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Influence of Shell Structure on Neutron and Proton Exchange in the Reactions of ^{144}Sm on ^{144}Sm and ^{154}Sm on ^{154}Sm

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The reactions of ^{144}Sm on ^{144}Sm and ^{154}Sm on ^{154}Sm have been studied at energies 30% in excess of the barrier. Whereas the number of exchanges nucleons is similar in both reactions, the number of exchanged protons is considerably larger at small energy losses in the ^{144}Sm system. On the basis of the shell-corrected liquid-drop potential energy surface these observations are attributed to the closed $N = 82$ neutron shell which, for ^{144}Sm, hinders the neutron exchange and leads to a preferential transfer of protons.

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Among the different reactions between complex nuclei the completely damped or deep-inelastic collisions have been studied most intensively. A problem of special interest is the microscopic mechanism responsible for the energy dissipation and for mass and charge transport between the colliding ions, respectively. In this context, systematic studies analyzing the increase of the variance σ_Z^2 of the element distributions as a function of the loss of total kinetic energy (TKEL) have been shown to be particularly instructive. In the earlier data reviewed by Schröder and Huizenga[1] σ_Z^2 appeared to be rather similar for different systems at not too large TKEL. Later results for the U+U system,[2,3] however, showed a much larger variance at given energy loss indicating a smaller average energy loss per exchanged proton. In contrast, in the Pb-Pb system[4] comparatively small σ_Z^2 values are observed. It has been suggested[3,4] that these differences might be due to the shell structure of target and projectile; the different TKEL versus σ_Z^2 curves, in fact, have been explained by means of a structure term which is connected with an average binding energy of the valence nucleons.[5] The general influence of the shell structure on the energy-loss mechanism has been worked out recently by Dakowski, Gobbi, and Nörenberg.[6]

The data mentioned so far do not contain any information on the mass variances σ_A^2. However, in order to prove a possibly existing influence of structure effects on the diffusion process it seems necessary to measure also the nuclear-mass distribution. The independent study of the transfer of neutrons and protons and their correlation then might shed some light onto the origin of such a correlation. At present a few data for simultaneously determined σ_Z^2 and σ_A^2 values[7-10] are available, which allow one to deduce a correlation coefficient.

In this Letter we present results of a study of the ^{144}Sm + ^{144}Sm and ^{154}Sm + ^{154}Sm systems at energies 30% in excess of the barrier (beam energies of 1000 and 970 MeV, respectively). The choice of identical reaction partners precludes any drift. The two systems with the same atomic number allow the study of two extreme cases: In the lighter system the colliding ions are spherical because of their closed neutron shell ($N=82$), while in the second one they are strongly deformed and neutron rich. It is expected that a comparison of these similar systems is particularly suited to display a possible influence of shell effects in damped heavv-ion collisions.

The experiments were performed with the UNILAC. Targets of 170 $\mu g/cm^2$ (enrichment 98%) were irradiated with currents of typically 1.5 particle nA. The experimental setup consisted of two large-area position-sensitive ionization chambers[11] mounted at opposite sides of the beam. Both detectors deliver information about the scattering angle, energy loss, and total energy; the latter two are used to determine the atomic number. In addition, the upper half of the right-hand and the lower half of the left-hand detector were covered with a thin parallel-plate avalanche counter, which in combination with the UNILAC micropulse structure ($\lesssim 400$ ps full width at half maximum) allowed for absolute time-of-flight determination for each fragment. Two settings of the right chamber were sufficient to cover the angular distribution of both systems. The left chamber was used exclusively to detect the coincident binary-reaction partner. The masses are calculated from the scattering angles and the difference in time of flight. It should be stressed that this method determines the average primary masses, if the neutrons are emitted isotropically from the primary fragments. In this case their velocity and emission angle do not change, on the average. Hence, in a symmetric system the so-deduced mass distributions have to be centered at symmetry. The data analysis was carried out event by event yielding fourfold differential cross sections $d^4\sigma/dA\,dZ\,dE\,d\theta$.

As the incident energies for the two systems were properly matched, the gross features are very similar. For "elastic scattering" (defined as events with kinetic energy losses less than 25 MeV) a quarter-point angle of $77° \pm 1.5°$ has been extracted for ^{144}Sm ($80° \pm 1.5°$ for ^{154}Sm). In the sharp-cutoff approximation these values lead to reaction cross sections of 1530 ± 150 and 1460 ± 150 mb, respectively; within the error bars these cross sections are exhausted by the measured inelastic components of events with TKEL in excess of 25 MeV. Angular distributions and the Wilczyński plots are quite alike. The maximum of the total-kinetic-energy distribution in the exit channel of the ^{154}Sm system is somewhat below that of the ^{144}Sm system, possibly pointing at even larger deformations of the outgoing fragments in the heavier system, where already target and projectile are strongly deformed.[12]

To obtain the mass and charge distributions of interest, the data have been cut into eight equally sized bins in TKEL ranging from 25 to 225 MeV. The first moments of the distributions, which are rather Gaussian in shape, are centered at the mass and atomic number of the respective projectile for all cuts in TKEL. Second moments of the A and Z distributions have been determined by fitting Gaussian functions. Their widths have been corrected for the experimental resolution, which was derived from the "elastic scattering" line to be $\Delta Z = 1.6$ and $\Delta A = 4.0$ (full width at half maximum).

The ratio of σ_A^2/σ_Z^2 for the two systems is displayed in the upper frame of Fig. 1. In the measured range of TKEL this ratio slightly decreases for the ^{154}Sm system, while it is strongly rising with TKEL for ^{144}Sm, approaching a slightly smaller value than in the ^{154}Sm system. The different behavior can be understood by the σ_A^2 and σ_Z^2 ratios for the two systems given in the middle frame of Fig. 1. $\sigma_A^2(^{144}\text{Sm})/\sigma_A^2(^{154}\text{Sm})$ is about 0.8 independent of TKEL, indicating a slightly enhanced nucleon exchange in the heavier system. However, $\sigma_Z^2(^{144}\text{Sm})/\sigma_Z^2(^{154}\text{Sm})$ is about 2 for the smallest TKEL measured and decreases to 1 with increasing TKEL, i.e., in the ^{144}Sm system the number of exchanged protons at small energy losses is twice as large in comparison to ^{154}Sm. This is taken as evidence for the hindrance of neutron transfer due to the $N=82$ shell closure. The effect gradually disappears with TKEL, and certainly has vanished at an excitation energy per fragment of ≈ 50 MeV.

As we have determined A and Z of each fragment we can calculate its neutron number N and obtain also σ_N^2. This quantity has been used to determine the correlation coefficient ρ, defined by

$$\sigma_A^2 = \sigma_N^2 + \sigma_Z^2 + 2\rho\sigma_N\sigma_Z .$$

The value of ρ is plotted in the lower frame of Fig. 1. As a result of the experimental resolution rather large uncertainties have to be assigned. The tendency of ρ to increase with excitation energy to $\rho \approx 1$ is obvious. It is interesting to note that at the highest TKEL the limit for fully correlated ($\rho = 1$) exchange of neutrons and protons, given by Beck, Dworzecka, and Feld-

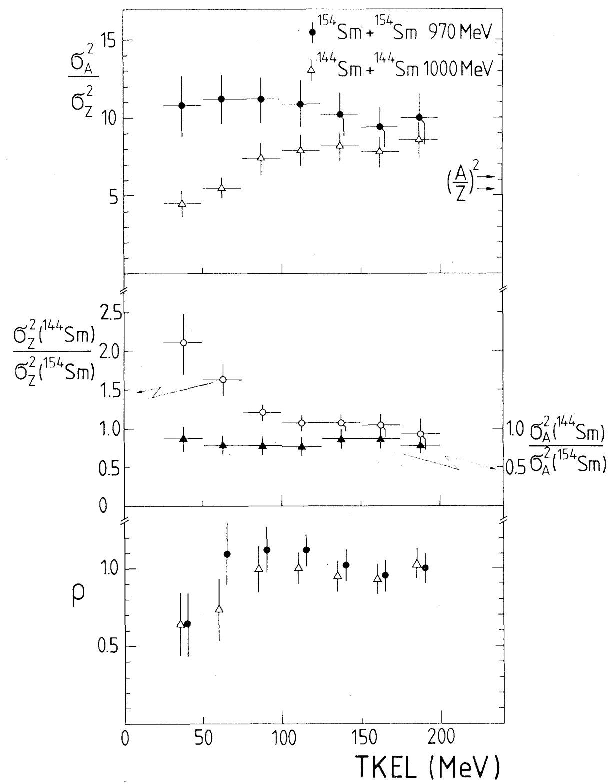

FIG. 1. Upper frame: σ_A^2/σ_Z^2 as function of total-kinetic-energy loss (TKEL) for $^{144}Sm + ^{144}Sm$ and $^{154}Sm + ^{154}Sm$. The horizontal bars reflect the bin width used; the vertical bars represent the errors due to statistics and unfolding of the experimental resolution in the various distributions. Middle frame: Ratio of the Z variances (open points) and the A variances (black triangles) for the two systems. Lower frame: Correlation coefficient ρ; the points have been slightly displaced, ^{144}Sm to the left and ^{154}Sm to the right of the bin center. The error bar is an estimate which accounts for the error in σ_A^2, σ_Z^2, and σ_N^2.

meier[13] to be $\sigma_A^2/\sigma_Z^2 = (A/Z)^2$, is significantly below the experiment. This could mean that even at the highest excitation energy not all the nucleons are involved in the exchange process. It should be mentioned that this large value is not caused by the procedure for the determination of A; the influence of sequential particle emission, e.g., which may change the second moments of the mass distributions (not the first ones), has been simulated by Monte Carlo calculations and was found to change σ_A^2 only within the error bars drawn in Fig. 1.[12]

These experimental results can be compared with calculations[6] concerning the influence of shell effects on the mean energy per transferred nucleon: For the ^{154}Sm system the ratio $dE/dP_{ex} : dE/dN_{ex}$, i.e., the energy dissipated per exchanged neutron over that per exchanged proton, is about 1, but only 0.5 in the ^{144}Sm system at a total energy loss between 40 and 50 MeV, the difference becoming smaller with increasing energy loss. Thus in comparing two equally sized energy-loss bins of the two systems one expects a preferential transfer of protons between the two ^{144}Sm nuclei in accordance with the present experimental observation.

We propose to discuss the differences in σ_A^2/σ_Z^2 for the two systems in an alternative way, i.e., in terms of the underlying potential-energy surface (PES). It has been calculated[3] as the sum of the shell-corrected liquid-drop binding energies (without pairing correction) and the nuclear and Coulomb potential for a central collision. The result is displayed in Fig. 2 for ^{144}Sm (left side) and ^{154}Sm (right side). Equipotential lines are drawn in the N-Z plane for the combined system. They are normalized with respect to the injection point. The dashed lines represent the Z/N ratio of the combined system which is equal to that of target and projectile. It coincides with the bottom of a PES calculated without shell corrections (liquid-drop PES). The influence of the $N = 82$ shell is readily visualized because it produces a strong dislocation. It changes drastically the minima of the PES which are indicated by heavy dots. They mark the isotopes of minimum potential at given Z, thus showing the path of minimum potential energy in the Z-N plane. Its slope $\Delta Z/\Delta N$ at the injection point is larger (smaller) than that of the PES bottom without shell correction for the ^{144}Sm (^{154}Sm) system.

As we know σ_N, σ_Z, and ρ, we can determine the line of regression of N on Z, which connects the maxima of the experimental N distributions for given values of Z. For a two-dimensional Gaussian distribution one obtains

$$N - N_0 = \rho(\sigma_N/\sigma_Z)(Z - Z_0),$$

where N_0 and Z_0 are the most probable values of N and Z of the distribution, i.e., the injection point. The line of regression of the first TKEL bin determined for $\rho = 0.65$ and σ_N, σ_Z is included in Fig. 2 as a heavy line for either system. It is only drawn for that Z, N region around Z_0, N_0 which contains the dominant part of the cross section of the first TKEL bin. The slope sensitively depends on ρ, which is not known precisely enough to draw quantitative conclusions. Nevertheless, one can argue that the slope of the lines of regression which were derived experimentally

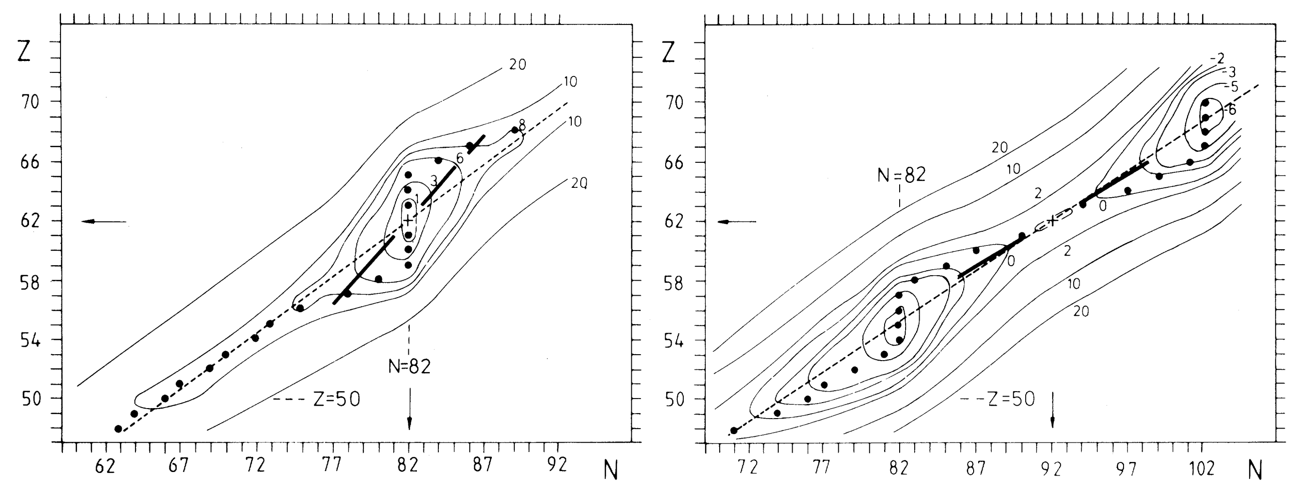

FIG. 2. Left side: Potential-energy surface calculated for $^{144}Sm + ^{144}Sm$, based on shell-corrected liquid-drop masses. The dashed line indicates the bottom of the PES without shell corrections. It coincides with Z/N line of the system. Heavy dots represent the isotopes of minimum potential energy determined for given Z. The solid line is the line of regression calculated for the first TKEL bin from the experimentally determined σ_Z, σ_N, and ρ. Right side: Same as the left side, but for $^{154}Sm + ^{154}Sm$.

differ in a way qualitatively consistent with the different directions of the valleys of minimum potential energy in the two systems. This fact demonstrates the influence of shell effects on neutron and proton transfer for not-too-large TKEL.

We conclude that the observations made for the energy dependence of σ_A^2 and σ_Z^2 for the two systems $^{144}Sm + ^{144}Sm$ and $^{154}Sm + ^{154}Sm$ are qualitatively explained by taking shell effects into account. They considerably modify the potential energy surface which the two nuclei in contact experience, and hence influence the neutron and proton exchange for not-too-large excitation energies.

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