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Charge-Asymmetry Equilibration in the Reaction of ^{129,132,136}Xe with ^{197}Au near the Interaction Barrier

J. V. Kratz, H. Ahrens, W. Bögl, W. Brüchle, G. Franz, M. Schädel, I. Warnecke, and G. Wirth
Gesellschaft für Schwerionenforschung mbH, D-61 Darmstadt, Germany

and

G. Klein and M. Weis
Institut für Kernchemie, Universität Mainz, D-65 Mainz, Germany
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Neutron-proton population ratios for quasielastic and inelastic processes in the reactions of 761-MeV ^{129}Xe, 769-MeV ^{132}Xe, and 795-MeV ^{136}Xe ions with thick ^{197}Au targets were determined radiochemically. Completely relaxed N/Z ratios are observed for damped collisions involving the transfer of $\Delta Z \geq 1$ charge units. The limiting condition $\Delta Z \approx 1$ corresponds to a characteristic time of the order of 10^{-22} sec which indicates the absence of dissipative forces in the equilibration of the charge-asymmetry mode.

Among the various modes involved in inelastic heavy-ion reactions the equilibration of the charge-asymmetry degree of freedom has been considered as the fastest one.[1] Experimental evidence derived from the scattering of Ar and Ca on various Ni and Zn isotopes[1,2] shows for these rather light systems that deep-inelastic reaction products have always equilibrated N/Z ratios even in the early stages of the relaxation process. For heavier systems, for which experimental data have not been available so far, the amount of nucleons to be transferred before N/Z equilibration is attained is larger and the lifetimes of the intermediate complex should be very short. Thus, the scattering of heavy projectiles on heavy targets, in particular at low c.m. energies, should be well suited to experimentally observe the evolution from unequilibrated to equilibrated N/Z population ratios in inelastic collisions and to compare its rate with known time scales such as the energy-loss rate[3] or the rate of charge diffusion.[3,4] This Letter reports results of an analysis of N/Z populations observed in inelastic reactions of Xe isotopes with ^{197}Au at $1.06B$.

In the present experiments, thick ^{197}Au targets were bombarded with ^{129}Xe, ^{132}Xe, and ^{136}Xe beams of 761, 769, and 793 MeV, respectively, using the Unilac accelerator. The effective c.m. energies[5] are only about 25 MeV above the interaction barrier B calculated with a radius parameter $R = 1.16(A_1^{1/3} + A_2^{1/3} + 2)$ fm. The reaction products were stopped in the target itself and in a cylindrical catcher foil placed upstream from the target, and were separated into fifteen chemical fractions after bombardment and assayed for x-ray and γ-ray activities. From these data a large number of integral cross sections $\sigma(Z,A)$ for individual isotopes ($35 \leq Z \leq 84$) were obtained which are used to define a surface of independent yields in a Z-A plane. The process to generate the surface was discussed in detail in Ref. 5. As is shown in Fig. 1(a), the cross sections reveal both the quasielastic and the binary inelastic component; in addition, there is evidence for a small probability of targetlike fragments for decay by sequential fission. Quasielastic and inelastic transfer both contribute approximately half the reaction cross section (400 mb). The integral cross section for sequential fission is 6 mb, too low to be observed indirectly as missing cross section of heavy binary inelastic products. Criteria for the disintegration of the integral cross sections for products near $Z = 54$ and $Z = 79$ into contributions from quasielastic and (partially) damped collisions are (i) a selectivity in the population of low-spin states in the quasielastic and of high-spin states in damped collisions,[6] (ii) unequilibrated N/Z ratios and narrow yield dispersions in the quasielastic transfer, and (iii) evidence for a lack of particle (neutron) evaporation in quasielastic processes, while the aver-

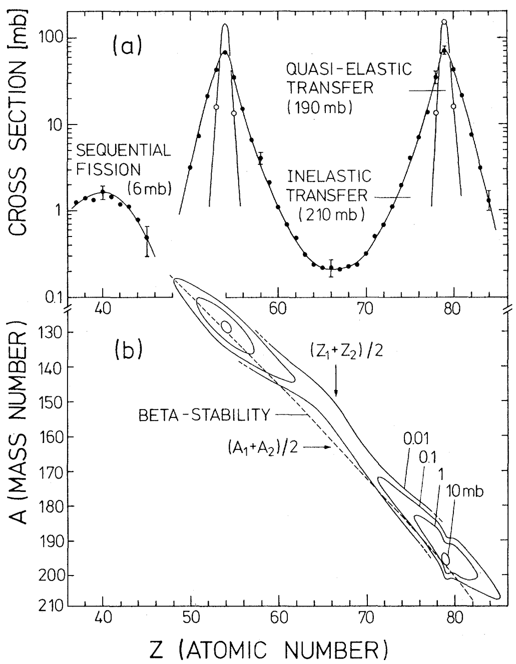

FIG. 1. The ^{197}Au + ^{129}Xe reaction at ≤ 761-MeV lab energy. (a) Charge distributions for the quasielastic, the binary inelastic component, and the sequential fission of targetlike fragments. Errors are included for selected points. (b) Independent-yield isopleths (millibarns) for the inelastic component.

age missing mass for the inelastic component is found to be larger than 2 mass units. Items (i) and (ii) are corroborated by measurements of isomer ratios and cross sections below the classical interaction barrier, where only quasielastic processes occur,[7] and item (iii) is corroborated by complementary experiments where angular distributions and c.m. energies were measured with catcher-foil techniques for individual isotopes.[8] The Z distribution for the binary inelastic component [Fig. 1(a)] is symmetric around $\frac{1}{2}(Z_1+Z_2)$ which signifies the absence of charged-particle evaporation from the primary fragments. The same conclusion can be drawn from statistical evaporation calculations.[9] The cross-section surface for the binary inelastic component is shown in Fig. 1(b). The independent yields for isotopes of a given element are well described by a Gaussian

$$P(A-A_p) \propto (2\pi\sigma_A^2)^{-1/2} \exp[(A-A_p)^2/2\sigma_A^2],$$

where σ_A denotes the width of the isotopic distribution and A_p represents the centroid, i.e., the most probable mass number for a given element. The $A_p(Z)$ values define the average N/Z ratio as a function of Z. Furthermore, the A_p values for complementary elements Z_l and Z_h are used to deduce the average missing mass associated with a given charge split (see Table I). The average missing mass as a function of Z increases as the amount of charge transfer increases. The large missing-mass values for symmetric charge splits are correlated with the large deviation of the yield locations in Fig. 1(b) from the line of β stability towards neutron-deficient isotopes at $\frac{1}{2}(Z_1+Z_2)$. Values of $\bar{\nu}_{tot} \approx 15$ at c.m. energies of ~25 MeV above the barrier have to be interpreted in terms of large fragment deformations in the exit channel which have not been observed to a comparable extent in lighter reaction systems.

TABLE I. Most probable mass numbers A_p and average missing-mass values $\bar{\nu}_{tot}$ for complementary elements Z_l and Z_h in the binary inelastic transfer of the ^{197}Au + ^{129}Xe reaction at $1.06B$. Typical errors in A_p are of the order of ± 0.5 mass units.

Z_l	A_p	Z_h	A_p	$\bar{\nu}_{tot}$
49		84	203.7	
50		83	201.1	
51	122.0	82	199.3	4.7
52	124.4	81	197.8	3.8
53	126.4	80	195.4	4.2
54	*128.5*	*79*	*195.4*	*2.1*
55	131.1	78	190.3	4.6
56	132.4	77	187.4	6.2
57	134.6	76	184.7	6.7
58	136.4	75	181.7	7.9
59	138.7	74	179.4	7.9
60	140.7	73	176.7	8.6
61	142.5	72	174.0	9.5
62	144.0	71	171.0	11.0
63	145.5	70	167.9	12.6
64	147.5	69	164.1	14.4
65	150.3	68	160.5	15.2
66	153.0	67	156.7	16.3

In order to derive a criterion for fully relaxed N/Z ratios some simple estimates based on a minimization of the potential energy for an intermediate complex being made of two target spheres[1] followed by statistical evaporation calculations[9] were performed and the results are indicated in Fig. 2. In these calculations the total excitation energy of the intermediate complex was estimated from the condition of complete energy damping assuming again a configuration of undeformed target nuclei. Such simple calculations will not allow us to predict correctly the absolute values of the N/Z ratios, in particular in the Z region

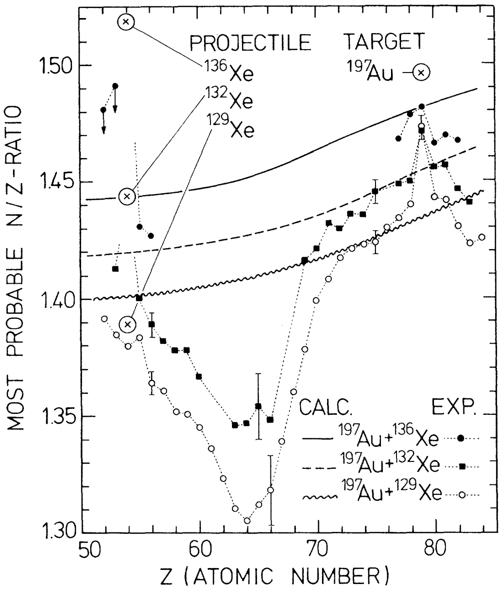

FIG. 2. Calculated fully relaxed N/Z ratios (lines) and experimental average N/Z ratios (symbols) as a function of Z for the inelastic transfer in the reactions ^{197}Au + ^{129}Xe, ^{132}Xe, or ^{136}Xe at $1.06B$. The N/Z ratios of the projectiles and the target are also indicated. Errors are given for selected points.

where the amount of total kinetic-energy (TKE) loss exceeds the limit of touching spheres. However, the predicted relative shift between the three calculated curves in Fig. 2 should be independent of the absolute inaccuracies of the calculations. Therefore, our criterion for completely relaxed N/Z ratios is an *almost parallel shift* of the N/Z ratios from neutron-deficient to more and more neutron-rich if the projectiles ^{132}Xe and ^{136}Xe are used instead of ^{129}Xe. On the other hand, in the case of unequilibrated N/Z distributions, widely separated N/Z ratios should be observed near $Z=54$ for the three different reactions, while the N/Z ratios near $Z=79$ should be the same, regardless of the choice of the projectile. Also indicated in Fig. 2 are the experimental results. Obviously, the low N/Z ratios observed for symmetric charge splits are not predicted by the model calculations which is the immediate consequences of an underestimation of the total excitation energy in the intermediate complex because the model does not allow for fragment deformations. The data in Fig. 2 for ^{136}Xe, ^{132}Xe, ^{129}Xe incident on ^{197}Au show for almost any amount of charge transfer ΔZ the characteristic parallel shift which we defined as the criterion for a complete relaxation of the N/Z mode. However, for damped collisions involving the transfer of $\Delta Z < 1$ the results are different: For $Z=79$ the centroids of the isotopic yield distributions A_p are much less shifted relative to each other than is expected for the case of equilibrated neutron-proton ratios. Even, within the experimental uncertainties of ± 0.005 in the resulting N/Z ratios the data for $Z=79$ have to be considered as identical. Furthermore, the N/Z values show a sharp structure at $Z=79$ towards the N/Z value of the target nucleus ^{197}Au. This effect is the reason for the discontinuity in the yield contours at $Z=79$ which we have shown in Fig. 1(b). Obviously, for the incompletely damped collisions leading to products in the immediate vicinity of ^{197}Au there is a memory of the original neutron-proton composition of the target nucleus and the choice of a neutron-rich or neutron-deficient projectile is of little influence. Accordingly, at $Z=54$ the (less complete) data in Fig. 2 indicate widely separated N/Z ratios and possibly again a peak structure towards the original projectile neutron-proton compositions.

Starting from the limiting condition $\Delta Z \approx 1$ one can now estimate the characteristic time for the N/Z mode. Table I shows that collisions with $\Delta Z > 1$ are associated with average missing-mass values larger than 4.4. Evaporation calculations show that the average excitation energy carried away per evaporated neutron is about 9–11 MeV. Thus, the complete relaxation of the N/Z mode requires a minimum amount of inelasticity (TKE loss) which is of the order of 40–50 MeV (if we neglect energy tied up in collective degrees of freedom). In order to correlate this limiting amount of inelasticity with a time scale we use the universal energy-loss rate of 4×10^{23} MeV/sec which was extracted by Huizenga *et al.*[3] from the data for several very heavy-ion reactions for the beginning of the relaxation process and obtain a characteristic time of about 1.2×10^{-22} sec for the relaxation of the N/Z mode. The average value for the charge diffusion coefficient D_Z within Nörenberg's diffusion model[4] as expected by Huizenga from the same experimental data[3] [$D_Z = (0.7\pm0.3)\times10^{22}$ (charge units)^2/sec] and our limiting condition $\Delta Z \approx 1$ result in a characteristic time of the order of 1.4×10^{-22} sec, which agrees with the first value within the uncertainties of such estimates. According to microscopic and hydrodynamical model calculations by Brosa and Krappe,[10] the measurement of an equilibration time of the order of $(1-2)\times10^{-22}$ sec in the Au + Xe reactions indicates that two-particle scattering or other dissipative processes do not seem to be of importance, i.e., that the N/Z mode is not overdamped like the mass-transfer mode. Also, the now available experimental evidence and theory[10] agree in that the characteristic times for N/Z relaxation depend only weakly on the size of target and projectile.

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Observation of the Proton-Pairing Vibration in ^{206}Pb

R. E. Anderson, P. A. Batay-Csorba, R. A. Emigh, E. R. Flynn,[a] D. A. Lind, P. A. Smith, and C. D. Zafiratos
Nuclear Physics Laboratory, Department of Physics, University of Colorado, Boulder, Colorado 80309

and

R. M. DeVries
Nuclear Structure Research Laboratory, University of Rochester, Rochester, New York 14627
(Received 14 July 1977)

The (^{3}He,n) reaction was studied at an incident beam energy of 33.3 MeV for targets of ^{204}Hg and ^{204,206,208}Pb. A 0^+ state at 4.1 ± 0.1 MeV in ^{206}Pb was excited with 70% of the cross section of the ^{206}Pb(^{3}He,n)^{208}Po(ground state) transition. This state lies at the predicted excitation energy of the proton-pairing vibration when particle-hole interactions are included.

Many nuclear phenomena can be described in terms of the coupling of three elementary modes of excitation: the single-particle, rotation-vibrational, and pairing modes. In heavier nuclei the first two modes have been well investigated experimentally by single-particle transfer and inelastic scattering. The pairing mode has also received considerable attention, with regard to the neutron degree of freedom, by the use of (t,p) and (p,t) reactions. The data around ^{208}Pb are in good agreement with a simple pairing vibrational model.[1] Indeed, all of the nuclear excitations investigated in the vicinity of ^{208}Pb appear to be well described by elementary modes. However, one important ingredient is missing. There exists no observation of excited proton-pairing 0^+ states or a systematic study of ground-state proton-pairing correlations for $Z=82$. Further, there has been recent interest in the possibility of α vibrations,[2] which are correlated four-particle, four-hole states analogous to the two-particle, two-hole proton- or neutron-pairing vibrations. The search for these α vibrations in the lead region[3] requires knowledge of the excitation energy of the previously unobserved proton-pairing vibration. The present Letter reports for the first time the observation of an excited proton-pairing vibrational 0^+ state in lead nuclei. Measurements of the appropriate differential cross sections and excitation energies permit a direct comparison to the harmonic pairing-vibration model.

Two-nucleon transfer reactions on targets with two nucleons less than a closed shell tend to pop-