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LARGE CLUSTER TRANSFER PROCESSES IN REACTIONS LEADING TO HEAVY ACTINIDES

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A model based on projectile fragmentation is proposed to describe the multinucleon transfer reactions leading to heavy actinides. The primary values of the cross sections for the formation of various isotopes are obtained by assuming that large clusters separated from the projectile are captured by the target. Data obtained at LBL and GSI for the Fm-, Md-, No-, and Lr-isotopes produced in the ^{16}O, ^{18}O, ^{22}Ne, ^{48}Ca + ^{254}Es reactions are well described by the above model after correction for neutron emission.

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

Процессы передачи массивных кластеров в реакциях, ведущих к образованию тяжелых актинидов

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Для описания реакций многонуклонных передач, ведущих к тяжелым актинидам, представлена модель, основанная на фрагментации бомбардирующей частицы. Первоначальные значения поперечных сечений для образования различных изотопов получаются, если предположить, что массивные кластеры, отделяющиеся от бомбардирующей частицы, захватываются мишенью. Данные полученные по LBL и GSI для изотопов Fm, Md, No и Lr, образованных в реакциях с ^{16}O, ^{18}O, ^{22}Ne, ^{48}Ca + ^{254}Es, хорошо описываются вышеуказанной моделью, если вводится коррекция на эмиссию нейтронов.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

During the last years, multinucleon transfer reactions have been used for the production of heavy actinides /1-3/. The understanding of the mechanism occurring in such reactions would be of great interest for allowing predictions of the production cross sections for heavier elements. The current interpretation of the reactions has

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been based so far on the theory of strongly damped collisions[4] in the context of the surviving probability of the primary products[5].

Systematic measurements for multinucleon transfer reactions in the case of the bombardment of a given target as, for example, ^{254}Es by various projectiles (^{16}O, ^{18}O, ^{22}Ne, and ^{48}Ca)[2,3] have revealed comparable cross sections for a ($\Delta Z, \Delta N$) transfer, despite a different isotope distribution for various elements (Fm, Md, No, Lr). Such a projectile dependence suggests that the fragmentation of the projectile occurs producing large clusters that are subsequently captured by the target (massive transfer, incomplete fusion or two-body breakup reaction). Much experimental evidence has been gathered recently which shows that projectile breakup processes are not negligible even at lower than 10 MeV/m incident energies[6] as happens to be the case of the above-mentioned reactions.

Starting with this observation we propose for multinucleon transfer reactions a simple model based on the following physical picture: the incoming projectile breaks up in the Coulomb and nuclear field of the target nucleus, the resulting large clusters being captured by the target nucleus. The hypothesis of a large cluster transferred as a whole is supported by experimental evidence for α and ^{8}Be transfer obtained in ^{12}C reactions on Au and Bi[7] as well as by the recently growing experimental evidence for the incomplete fusion reactions.

Therefore we consider the process:

$$P + T \rightarrow F_1 + F_2 + T \rightarrow F_1 + (F_2 + T),$$

where P, T, F_1, F_2 denote the projectile, target and the two fragments resulting from the projectile breakup. The transfer cross section for a $F_i\,(Z_i, N_i)$ cluster is given by the fragmentation probability of the projectile ($\gamma_P^{F_i}$) multiplied by the capture probability $\sigma_c(F_i, T)$:

$$\sigma(F_i) = K \gamma_P^{F_i} \cdot \sigma_c(F_i, T), \tag{1}$$

where K is a normalization factor.

The fragmentation probability is given by the Friedman model[8]:

$$\gamma_P^{F_i} \sim S_{F_i} \frac{e^{-2\mu_{F_i} x_{0_{F_i}} b}}{x^3_{0_{F_i}} (1 - b)}, \tag{2}$$

where $\mu_{F_i} = \sqrt{2m_r E^i_S}$ (m_r is the reduced mass of the two fragments and E^i_S represents the separation energy of the fragment F_i from the projectile) and the cutoff radius of the cluster internal wave functions $x_{0F_i} = 1.2 A^{1/3}_{F_i}$ fm.

S_{F_i} is the spectroscopic factor which represents the relative probability for finding together the necessary protons and neutrons which must be removed from the projectile to produce the fragment /8/. In the case of unstable particles as, e.g., ^{5}He, ^{7}He, ^{5}Li, ^{6}Be, ^{8}Be, a second fragmentation was taken into account multiplying $\gamma_P^{F_i}$ by the corresponding spectroscopic factor S'_{F_i}.

The capture probability was calculated in the semiclassical approximation by integrating over the energies of the fragment:

$$\sigma_c(F_i, T) = \pi R^2_{F_i} \int_{V_{F_i,T}}^{E_{max}} \left(1 - \frac{V_{F_i,T}}{E}\right) dE. \qquad (3)$$

Here $\pi R^2_{F_i}$ is the geometrical cross section with $R_{F_i} = 1.22\,(A^{1/3}_{F_i} + A^{1/3}_T)$. $V_{F_i,T}$ is the Coulomb barrier and E_{max} is the maximum energy of the fragment as determined by the projectile energy (E_P) the separation energy of the fragment $E_S^{F_i}$ and the Q_{F_i}-value for the reaction in which the fragment is captured by the target:

$$E_{max} = [m_T/(m_P + m_T)] \times E_P + E_S^{F_i} + Q_{F_i}.$$

The Coulomb barrier was calculated in the touching sphere approximation

$$V_{F_i,T} = \begin{cases} \dfrac{Z_{F_i} Z_T e^2}{r_c(A^{1/3}_{F_i} + A^{1/3}_T)} & (4) \\ \dfrac{Z_T e^2}{r_c A^{1/3}_T} \quad \text{for protons} & (4') \end{cases}$$

where

$$r_c = \begin{cases} 1.81 \text{ fm for protons} \\ 2.452 - 0.408 \log_{10}(Z_{F_i} Z_T) \text{ for } ^4\text{He} \\ 2.0337 - 0.2412 \log_{10}(Z_{F_i} Z_T) \quad (Z_{F_i} Z_T \leq 500) \end{cases} \qquad (5)$$

was taken from the existing systematics /9/.

As the transfer products result in an excited state, the primary distribution is modified by neutron emission. This fact is taken into account by inserting into eq.(1) a depletion factor:

$$D = 1 - \Sigma f_m , \qquad (6)$$

where $f_m = [\Gamma_n / (\Gamma_n + \Gamma_f)]^m$ is the emission probability of the m-th neutron and is calculated by using the empirical formula of Sikkeland et al.[10] for Γ_n / Γ_f.

A "feeding" factor taking into account the population of a given isotope by neutron emission from higher mass isotopes was also introduced in eq.(1).

A constant ratio Γ_f / Γ_n was assumed over the whole range of excitation energies.

The consideration of the detailed energy distribution of the fragment and the corresponding excitation energies shows a tremendous variation of the Γ_f / Γ_n ratio over the spectrum but does not change drastically the overall isotope distribution.

However such an estimation and of course a detailed calculation of the fission barriers for various isotopes will be taken into account in a further analysis.

The predictions of the model have been compared to the recent measurements performed at GSI and LBL [2,3] for the multinucleon transfer reactions produced by ^{16}O, ^{18}O, ^{22}Ne and ^{48}Ca on ^{254}Es at E/A ~ 4.5 MeV/u. By considering that $^{255\text{-}257}Fm$ isotopes are produced by ^{1-3}H capture and the $^{253,254}Fm$ are only the result of neutron emission the isotopic yields were calculated as shown above. The separation energies as well as Q-values have been calculated by using the existing tables [11]. The normalization factor is determined for proton transfer and is unique for a given system. Similarly, $^{256-261}Md$ isotopes correspond to the capture of ^{2-7}He fragments while $^{254,255}Md$ result from their deexcitation by neutron emission. Large clusters as ^{3-8}Li and ^{4-9}Be are associated with the formation of the $^{257-262}No$ and $^{258-263}Lr$, whose neutron emission leads to $^{254,255,256}No$ and $^{256,257}Lr$.

The results for the studied systems are shown on figs.1-4.

The theoretical predictions follow the general trend of the isotopic yields and give values quite close to the experimental ones.

We should mention that larger discrepancies are observed for ^{261}Md, $^{260-262}No$, $^{261-263}Lr$ whose cross sections are obtained by extrapolating the measured isotopic distributions[3].

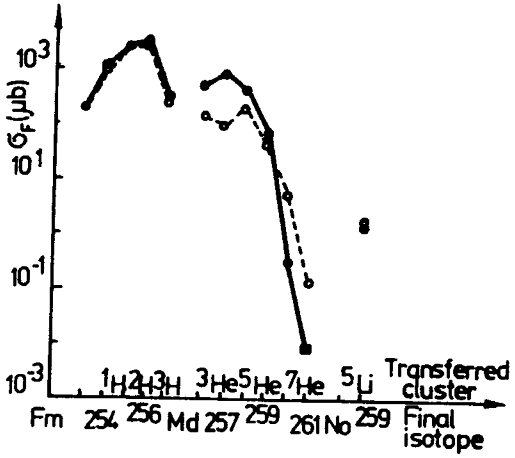
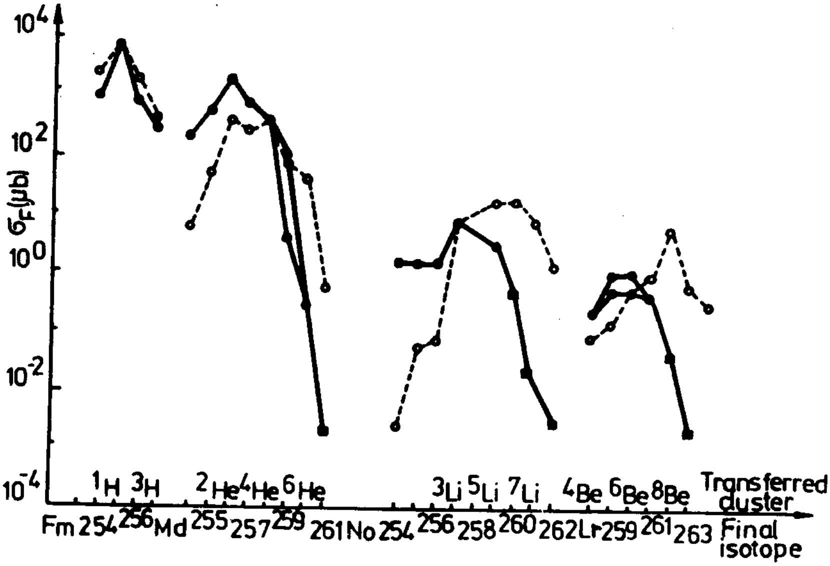


Fig.1. Comparison of measured (black points) and calculated (open points) isotopic cross sections for the 98 MeV ^{18}O on ^{254}Es. Black squares represent the values obtained by extrapolating the experimental distribution.

Fig.2. Same as in fig.1 but for 126 MeV ^{22}Ne on ^{254}Es.



In trying to apply the model in the case of ^{238}U + + ^{238}U /12/, it resulted that the primary isotopic distribution itself, not corrected for neutron emission follows the experimental one.

To summarize, the conclusions are following:

1. Multinucleon transfer cross sections for heavy actinides are well described by considering that the reaction occurs by projectile fragmentation and subsequent capture of the fragment by the target. The depletion of the initial states by neutron emission must be taken into account.

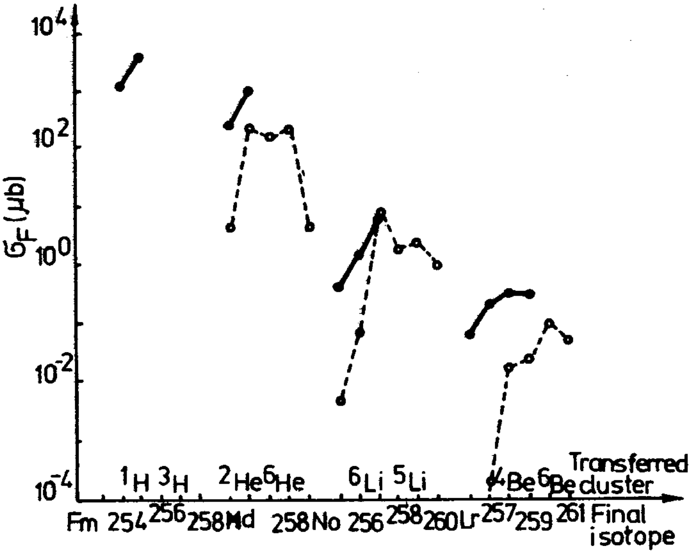


Fig.3. Same as in fig.1 but for 101 MeV ^{16}O on ^{254}Es.

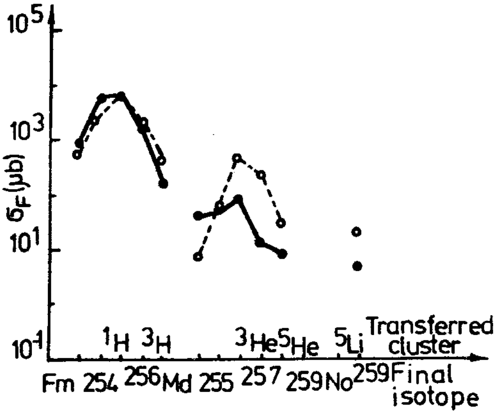


Fig.4. Same as in fig.1 but for 266 MeV ^{48}Ca on ^{254}Es.

2. The model could be extended to predict multinucleon transfer cross sections for various nuclei with a proper estimation of neutron emission.

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