Isospin relaxation in the reaction ^{98}Mo + ^{98}Mo at 14.7 MeV/nucleon

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(Received 15 March 1988)

The isospin relaxation is studied at high incident velocity for short interaction times where large collective amplitudes can play an important role. For the ^{98}Mo + ^{98}Mo collision at 1440 MeV incident energy, the triple differential cross section $d^3\sigma/dA\,dZ\,dE_{\rm loss}$ of the reaction products has been measured. The symmetric ^{98}Mo system was found to offer the best possibilities to obtain in a unique way the primary distributions in the (A,Z) plane, using a χ^2 method. Corrections due to particle evaporation and experimental resolution are taken into account. The predictions of the statistical model and of a collective model with quantum treatment of the charge asymmetry degree of freedom are compared with the primary isobaric variances.

During a collision between a projectile and a target which differ in their neutron to proton ratio N/Z, a rearrangement may occur induced by the isospin forces, called isospin relaxation or N/Z equilibration. In dissipative collisions at incident energies of a few MeV/nucleon in excess of the Coulomb barrier, the neutron and proton distributions of the projectilelike products show that the ratio N/Z is one of the fastest degrees of freedom to become equilibrated in the dinuclear system. On the other hand, in peripheral processes at higher incident energies the product distribution reflects the initial N/Z value of the target and projectile. Theoretically the N/Z equilibration has been treated in two different ways: In the weak coupling case strong quantal effects are expected, while in the strong coupling limit one expects classical thermal equilibrium.

The conditional variances of the proton number distribution for fixed mass asymmetry ($\sigma^2_{Z\,|\,A}$), often referred to as the isobaric variances, have been considered as the most appropriate quantity to investigate the isospin equilibration process. The weak coupling models predict that, as long as the collective phonon energy $\hbar\omega$ is much larger than the temperature T, the $\sigma^2_{Z\,|\,A}$ should rise fast, present a damped or overdamped oscillation, and remain constant up to the energy losses ($E_{\rm loss}$) for which the corresponding T starts to be comparable to $\hbar\omega$. Such behavior reflects the zero point motion in the isospin degree of freedom.

In the strong coupling limit, $\sigma^2_{Z\,|\,A}$ quickly reaches its classical thermal limit proportional to the square root of the excitation energy and thus should increase monotonically with $E_{\rm loss}$.

At large $E_{\rm loss}$ both models give the same results. The main difference between these two limits is expected for short interaction time or at small $E_{\rm loss}$. The most appropriate way to have access to short interaction times is to study these phenomena at higher incident energies,[1] like in this case where variances were measured for the first time at 11 MeV/nucleon in excess of the barrier. A recent review of these aspects, concerning the N/Z equilibration process, can be found in Ref. 2.

In spite of the large amount of experimental work published on this subject, the situation remains ambiguous. Various sources of distortion in the primary (A,Z) product distribution prior to evaporation make a comparison with theoretical predictions rather difficult. Recently attention has been drawn[3] to the uncertainties in the procedure used to determine the moments of the experimental distribution. Furthermore, serious distortions are introduced by sequential evaporation at higher energies.[4] Detailed evaporation calculations for the system ^{56}Fe+^{165}Ho (Ref. 5) have shown a focusing effect which makes it difficult to determine the primary distribution accurately and unambiguously. This distortion is caused mainly by charged particle evaporation. When evaporation heavily distorts the primary distribution, substantially different primary distributions can produce, after evaporation corrections, the same secondary distribution. In these cases, folding the evaporation in a theory and obtaining agreement with the experimental data, it is not sufficient for claiming the reliability of the model. Especially in the presence of charged particle evaporation it is essential to demonstrate that it is possible to obtain the primary distribution in a unique way. In this sense there is no work in the literature which gives a reliable primary distribution and indicates the role played by the various sources of distortion.

In this Brief Report we will show that, for the system studied here, it is possible to obtain the primary distribution in a unique way with good accuracy.

The choice of the symmetric ^{98}Mo + ^{98}Mo system aims at optimum conditions for a determination of the $\sigma^2_{Z\,|\,A}$

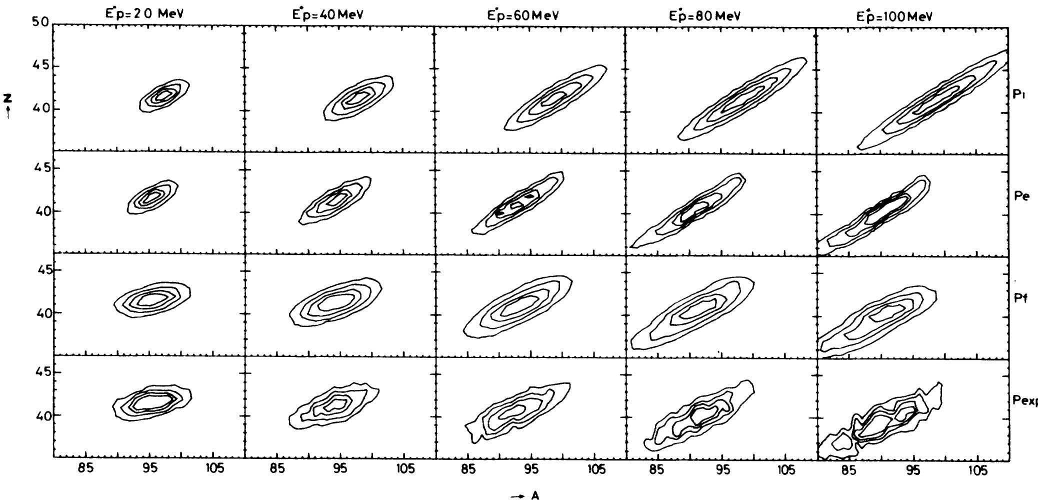

FIG. 1. The first row shows the primary distribution $P_i(A_i,Z_i)$, the second row the secondary distributions $P_e(A_e,Z_e)$ after evaporation, and the third row after experimental resolution correction $P_f(A_f,Z_f)$. In the last row the experimental distributions $P_{exp}(A_{exp},Z_{exp})$ are displayed. The contour lines are drawn at the levels of 20%, 40%, 60%, and 80% of the maximum value.

values. For lighter systems a deexcitation by alpha particles makes a determination of the primary (A,Z) distribution difficult. This is also true for asymmetric systems where the partition of the excitation energy is rather poorly known for the binary products. For an unambiguous reconstruction, a neutron-rich system offers the best possibilities. Heavier systems would have imposed additional limitations due to poorer mass resolution. The relevant parameters needed to characterize the primary distribution for a given projectilelike excitation energy $[P(A,Z,E_p^*)=d\sigma^3/(dA\,dZ\,dE_p^*)]$ are as follows: the centroids A_0 and Z_0, the variances σ_Z^2 and σ_A^2, and the correlation coefficient $\rho_{AZ}=\sigma_{AZ}^2/\sigma_A\sigma_Z$. In the (A,Z) plane a two-dimensional normal distribution

$$P_i(A_i,Z_i)=N\exp[c_1(A-A_0)^2+c_2(Z-Z_0)^2 -2c_3(A-A_0)(Z-Z_0)]$$

has been used, where

$$c_1=-\sigma_Z^2/2c,\quad c_2=-\sigma_A^2/2c\ ,$$

$$c_3=-\sigma_{AZ}^2/2c,\quad c=\sigma_A^2\sigma_Z^2-\sigma_{AZ}^4\ .$$

Following the method of Ref. 5 the distribution after evaporation is obtained by

$$P_e(A_e,Z_e)=\Sigma_{Ai}\Sigma_{Zi}M(A_e,Z_e,A_i,Z_i,E_i^*)P_i(A_i,Z_i)\ ,$$

with $M(A_e,Z_e,A_i,Z_i,E_i^*)$ being the probability that the primary fragment (A_i,Z_i) at excitation energy E_i^* will populate, after evaporation, the nuclide (A_e,Z_e).

We have performed evaporation calculations with the code PACE (Ref. 6) at five excitation energies (20, 40, 60, 80, and 100 MeV) for an array of nuclides covering a large range of masses ($A_{min}=83$, $A_{max}=110$) and charges ($Z_{min}=33$, $Z_{max}=50$), representing all possible primary fragments of interest for this reaction. For the reaction $^{98}Mo+{}^{98}Mo$ at 14.7 MeV/nucleon, the fragment spin corresponding to an excitation energy

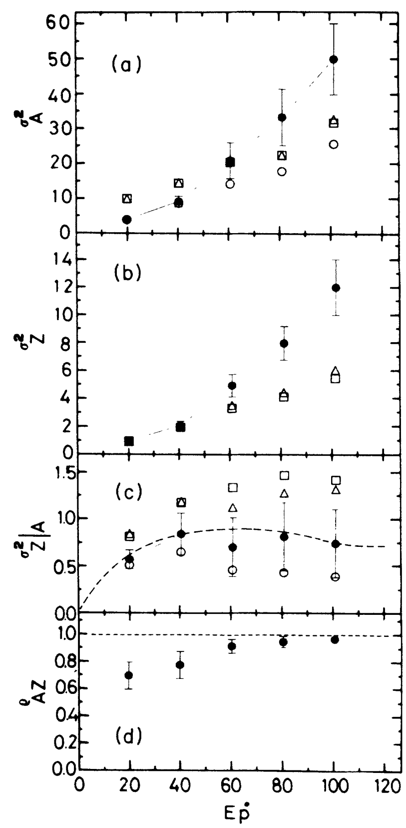

FIG. 2. (a) Total mass, (b) total charge variances, (c) charge variance for fixed mass asymmetry, and (d) correlation coefficient as a function of projectilelike excitation energy (E_p^*). The filled circles are the primary values, open circles the values after evaporation correction, squares including the finite experimental resolution, and open triangles experimental values. The full line is to guide the eye. The dashed and dotted lines are explained in the text.

$E_p^* = 100$ MeV is $10\hbar$, obtained from the model by Wolschin.[7] Up to a value of the intrinsic angular momentum of $20\hbar$, the calculated charge and mass multiplicities are constant. Therefore we have performed the PACE calculations with zero angular momentum. In the next step the experimental charge and mass resolution ($\sigma_Z = 0.27$, $\sigma_A = 2.5$) is incorporated via a Monte Carlo procedure.

The final distribution $P_f(A_f, Z_f)$ can be fitted to the experimental one using a χ^2 method. In a first step the values of the centroid (A_0, Z_0) have been determined by a χ^2 minimization procedure. In a second step we have calculated the χ^2 in the three-dimensional space of the parameters σ_A, σ_Z, and ρ_{AZ}. For this neutron-rich system and only for a neutron-rich system the fit converges to a well-defined χ^2 minimum region and allows us to extract the primary distribution in a unique way. More details on the fitting procedure and on the results will be presented elsewhere.[8]

Figure 1 shows the contour maps for the calculated primary (A,Z) distribution $P_i(A_i, Z_i)$, the calculated secondary distribution $P_e(A_e, Z_e)$ (the experimental resolution not included), and $P_f(A_f, Z_f)$ (where the experimental resolution was taken into account). The last row shows the experimental distribution $P_{\rm exp}(A_{\rm exp}, Z_{\rm exp})$ integrated over a 10 MeV excitation energy bin. One can follow the evolution of these distributions for five selected excitation energies. The quantitative results are presented in Fig. 2, where the variances for the total charge and mass distributions and for the isobaric distribution together with the correlation coefficient are shown as a function of E_p^*. The isobaric distributions are shown with a bin width of two mass units. Several general features appear:

(i) After the evaporation there is a shrinking of the σ_A^2 and σ_Z^2 which increases with increasing excitation energy [Figs. 2(a) and (b)]. This effect can be attributed to charged particle emission which, for this system, starts to set in at $E_p^* > 40$ MeV.

(ii) The finite experimental mass resolution broadens the distributions. The variances after this correction (open square in Fig. 2) are in very good agreement with the experimental data (open triangles). It should be noticed that the isobaric variances are much more sensitive to the mass resolution than the total variances σ_A^2. This is reflected in the error bars [Figs. 2(a) and (c)]. However, this effect, although important, does not prevent us from obtaining the primary distribution in a unique way. We have also applied this method to the proton-rich system ^{92}Mo + ^{92}Mo, measured in the same experiment,[9] and were unable to obtain the primary distribution.

(iii) A strong correlation is present in the $P_i(A_i, Z_i)$ also at small excitation energies. The behavior of the correlation coefficient ρ_{AZ} is consistent with the increase of the correlation of neutron and proton exchange with increasing dissipated energy as predicted by several models.[2,10]

Since we now have $\sigma_{Z|A}^2$ for the primary distribution as a function of energy loss, we can compare the experimental result with the prediction of two models, one with strong and the other with weak coupling.

In the weak coupling limit the model of Ref. 11 gives an analytical expression for the $\sigma_{Z|A}^2$:

$$\sigma_{Z|A}^2 = \left[\tfrac{1}{2}a^2 \left[\cos(\omega_d t) + \frac{\beta'}{2\omega_d}\sin(\omega_d t) \right]^2 + \frac{\hbar^2}{2a^2 B\omega_d^2}\sin^2(\omega_d t) \right] \exp(-\beta' t) + \frac{\hbar}{2B\omega_d}[1-\exp(-\beta' t)]\coth\left[\frac{\hbar\omega_d}{2T}\right]$$
$$+ \frac{\hbar}{2B\omega_d}\frac{\beta'^2}{\beta'^2+4\omega_d^2}\coth\left[\frac{\hbar\omega_d}{2T}\right]$$
$$\times[1-\exp(-\beta' t)\cos(2\omega_d t) + \exp(-\beta' t)(2\omega_d/\beta')\sin(2\omega_d t)] \,,$$

where β' is a friction coefficient and $\omega_d = \omega[1-(\beta'/2\omega)^2]^{1/2}$ with $\omega = (K/B)^{1/2}$.

The stiffness K is given by

$$K = 8ka_1[(1/A_1)+(1/A_2)] - 8ka_2[(1/A_1^{4/3})+(1/A_2^{4/3})] - 2a_3[(1/A_1^{1/3})+(1/A_2^{1/3})] - (2e^2/R)$$

($a_1 = 15.4949$ MeV, $a_2 = 17.9438$ MeV, $k = 1.7826$, $a_3 = 0.7053$ MeV, and $e^2 = 1.44$ MeV fm).

The contact times have been calculated using the code DONA (Ref. 7), and the dependence of the inertia parameter B on the impact parameters has been evaluated using the results of the hydrodynamical model of Ref. 12. The predictions of this calculation are presented by a dashed line in Fig. 2(c).

In the strong coupling limit $\sigma_{Z|A}^2 = T/K$, where K is the stiffness parameter. The dotted line in Fig. 2(c) corresponds to such a prediction[13] where $T = (aE_p^*)^{1/2}$ with $\omega = (K/B)^{1/2}$ and $a = 10/A$. B is the inertia parameter.

The presented model descriptions, which represent two extreme cases, are simple and analytical. More extensive theoretical calculations like the independent particle exchange model[14] would also be of interest, but is outside the scope of this work.

In conclusion, we have shown that for the neutron-rich system ^{98}Mo + ^{98}Mo the primary isobaric variances can be reliably determined in spite of the distortions introduced by the evaporation process and by the experimental resolutions. It is found that this reaction is a good test for the isospin relaxation process where, due to the short interaction time, large collective amplitudes can be expected and where the primary isobaric variances can be uniquely determined. On the contrary, in the presence of a strong charge particle emission, the reconstruction of the primary distribution can become impossible. It must be concluded that only detailed primary distribution reconstructions like the ones presented here allow us to draw any conclusions on the reliability of model calculations. For the system ^{98}Mo + ^{98}Mo the prediction of the collective model reproduces the measured $\sigma^2_{Z\,|\,A}$ distribution well.

ACKNOWLEDGMENTS

One of us (M.P.) was supported by the scientific exchange agreement between the Federal Republic of Germany and Romania. The authors wish to thank K. D. Hildenbrand, L. G. Moretto, and W. D. Myers for fruitful discussions.

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