Heavy-Residue Isoscaling as a Probe of the Process of N/Z Equilibration

G.A. Souliotis\textsuperscript{a}, M. Veselsky\textsuperscript{a,b}, D. V. Shetty\textsuperscript{a}, S. J. Yennello\textsuperscript{a}.

\textsuperscript{a} Cyclotron Institute, Texas A\&M University, College Station, TX 77843, USA
\textsuperscript{b} Institute of Physics, Slovak Academy of Sciences, Dubravska 9, 84228 Bratislava, Slovakia

Abstract

The isotopic and isobaric scaling behavior of the yield ratios of heavy projectile residues from the collisions of 25 MeV/nucleon \textsuperscript{86}Kr projectiles on \textsuperscript{124}Sn and \textsuperscript{112}Sn targets is investigated and shown to provide information on the process of N/Z equilibration occurring between the projectile and the target. The logarithmic slopes $\alpha$ and $\beta'$ of the residue yield ratios with respect to residue neutron number $N$ and neutron excess $N-Z$ are obtained as a function of the atomic number $Z$ and mass number $A$, respectively, whereas excitation energies are deduced from velocities. The relation of the isoscaling parameters $\alpha$ and $\beta'$ with the N/Z of the primary (excited) projectile fragments is employed to gain access to the degree of N/Z equilibration prior to fragmentation as a function of excitation energy. A monotonic relation between the N/Z difference of fragmenting quasiprojectiles and their excitation energy is obtained indicating that N/Z equilibrium is approached at the highest observed excitation energies. Simulations with a deep-inelastic transfer model are in overall agreement with the isoscaling conclusions. The present residue isoscaling approach to N/Z equilibration offers an attractive tool of isospin and reaction dynamics studies in collisions involving beams of stable or rare isotopes.

\textbf{Key words:} Heavy Residues, N/Z equilibration, Deep-inelastic transfer, Isoscaling, Fermi Energy, Nuclear reactions
\textbf{PACS:} 25.70.Mn,25.70.Lm,25.70.Pq

\footnote{E-mail address: soulioti@comp.tamu.edu}

Preprint submitted to Elsevier Science 17 November 2018
1 Introduction

The recent progress in the field of Rare Isotope Beams (RIB) worldwide opens up new and exciting frontiers in the studies of nuclear structure and nuclear reactions (e.g. [1,2]). For the latter in particular, the availability of beams with large neutron-to-proton ratio, N/Z, provides the opportunity to explore the collision dynamics of very isospin-asymmetric nuclear systems [3]. In such reactions, the N/Z degree of freedom (loosely called “isospin” degree of freedom) and its equilibration have prominent roles and can serve as valuable probes of the symmetry energy term of the nuclear equation of state [4,5]. Extensive work in deep-inelastic heavy-ion collisions at low energies (E/A < 10 MeV, for a review see, e.g., [6,7]) provided insight into the relevant reaction mechanisms [8,9,10]. At these energies, the collisions are of binary character involving a transient dinuclear complex. A fast redistribution of neutrons and protons takes place between the interacting projectile and target and characterizes the process of N/Z (or isospin) equilibration (or relaxation), governed predominantly by the potential energy surface of the dinuclear complex. At medium energies, recent work [11,12] indicated that essentially above the Fermi energy isospin equilibrium is not reached even for the most damped (central) collisions. In these studies, isotopic [11] or isobaric [12] yield ratios of selected intermediate-mass fragments (IMF) were used to probe isospin equilibration in near-central collisions. Insight into isospin equilibration has also been provided in a recent study of reconstructed quasiprojectiles undergoing multifragmentation following a deep-inelastic collision [13]. In addition, IMF isotopic yield ratios were employed in a recent work to probe the degree of N/Z equilibrium in peripheral collisions of $^{124,112}$Sn + $^{124,112}$Sn at 50 MeV/nucleon [14]. Parallel studies have also been performed at relativistic energies [15]. A recent theoretical treatment of N/Z transport and equilibration is given in [16].

It would be of great interest to probe experimentally the evolution towards N/Z equilibrium as a function of the excitation energy (or the impact parameter) from the very peripheral to the most damped collisions. In such an endeavor, the properties of heavy residues appear of central importance. As well known, in deep-inelastic collisions at low and medium energies, a large fraction of the reaction cross section corresponds to the production of heavy residues, i.e., large surviving remnants of the projectile (or target) after evaporation of neutrons, protons or light charged particles [17]. The velocities of the residues, strongly correlated to their mass, provide information on the excitation energy imparted into the collision partners. The N/Z of the residue is reminiscent of the N/Z of the corresponding hot primary fragment, but the former is substantially affected by the evaporation process. Efforts to reconstruct the primary quasiprojectile [9,10] based on evaporation codes provide a first picture of the process of N/Z equilibration as a function of the excitation energy.
energy and thus, the interaction time. It should be noted that information on N/Z equilibration has also been obtained recently in prompt $\gamma$-ray studies [18] in which enhanced emission of dipole $\gamma$ rays during the N/Z equilibration process was observed in isospin asymmetric reactions.

In the present study, we will describe a new experimental approach to follow the process of N/Z equilibration based on heavy-residue isoscaling. The approach employs yield ratios of isotopically resolved heavy residues obtained from two isospin-asymmetric reactions in conjunction with high-resolution measurement of residue velocities. This Letter is organized as follows. In section 2, a concise description of the experimental measurements of heavy projectile residues from the reactions of $^{86}$Kr (25MeV/nucleon) with $^{124}$Sn and $^{112}$Sn targets is given. In section 3, the analysis of residue yield ratios and the procedure to extract information about N/Z equilibration are described, followed by model comparisons. Finally a summary and conclusions are given in Section 4.

2 Experimental Details

The experimental measurements and analysis procedures are described in detail in our recent article [19] in which a detailed study of isotopic scaling of heavy projectile fragments from 25 MeV/nucleon $^{86}$Kr-induced reactions on $^{124,112}$Sn and $^{64,58}$Ni is reported. Herein we present a subsequent analysis of the Kr+Sn data with the aim of obtaining detailed information on the N/Z equilibration process. For completeness, a short description of the experimental conditions follows. The measurements were performed at the Cyclotron Institute of Texas A&M University. A 25 MeV/nucleon $^{86}$Kr$^{22+}$ beam (\(\sim1\) pnA) from the K500 superconducting cyclotron interacted with $^{124}$Sn and $^{112}$Sn targets. Projectile residues were analyzed with the MARS recoil separator [20]. The primary beam struck the target at an angle of 4.0° relative to the optical axis of MARS. At the focal plane of MARS, the fragments were collected in a 5×5 cm $\Delta$E–E Si detector telescope. Time-of-flight was measured between two PPACs (parallel plate avalanche counters) placed at the MARS dispersive image and at the focal plane, respectively. The horizontal position provided by the first PPAC and the field measurement of the MARS first dipole magnet were used to determine the magnetic rigidity, $B\rho$. The reaction products were characterized event-by-event using energy-loss, residual energy, time-of-flight, and $B\rho$. These quantities were calibrated with a low intensity $^{86}$Kr beam and other beams at 25 MeV/nucleon. With the procedures described in Ref. [19,21], the atomic number $Z$, the ionic charge $q$, the mass number $A$ and the velocity of the fragments were obtained with high resolution. The resolutions of $Z$, $q$ and $A$ were 0.5, 0.4 and 0.6 units, respectively, for near projectile residues. Summation over the ionic charge states provided yield distributions.
with respect to \(Z, A\) and velocity from which the yield distributions employed in this work were obtained. We note that the measurements were performed in the magnetic rigidity range of 1.3–2.0 T m (by superposition of successive settings of the separator) and angular range of 2.7°–5.4° [19] which lies inside the grazing angle of 6.5° of the Kr+Sn systems at 25 MeV/nucleon. This \(B\rho\) and angular range enabled efficient collection of heavy projectile residues produced in a large range of energy damping, from quasielastic to deep-inelastic collisions.

### 3 Results and Discussion

Before discussing residue isoscaling and N/Z equilibration, we will examine the characteristics of residue velocities and the information on excitation energy that they can provide. It is well known that peripheral reactions between massive nuclei around the Fermi energy [17] proceed via a deep-inelastic transfer mechanism involving substantial nucleon exchange [13,22,23]. This mechanism is responsible for the creation of highly excited primary products that de-excite to produce the observed fragments. Information on the excitation energy of the primary fragments from the present reactions can be obtain from the measured velocity versus mass number \(A\) (or atomic number \(Z\)) correlations. Fig. 1a presents the average velocities of the projectile fragments as a function of \(A\). Closed symbols correspond to the reactions with the neutron-rich \(^{124}\text{Sn}\) target and open symbols to those with the neutron-poor \(^{112}\text{Sn}\) target. (As we observe, the average velocities from the reactions with the two targets are, within the experimental uncertainties, roughly the same.) In this figure, we observe that for fragments close to the projectile, the velocities are slightly below that of the projectile, corresponding to very peripheral, low-excitation energy events. A monotonic decrease of velocity with decreasing \(A\) is observed, indicative of larger dissipation and thus, higher excitation energies. A similar correlation of velocity with the atomic number \(Z\) of the fragments is obtained, as presented in Fig. 1a of [19].

The descending velocity–mass correlation continues down to \(A\sim 65\). For lower masses, the average velocity appears to increase slowly. As pointed out in [19], the observation of a minimum velocity for \(A<65\) (\(Z<28\)) indicates that these residues originate from primary fragments with a maximum observed excitation energy. Fragments with \(A\) near the projectile down to \(A\sim 65\) originate from evaporative type of de-excitation which preserves, on average, the emission direction of the residues. In this case, the residue velocity can be employed to obtain excitation energy. Residues with lower \(A\) may arise from cluster emission or multifragmentation and the velocity of the inclusively measured fragments is not monotonically correlated with excitation energy and mass [19]. (These lower mass fragments are not the focus of the present work.
Employing the observed average residue velocities for the Kr+Sn systems and, furthermore, assuming binary kinematics and equal division of excitation energy (which is a reasonable approximation for the present reactions [13,24]), we can estimate an average excitation energy per nucleon for the hot quasiprojectile fragments as a function of mass as presented in Fig. 1b. Using the Fermi gas relationship \( E^* = \frac{A}{K}T^2 \), with \( T \) the temperature and \( K \) the inverse level density parameter, taken as \( K=13 \text{ MeV} \) [25], we can also estimate the temperature of the Kr-like quasiprojectiles. We note that, at the maximum observed excitation energy of 2.2 MeV/nucleon, the temperature is 5.3 MeV, which is near the threshold for multifragmentation [13,25,26].

Having presented the excitation energy characteristics of the measured residue data, we will examine the isoscaling properties of their yields. It has been shown [27,28,29,30], that the ratio \( R_{21} = Y_2(N, Z)/Y_1(N, Z) \) of the yields of a given fragment \((N,Z)\) from two reactions with similar excitation energies and similar masses, which differ only in \(N/Z\), eliminates the effects of secondary decay and provides information about the excited primary fragments. An exponential relation with respect to \(N\) and \(Z\) of the form:

\[
R_{21}(N, Z) = Y_2(N, Z)/Y_1(N, Z) = C \exp(\alpha N + \beta Z) \tag{1}
\]

has been obtained both experimentally and theoretically and has been termed isotopic scaling or isoscaling. In the framework of the grand canonical ensemble, the scaling parameters \(\alpha\) and \(\beta\) are expressed as \(\alpha = \Delta \mu_n/T\) and \(\beta = \Delta \mu_p/T\), with \(\Delta \mu_n\) and \(\Delta \mu_p\) being the differences in the neutron and the proton chemical potentials and \(T\) the temperature of the fragmenting systems [27]. \(C\) is an overall normalization constant.

For the Kr+Sn data, we construct the yield ratio \(R_{21}(N, Z)\) using the usual convention that index 2 refers to the more neutron-rich system and index 1 to the less neutron-rich one. Fig. 2a shows the isotopic yield ratios \(R_{21}(N,Z)\) as a function of fragment neutron number \(N\) for several isotopes. As also described in [19], for each \(Z\), exponential functions of the form \(C \exp(\alpha N)\) were fitted to the data and are shown in Fig. 2a for the selected isotopes. In Fig. 2b, we present the slope parameter \(\alpha\) of the exponential fits as a function of \(Z\). As already pointed out in [19], the parameter \(\alpha\) remains roughly constant at an average value of 0.43±0.01 for elements up to \(Z\sim26\) (corresponding to primary events with the maximum observed excitation energy of 2.2 MeV/nucleon) and decreases gradually for larger fragments.

In addition to the isotopic scaling discussed above, we will present the scaling relation in an alternative expression, namely, as isobaric scaling. As pointed
out by Botvina [30], the isoscaling relation of Eq. 1 can also be expressed as:

$$R_{21}(A, N - Z) = C \exp\{\alpha' A + \beta' (N - Z)\}$$  \hspace{1cm} (2)

with $\alpha' = (\alpha + \beta)/2$ and $\beta' = (\alpha - \beta)/2$. This isobaric scaling relation expresses an exponential dependence of the yield ratios of a given fragment of an isobaric chain $A$ on the neutron excess $N-Z$ (or, equivalently, on the third component of the isospin $t_z = (N-Z)/2$). In a manner similar to isotopic scaling, the scaling parameters $\alpha'$ and $\beta'$ express differences of chemical potentials $\mu_A$ and $\mu_{N-Z}$ conjugate to the variables $A$ and $N-Z$. These potentials are connected to $\mu_n$ and $\mu_p$ via the relations: $\mu_A = (\mu_n + \mu_p)/2$ and $\mu_{N-Z} = (\mu_n - \mu_p)/2$. These expressions lead to the following relations for the isobaric scaling parameters:

$$\alpha' = \frac{\Delta(\mu_n + \mu_p)}{2T} \quad \text{and} \quad \beta' = \frac{\Delta(\mu_n - \mu_p)}{2T}.$$  

In the isobaric scaling expression of Eq. 2, the dependence on $A$ via $\alpha'$ is weak, since the coefficient $\alpha'$ is close to zero [30] and it will not be considered in the present study. From the data, we construct the yield ratio $R_{21}(A, N - Z)$ again with the convention that index 2 refers to the more neutron-rich system. Fig. 3a shows the yield ratios $R_{21}(A,N-Z)$ as a function of fragment neutron-excess $N-Z$ for several isobars. In this figure, we see that the ratios for each isobaric chain exhibit a remarkable exponential behavior. For each $A$, an exponential function was fitted to the data and also shown in Fig. 3a for the selected masses. In Fig. 3b, we present the slope parameter $\beta'$ of the exponential fits as a function of $A$. The slope parameter $\beta'$ remains roughly constant at an average value of 0.47±0.01 for $A < 60$ and decreases monotonically for $A > 60$. We note that the isobaric scaling parameter $\beta'$ herein obtained for the low-mass range is in very good agreement with the expected value of $(\alpha - \beta)/2$ if the experimentally obtained values of the isoscaling parameters $\alpha = 0.43\pm0.01$ and $\beta = -0.50\pm0.01$ [19] are used.

In the following, we will use the relation of the isoscaling parameters $\alpha$ and $\beta'$ with the primary fragment $N/Z$ to extract information on $N/Z$ equilibration. In the framework of the grand canonical approximation of the statistical multifragmentation model (SMM) [30], the isoscaling parameters $\alpha$ and $\beta'$ can be directly related to the coefficient $C_{\text{sym}}$ of the symmetry energy term of the nuclear binding energy and the $N/Z$ of the primary fragmenting systems. The following expressions are obtained:

$$\alpha = 4 \frac{C_{\text{sym}}}{T} \left(\frac{Z_1}{A_1} - \frac{Z_2}{A_2}\right)^2 \hspace{1cm} (3)$$

$$\beta' = 4 \frac{C_{\text{sym}}}{T} \left(\frac{Z_1}{A_1} - \frac{Z_2}{A_2}\right) \hspace{1cm} (4)$$

in which $Z_1,A_1$ and $Z_2,A_2$ refer to the fragmenting quasiprojectiles from reac-
tions 1 and 2, respectively. From these equations, after some manipulation we obtain:

\[
\alpha = 8 \frac{C_{\text{sym}}}{T} \left( \frac{Z}{A} \right)_{\text{ave}}^3 \Delta \left( \frac{N}{Z} \right)_{qp} \quad (5)
\]

\[
\beta' = 4 \frac{C_{\text{sym}}}{T} \left( \frac{Z}{A} \right)_{\text{ave}}^2 \Delta \left( \frac{N}{Z} \right)_{qp} \quad (6)
\]

where \((Z/A)_{\text{ave}}\) is the average \(Z/A\) of the quasiprojectiles, taken to be the average \(Z/A\) of the composite systems \(^{86}\text{Kr}+^{124}\text{Sn}\) and \(^{86}\text{Kr}+^{112}\text{Sn}\), and \(\Delta(N/Z)_{qp}\) expresses the \(N/Z\) difference of fragmenting quasiprojectiles corresponding to a given value of fragment \(Z\) or \(A\), scaling parameters \(\alpha\) or \(\beta'\) and the corresponding temperatures \(T\). Assuming that fragmentation occurs at normal density, using \(C_{\text{sym}} = 25\) MeV [30], the \(\alpha\) and \(\beta'\) values obtained from the isotopic (Fig. 2b) and isobaric (Fig. 3b) scaling fits, respectively, and temperatures determined from excitation energies, we can determine the values of \(\Delta(N/Z)_{qp}\) as a function of the observed fragment atomic number \(Z\), as well as, mass number \(A\). Subsequently, plotting \(\Delta(N/Z)_{qp}\) versus the average \(E^*/A\) value corresponding to each \(Z\) or \(A\), we obtain the correlations presented in Fig. 4a. The open circles correspond to the isotopic scaling procedure, whereas the full circles to the isobaric scaling procedure. In this figure, the horizontal dotted line expresses the \(N/Z\) difference of fragmenting quasiprojectiles under the condition of isospin equilibrium.

The points from the isotopic scaling approach are in very good overall agreement with the values obtained from the isobaric scaling approach, in practice indicating the equivalence of these two procedures. It should be noted that in the latter procedure, because of the larger (more than double) number of integers \(A\), as compared to \(Z\), a more detailed mapping of the primary \(N/Z\) vs \(E^*/A\) correlation is achieved in the excitation energy region from very peripheral to more damped collisions (Fig. 4a).

The correlations presented in Fig. 4a show the evolution of the \(N/Z\) equilibration process in the present isospin-asymmetric collisions. The monotonic increase of \(\Delta(N/Z)_{qp}\) with excitation energy can be understood as a result of the mechanism of nucleon exchange. Fragments close to the projectile are produced in very peripheral collisions in which a small number of nucleons is exchanged and thus, the \(N/Z\) difference of the fragmenting quasiprojectiles from \(^{86}\text{Kr}+^{124}\text{Sn}\) and \(^{86}\text{Kr}+^{112}\text{Sn}\) is small. Fragments progressively further from the projectile originate from collisions with larger projectile–target overlap in which a large number of nucleons is exchanged and their excitation energy is higher. In such cases, the \(N/Z\) difference of the fragmenting quasiprojectiles is progressively larger, eventually approaching, for this energy regime, the \(N/Z\) difference corresponding to isospin equilibration. The conclusion that \(N/Z\) equilibration is attained for the most damped collisions is rather expected in
accord with recent BUU calulations [5]. The experimental determination of the $\Delta(N/Z)_{qp}$ vs $E^*/A$ correlation (Fig. 4a) is the basis of the present approach to study the process of N/Z equilibration. As we have indicated, it is primarily based on the N/Z information provided by the isoscaling parameters $\alpha$ and $\beta'$. In addition, it utilizes the connection of the average excitation energy with fragment size (Z or A) ensued by the binary character of the collisions.

It would be instructive to compare the results of N/Z – $E^*/A$ correlations obtained from the present data via the isoscaling approach with model simulations appropriate for this energy regime. In Fig. 4b, we show the predictions of the deep-inelastic transfer (DIT) code of Tassan-Got [31] which has recently been successfully applied in a variety of studies at Fermi energies (e.g. [13,21,26]). The DIT model simulates stochastic nucleon exchange in a Monte Carlo fashion. The predicted average N/Z-$E^*/A$ correlations for the hot quasiprojectiles from $^{86}$Kr+$^{124}$Sn and $^{86}$Kr+$^{112}$Sn are shown by the upper and lower full lines, respectively. The upper and lower dotted lines indicate the N/Z values expected for fully equilibrated quasiprojectiles, whereas the horizontal full line indicates the N/Z of the projectile. Using these correlations we obtain the $\Delta(N/Z)$ – $E^*/A$ correlation shown by the full line in Fig. 4a. As we see in this figure, the results of the isoscaling procedure seem to follow the model prediction up to $E^*/A \sim 2.0$ MeV, whereas beyond this energy, the DIT model indicates that N/Z equilibration is reached at larger excitation energies. We think that this difference is mainly due to the inability of the residue velocity approach to determine correctly the excitation energies near and beyond the onset of multifragmentation ($E^*/A \sim 2.2$ MeV/nucleon). Kinematical reconstruction of the quasiprojectiles is necessary to determine these larger excitation energies (see, e.g. [13]). Finally, we note that results similar to those of the DIT code are obtained with another widely used model, the nucleon exchange model (NEM) of Randrup [32], shown in Figs. 4a,b by the thin dashed lines.

From the aforementioned discussion, we see that we can follow in detail the evolution of the N/Z equilibration process as a function of excitation energy from the quasi-elastic regime up to very damped collisions, provided that surviving residues are produced whose velocity is correlated to their size. Due to the mechanism of nucleon exchange, the assumption of equal division of excitation energy between the projectile and the target is a good approximation for not too long interaction times (and, thus, not too high excitation energies). [At the longest interaction times (highest excitation energies), the dinuclear system will approach thermal equilibrium.] The maximum observed excitation energies inferred from residue velocities are $\sim 2.2$ MeV/nucleon, which are moderate compared to the highest (5–6 MeV/nucleon) that can be attained in the most damped collisions for the present systems. We also point out that, as discussed in detail in the work of Botvina et al. [30], grand canonical statistics at its low temperature limit can be used as an approximation to
describe residue deexcitation on which Eqs. 3–6 are based. Another question that might be raised from the present treatment of data spanning a wide range of energy dissipation is why non-equilibrium in the N/Z degree of freedom at the separation stage is consistent with an equilibrium statistical description (here, in a grand canonical approximation). We point out that the degree of N/Z equilibrium at the separation stage is determined by the dynamics of the collision and the corresponding interaction time. The grand canonical statistics is applied to the de-excitation of the hot quasiprojectile residue under the assumption (usual for treatment of de-excitation) that enough time has elapsed after the separation so that its degrees of freedom are equilibrated. Thus, the excited quasiprojectile is assumed to be characterized by a value of N/Z, along with its excitation energy and spin; for this hot residue the grand canonical statistics (in its low temperature limit) can be applied.

It would be very interesting to study not only the evolution of the N/Z equilibration process in a variety of isospin asymmetric systems, but also the transition from N/Z equilibration to non-equilibration as a function of the projectile energy. It may also be noted that the present approach (with the possible inclusion of kinematical reconstruction of quasiprojectiles) can be efficiently applied to collisions at the limits of N/Z asymmetry, taking advantage of current and future rare isotope beam facilities. Studies of the N/Z degree of freedom with the present approach can also complement studies employing intermediate (IMF) or light charged particle (LCP) yield ratios from hot primary fragments undergoing multifragmentation [11,12,14]. Finally, it may be pointed out that detailed studies of the N/Z degree of freedom and its equilibration in reactions around the Fermi energy can offer a quantitative testing ground of current transport models of heavy-ion reactions (e.g. [33,34,35]) and provide information on the symmetry energy part of the nuclear equation of state.

4 Summary and Conclusions

In summary, a new experimental approach to study the process of N/Z equilibration has been presented. The approach is based on the N/Z information contained in the isotopic and the isobaric yield ratios of heavy residues from two isospin-asymmetric deep-inelastic collisions. The corresponding isoscaling parameters $\alpha$ and $\beta'$ of the residue yield ratios with respect to residue neutron number N and neutron excess N–Z are obtained as a function of the atomic number Z and mass number A, respectively. Residue excitation energies are deduced from velocities. The relation of the isoscaling parameters $\alpha$ and $\beta'$ with the N/Z of the primary (excited) projectile fragments provides access to the degree of N/Z equilibration prior to fragmentation as a function of excitation energy. Simulations with a deep-inelastic transfer model are in agreement
with the isoscaling data, at low and moderate excitation energies, whereas
limitations in the excitation energy determination near and above the mul-
tifragmentation threshold may be responsible for an observed disagreement
between the data and the model. The present residue isoscaling approach may
offer a sensitive probe of isospin and reaction dynamics studies in collisions
involving stable, as well as, rare isotope beams.

5 Acknowledgements

We wish to thank to A. Botvina for insightful discussions. We are also thankful
to L. Tassan-Got for using the DIT code and J. Randrup for using the NEM code. This work was supported in part by the Robert A. Welch Founda-
tion through grant No. A-1266, and the Department of Energy through grant
No. DE-FG03-93ER40773. M.V. was also supported through grant VEGA-
2/1132/21 (Slovak Scientific Grant Agency).

References

[1] “Opportunities in Nuclear Science: A Long-Range Plan for the Next Decade”,
April 2002, DOE–NSF Nucl. Science Advisory Committee,
accessible at www.er.doe.gov/production/henp/np/nsac/nsac.html.

[2] Radioactive Nuclear Beam Facilities, NuPECC Report, April 2000; see also
EURISOL web page: www.ganil.fr/eurisol/

[3] “Isospin Physics in Heavy-Ion Collisions at Intermediate Energies” B.-A. Li,
W.U. Schroeder eds. (Nova Science, New York, 2001).

[4] B.-A. Li, C.M. Ko, Phys. Rev. C 57 (1998) 2065.

[5] B.-A. Li, S.J. Yennello, Phys. Rev. C 52 (1995) 1746.

[6] V.V. Volkov, Phys. Rep. 44 (1978) 93.

[7] W.U. Schoeder, J.R. Huizenga in “Treatise on Heavy-Ion Science” D.A. Bromley
ed. (Plenum, New York, 1984) Vol. 2 p. 113.

[8] H. Freiesleben, J.V. Kratz, Phys. Rep. 106 (1984) 1.

[9] M. Petrovici et al., Nucl. Phys. A 477 (1988) 277.

[10] R. Planeta et al., Phys. Rev. C 38 (1988) 195.

[11] S.J. Yennello et al., Phys. Lett. B 321 (1994) 15.

[12] H. Johnston et al., Phys. Lett. B 371 (1996) 186.
[13] M. Veselsky et al., Phys. Rev. C, 62 (2000) 064613.

[14] M.B. Tsang et al, Phys. Rev. Lett. 92 (2004) 062701.

[15] F. Rami et al., Phys. Rev. Lett. 84 (2000) 1120.

[16] L. Shi and P. Danielewicz, Phys. Rev. C, 68 (2003) 064604.

[17] H. Fuchs, K. M"ohring, Rep. Prog. Phys. 57 (1994) 231.

[18] D. Pierroutsakou et al., Eur. Phys. J. A 16 (2003) 423.

[19] G.A. Souliotis et al., Phys. Rev. C 68 (2003) 024605.

[20] R.E. Tribble, R.H. Burch and C.A. Gagliardi, Nucl. Instr. and Meth. A 285 (1989) 441.

[21] G.A. Souliotis et al., Phys. Lett. B 543 (2002) 163.

[22] J.F. LeColley et al., Phys. Lett. B 325 (1994) 317.

[23] M. Morjean et al., Nucl. Phys. A 591 (1995) 371.

[24] H. Madani et al., Phys. Rev. C 54 (1996) 1291.

[25] J.B. Natowitz et al, Phys. Rev. C 65 (2002) 034618.

[26] M. Veselsky et al., Nucl. Phys. A 724 (2003) 431.

[27] M.B. Tsang et al., Phys. Rev. Lett. 86 (2001) 5023.

[28] M.B. Tsang et al., Phys. Rev. C 64 (2001) 041603.

[29] M.B. Tsang et al., Phys. Rev. C 64 (2001) 054615.

[30] A.S. Botvina, O.V. Lozhkin, W. Trautmann, Phys. Rev. C 65 (2002) 044610.

[31] L. Tassan-Got and C. Stefan, Nucl. Phys. A 524 (1991) 121.

[32] J. Randrup, Nucl. Phys. A 307 (1978) 319.

[33] B.-A. Li, C.M. Ko, W. Bauer, Int. Jou. Mod. Phys. E 7 (1998) 147.

[34] J.-Y Liu et al., Phys. Rev. C 67 (2003) 024608.

[35] A. Ono et al., Phys. Rev. C 66 (2002) 014603.
Fig. 1. (a) Average velocity versus mass number A correlations for projectile residues from the reactions of $^{86}$Kr (25MeV/nucleon) with $^{124}$Sn and $^{112}$Sn. Full circles represent the data with the $^{124}$Sn target and open circles those with the $^{112}$Sn target. The dashed line (marked “PR”) gives the projectile velocity, whereas the arrow indicates the minimum average residue velocity. (b) Excitation energy per nucleon evaluated from residue velocities (see text).
Fig. 2. (a) Yield ratios $R_{21}(N, Z) = Y_2(N, Z)/Y_1(N, Z)$ of projectile residues from the reactions of $^{86}$Kr (25MeV/nucleon) with $^{124,112}$Sn with respect to N for the Z's indicated. The data are given by alternating filled and open circles, whereas the lines are exponential fits. (b) Isotopic scaling parameter $\alpha$ as a function of Z (closed circles). The straight line is a constant value fit for the lighter fragments Z=10–26 (see text).
Fig. 3. (a) Yield ratios $R_{21}(A, N-Z) = Y_2(A, N-Z)/Y_1(A, N-Z)$ of projectile residues from the reactions of $^{86}$Kr (25MeV/nucleon) with $^{124,112}$Sn with respect to N–Z for the masses indicated. The data are given by alternating filled and open circles, whereas the lines are exponential fits. (b) Isobaric scaling parameter $\beta'$ as a function of A. The straight line is a constant value fit to the data in the lighter residue range A=25–60 (see text).
Fig. 4. (a) Difference in N/Z of fragmenting quasiprojectiles obtained using Eqs. 5, 6 (see text) as a function of excitation energy per nucleon for projectile residues from the reactions $^{86}$Kr (25MeV/nucleon)+$^{124,112}$Sn. Open circles: isotopic scaling; closed circles: isobaric scaling. The full and dashed lines are predictions of the DIT model [31] and the NEM model [32], respectively. The horizontal dotted line gives the N/Z difference of isospin-equilibrated fragmenting quasiprojectiles. (b) Model predictions of average N/Z of fragmenting quasiprojectiles used to get the differences shown in panel (a). As above: full lines: DIT model; dashed lines: NEM model. The horizontal full line indicates the projectile N/Z and the horizontal dotted lines give the N/Z values of isospin-equilibrated quasiprojectiles.