + \mu R^2,$$

$$J_3 = \frac{2}{5} M_3 R_3^2, \quad J_4 = \frac{2}{5} M_4 R_4^2.$$

$$\mu = \frac{M_3 \cdot M_4}{M_3 + M_4}, \quad R = r_0(A_3^{1/3} + A_4^{1/3}), \qquad (3)$$

where M_3, R_3 and M_4, R_4 are the masses and radii of the fragments. In calculating the exit rotational energy a "sticking" situation was assumed. The intrinsic moments of inertia of the fragments, J_3 and J_4, were taken to be rigid-body ones for a spherical shape. The radii of the final nuclei, R_3 and R_4, were taken according to the data of ref.[26]. The quantity r_0 is a parameter of our calculation.

The excitation energy characterizing a fragment with mass A_3 (one of the gold isotopes) was equal to

$$E^*(A_3) = E^* \frac{A_3}{A_1 + A_2}. \tag{4}$$

Thus, the first stage of the nuclear process, involving nucleon and energy exchange within the DNS and its decay, leads to the production of a number of gold isotopes, each of which has a definite yield and certain excitation energy.

The second stage of the process consists of de-excitation by neutron evaporation. As is known, in this case the emission of different numbers of neutrons is possible. As a result, each primary gold isotope transforms to several other gold isotopes with smaller masses. The final yields of different gold isotopes were found by summing up the yields of isotopes of a certain mass number A, but produced in different ways: via different transfer channels or by the evaporation of different numbers of neutrons.

The calculation of the probability of the emission of different numbers of neutrons was carried out using the Jackson method[27]. The fission of the excited gold isotopes might be neglected in view of the small value of Γ_n/Γ_f.

The calculation took into account the excitation energy variation due to the use of thick targets. The excitation function of multinucleon transfers, especially if the heaviest ions are used, are close to the energy dependence of the total reaction cross section $\sigma_R(E)$. In our calculation we assumed the cross section for the formation of primary gold isotopes at an energy E to be proportional to $(1 - B_i/E)$, where B_i is the entrance Coulomb barrier, and E is the ion energy for a given depth of the target. It should be noted that the DNS excitation energy variation does not affect the ratio of the yields of different primary gold isotopes, influencing only the number of the emitted neutrons.

The critical angular momentum ℓ_{cr} for the system $^{181}Ta + ^{40}Ar$ at a bombarding energy of 290 *MeV* is somewhat smaller than 100, if one takes into account ℓ_{cr} for the system $^{232}Th + ^{40}Ar$ [28]. The interval of $\Delta\ell$, in which deep inelastic transfers occur, lies between 10 and 15 (ref.[14]). The excitation energy of the DNS varies as a function of ℓ. However, a deviation of the rotational energy from its average value in the interval ℓ_{cr}, $\ell_{cr} + \Delta\ell$ is much smaller than that of the thermal excitation energy of the DNS. Therefore, the use of the average value of the entrance angular momentum $\bar{\ell}$ will not give any appreciable error in the calculation of the neutron evaporation process.

The ℓ_{cr} value for the systems $^{181}Ta + ^{86}Kr$ and $^{181}Ta + ^{136}Xe$ is substantially smaller than for the combination $^{181}Ta + ^{40}Ar$ (refs.[16-22]). On the contrary, the range of the ℓ variation increases sharply. In these cases, however, one may use the average value of the angular momentum $\bar{\ell}$. A considerable increase in the moment of inertia of the DNS produced on ^{86}Kr and ^{136}Xe ions leads to the reduction of the rotational energy of the system. The E_{rot} fraction in the energy balance of the DNS drops thus permitting the use of $\bar{\ell}$.

3. *RESULTS AND DISCUSSION*

In *Fig. 3* the calculated cross sections for the production of gold isotopes in the system $^{181}Ta + ^{40}Ar$ **at 290 *MeV*** are compared with the experimental data obtained at different values of the parameters r_0, $\bar{\ell}$ and T. The Q_{gg}-systematics in the form of (1) reproduce only the ratio of isotopic production cross sections for a certain element. Therefore the calculated data are normalized to

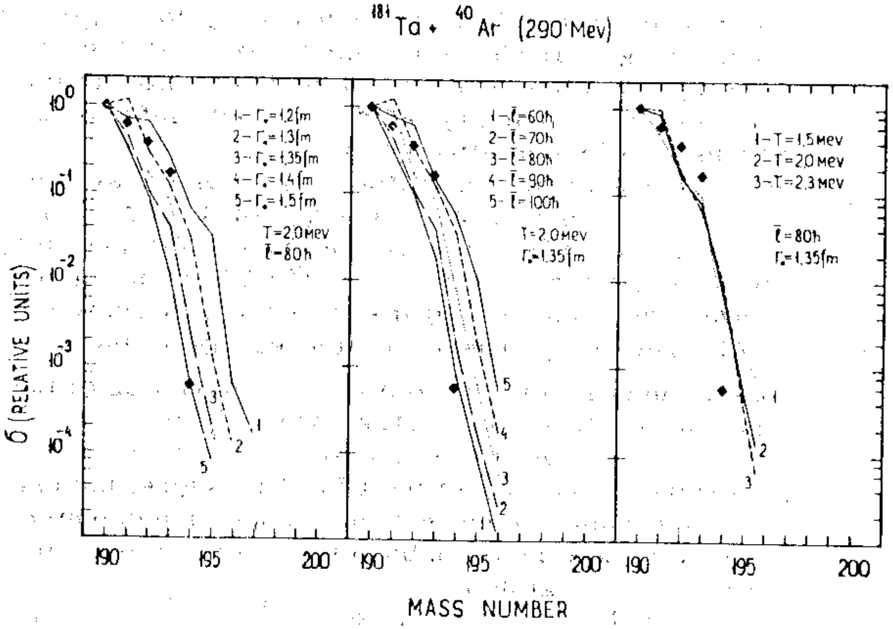


Fig. 3. Comparison of calculated curves and experimental points for the yield of gold isotopes in the system ^{181}Ta+^{40}Ar at a bombarding energy of 290 MeV. The r_0, $\bar{\ell}$ and T parameters are varied.

the experimental cross section for the production of the isotope ^{190}Au.

The cross section ratio is influenced mostly by the r_0 variation. This is rather natural since the excitation energy of the DNS is most sensitive to variations of this parameter.

The best agreement between the calculated and experimental data has been obtained for the following values of the parameters: r_0 = 1.35 *fm*, $\bar{\ell}$ = 80 ħ and T = 2.0 *MeV*.

Figures 4 and *5* show an analogous comparison of the calculated and experimental data for the system ^{181}Ta+^{86}Kr (550 *MeV*) and ^{181}Ta+^{136}Xe(840 *MeV*). One can see that in these cases one succeeds in obtaining good agreement between the calculation and experiment. The most suitable values of the parameters r_0, $\bar{\ell}$ and T for all the three

Table

The optimal values of r_0, $\bar{\ell}$ and T

	Ar	Kr	Xe
r_0 (fm)	1.35	1.3	1.3
$\bar{\ell}$ (ħ)	80	100	70
T (MeV)	2.0	2.0	1.6

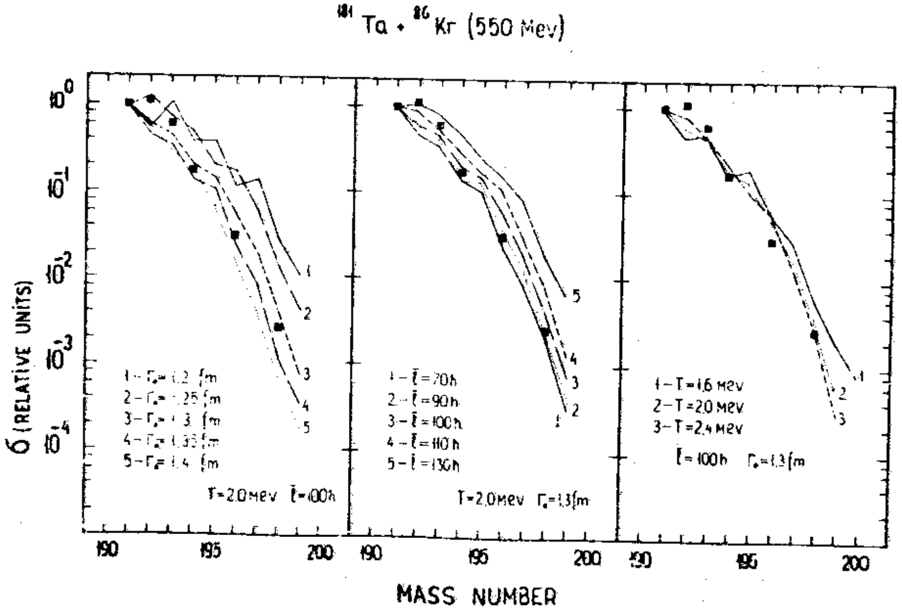


***Fig. 4.** Comparison of calculated curves and experimental points for the yield of gold isotopes in the systems [^{181}Ta+^{86}Kr] at a bombarding energy of 550 MeV. The r_0, $\bar{\ell}$ and T parameters are varied.*

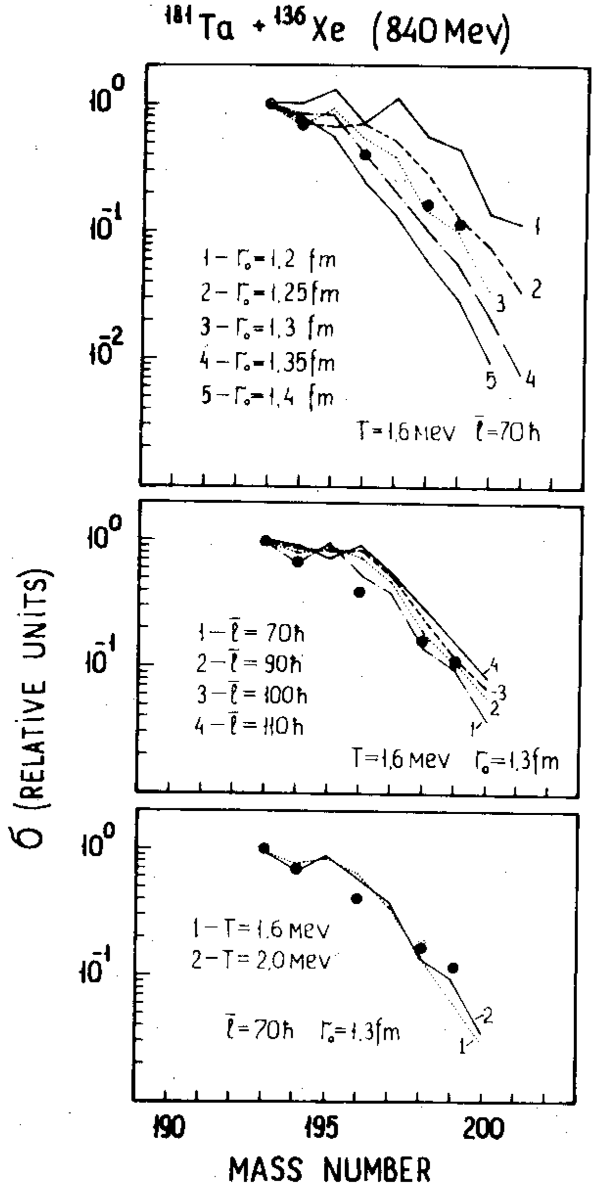


Fig. 5. Comparison of calculated curves and experimental points for the yield of gold isotopes in the system ^{181}Ta+^{136}Xe at a bombarding energy of 840 MeV. The r_0, $\bar{\ell}$ and T parameters are varied.

systems are listed in the *table*. It is noteworthy that these values are rather realistic.

Both the calculated and experimental data for all the three combinations are shown in *fig. 6*. Despite the substantial difference in the shapes of the experimental

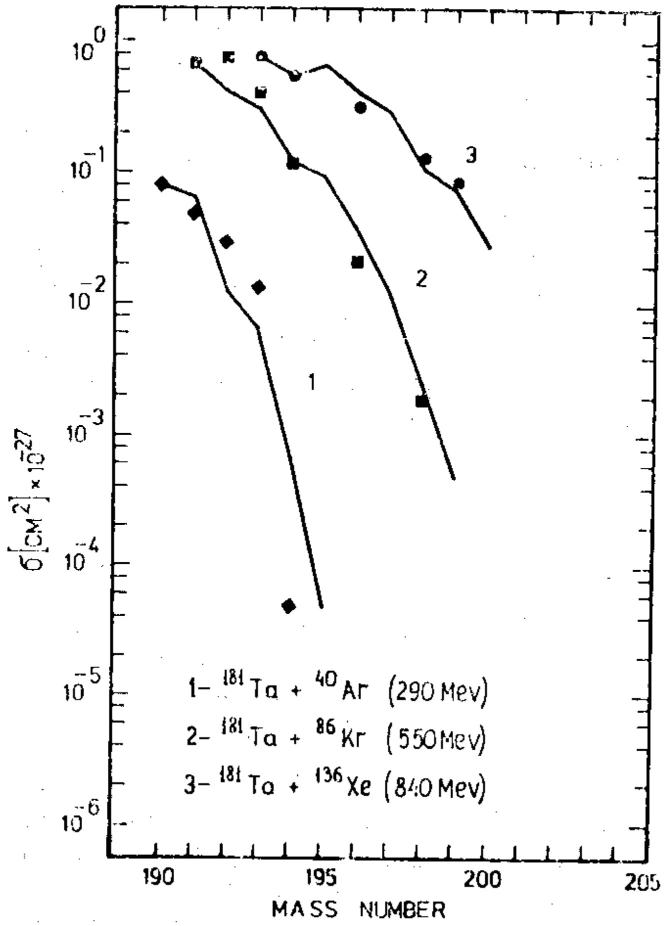


Fig. 6. Comparison of the calculated yield of gold isotopes in the systems ^{181}Ta + ^{40}Ar, ^{181}Ta + ^{86}Kr and ^{181}Ta+^{136}Xe for the optimal values of the parameters r_0, ℓ and T with experimental data. The calculated data are normalized to the experimental cross section of the isotope with a minimum A value.

dependences $\sigma(A)$ for different ions, the calculated curves reproduce them fairly well. This means that the assumptions, underlying the calculation, concerning the mechanism of the reactions, the distribution of thermal energy between the fragments, and the rotational energy of the system reflect the real nuclear processes leading to the formation of gold isotopes.

The experimental cross sections and those for the primary gold isotopes calculated in the framework of the Q_{gg} -systematics are compared in *fig. 7*. As one can see, the shape of the calculated curves, $\sigma(A)$, on the average, follows that of the experimental ones. The neutron evaporation process causes two changes in the primary distribution $\sigma(A)$, namely, it displaces $\sigma(A)$ in the direction of the smaller A by a value equal to the average number of the evaporated neutrons, and smears out the parity effect. The latter effect manifests itself most strongly in the bombardment of thick targets, as in ref. /1/. In this case the same primary isotopes are produced with different excitation energies, which leads to the smearing out of the parity effect.

4. *CONCLUSION*

(i) The Q_{gg}-systematics describe the relative yield of multinucleon transfer products for such heavy ions as ^{40}Ar , ^{86}Kr and ^{136}Xe.This means that the Q_{gg}-systematics represent one of the main regularities involved in the interaction of two complex nuclei in deep inelastic collisions.

(ii) The calculation made use of the assumption concerning the balanced distribution of thermal excitation energy between the nuclei forming the double nuclear system. The good agreement between the calculated and experimental data can be regarded as evidence for the validity of such an assumption.

(iii) In the bombardment of heavy nuclei with the heaviest possible ions the factor $Q_{gg} - \delta(n)$ varies comparatively slowly as the number of transferred neutrons

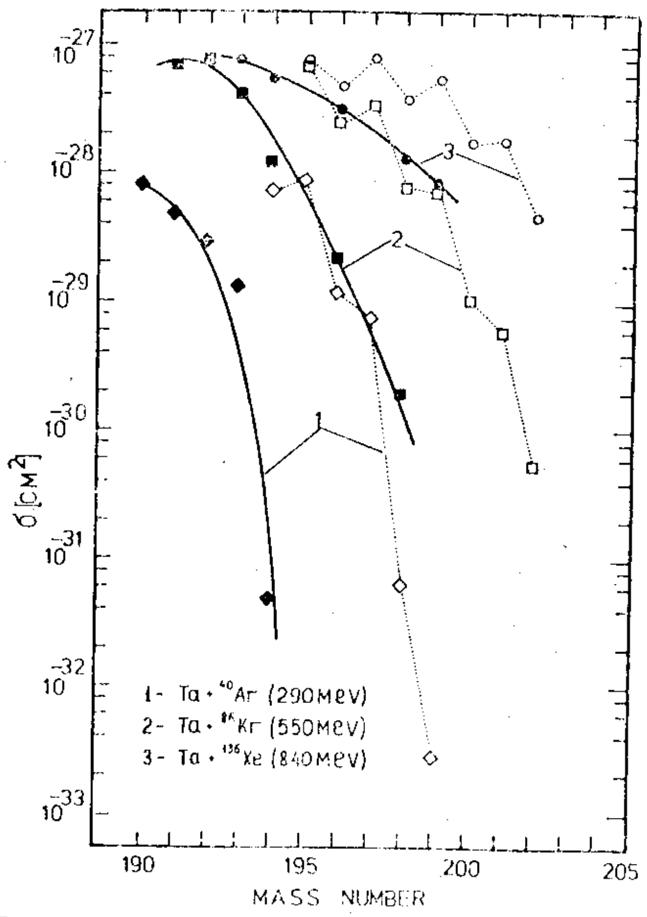


Fig. 7. Comparison of cross sections for the production of gold isotopes in the same systems at the same bombarding energies, as in fig. 6., with the calculated yield of primary gold isotopes. The yield was calculated using the generalized Q_{gg} -systematics without taking neutron emission into account.

increases. This offers a possibility of obtaining in multinucleon transfer reactions the isotopes of heavy elements with a very large neutron excess.

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REFERENCES

1. Oganessian Yu.Ts. et al. Yad.Fiz., 1974, 18, p. 734. (Sov. J.Nucl.Phys., 1974, 18, p. 377).
2. Volkov V.V. Particles and Nucleus, 1975, 6, part 4, p. 1040.
   Volkov V.V. Nucleonica, 1976, 21, p. 53.
3. Lefort M. Nucleonica, 1976, 21, p. 111.
4. Galin J. J.de Phys., 1976, 37, p. C5-83.
5. Moretto L.G., Schmitt R. J.de Phys., 1976, 37, p. C5-109.
6. Nörenberg W. J. de Phys., 1976, 37, p. C5-141.
7. Schröder W.U., Huizenga J.R. Ann.Rev.Nucl.Sci., 1977, 27, p. 465.
8. Volkov V.V. Intern.Conf. on Reactions between Complex Nuclei, Nashville, June 1975, vol. 2, Invited Papers (Noth-Holland Publ. Co. American Elsevier, New York, 1974), p. 363.
   Volkov V.V. Lecture Notes in Physics vol. 33. Classical and Quantum Mechanical Aspects of Heavy Ion Collisions. Springer-Verlaf Berlin-Heidelberg-New-York, 1975, p. 253.
9. Artukh A.G. et al. Izvestija Acad. Nauk, 1975, 39, p. 2.
10. Bondorf J.P. et al. J. de Phys., 1971, 32, p. C6-145.
11. Yoshie M. et al. Proceedings of the INS-IPCR Symposium on Cluster Structure of Nuclei and Transfer Reactions Induced by Heavy Ions. Tokyo, March, 17-22, 1975, p. 613.
12. Cormier T.M. Proc. of the Symposium on Macroscopic Features of Heavy Ion Collisions, vol. 1, p. 153, 1-3 April 1976. ANL/PHY-76-2.
13. Jacmart J.C. et al. Nucl.Phys., 1975, A242, p. 175.
14. Oganessian Yu.Ts., Yu.E.Penionzhkevich JINR, E7-9187, Dubna, 1975.
15. Kratz J.V. et al. Phys.Rev., 1976, C13, p. 2347.
16. Moretto L.G. et al. Nucl.Phys., 1976, A259, p. 173.
17. Vandenbosch R., Webb M.P., Thomas T.D. Phys.Rev., 1976, C14, p. 143.

18. Moretto L.G. et al. Phys.Rev.Lett., 1976, 36, p. 1069.
19. Galin J. et al. Nucl.Phys., 1975, A255, p. 472.
20. Otto R.J. et al. Phys.Rev.Lett., 1976, 36, p. 135.
21. Schröder W.V. et al. Phys.Rev.Lett., 1976, 36, p.514.
22. Vandenbosch R. et al. Nucl.Phys., 1976, A269, p. 210.
23. Brucherseifer H. et al. JINR, P6-10010, Dubna, 1976.
24. Sann H. et al. GSI-Bericht P-5-77.
25. Myers W.D., Swiatecki W.J. Nucl.Phys., 1966, 81, p.1. Report UCRL-11980, 1965.
26. Elton L.R.B. Nuclear Sizes, Oxford University Press., 1961.
27. Jackson J.D. Canad. J. Phys., 1956, 34, p. 767.
28. Artukh A.G. et al. Nucl.Phys., 1973, A215, p. 91.

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