Isoscaling in Peripheral Nuclear Collisions around the Fermi Energy and a Signal of Chemical Separation from its Excitation Energy Dependence

M. Veselsky,[1,2,*] G. A. Souliotis,[1] and S. J. Yennello[1]

[1] *Cyclotron Institute, Texas A&M University, College Station, TX 77843*

[2] *Institute of Physics of the Slovak Academy of Sciences, Bratislava, Slovakia*

(Dated: August 9, 2018)

The isoscaling is investigated using the fragment yield data from fully reconstructed quasi-projectiles observed in peripheral collisions of ^{28}Si with ^{124,112}Sn at projectile energies 30 and 50 MeV/nucleon. The excitation energy dependence of the isoscaling parameter β' is observed which is independent of beam energy. For a given quasi-projectile produced in reactions with different targets no isoscaling is observed. The isoscaling thus reflects the level of N/Z-equilibration in reactions with different targets represented by the initial quasi-projectile samples. The excitation energy dependence of the isoscaling parameter β', corrected for the trivial 1/T temperature dependence, does not follow the trend of the homogeneous system above 4 MeV/nucleon thus possibly signaling the onset of separation into isospin asymmetric dilute and isospin symmetric dense phase.

PACS numbers: 25.70.Mn,25.70.Lm,25.70.Pq

The isotopic composition of nuclear reaction products provides important information on the reaction dynamics and the possible occurrence of a phase transition in the asymmetric nuclear matter [1, 2], which is supposed to lead to separation into a symmetric dense phase and asymmetric dilute phase. It has been discussed in literature [3, 4, 5, 6] to what extent such a phase transition is generated by fluctuations of density or concentration, typically suggesting a coupling of different instability modes. The N/Z (neutron to proton ratio) degree of freedom and its equilibration was studied experimentally in detailed measurements of the isotopic distributions of emitted fragments [7, 8, 9, 10, 11, 12, 13]. Isotopically resolved data in the region Z=2–8 have revealed systematic trends, which however are substantially affected by the decay of the excited primary fragments. It has recently been shown [14] that the effect of sequential decay of primary fragments can be overcome by comparing the yields of fragments from two similar reactions. For statistical fragment production in two reactions with different isospin asymmetry, but at the same temperature, the ratio R_{21}(N,Z) of the yields of a given fragment (N,Z) exhibits an exponential dependence on N and Z. This scaling behavior is termed isoscaling [14] and has been observed in a variety of reactions under the conditions of statistical emission and equal temperature [15, 16, 17, 18].

In this study, we present an isoscaling analysis of a recent fragment yield data [10, 11, 19, 20] obtained by charged-particle calorimetry of hot thermally equilibrated quasi-projectiles from the reactions ^{28}Si+^{124,112}Sn at 30 and 50 MeV/nucleon. The angular coverage and granularity of the forward-angle multidetector array FAUST [21] allowed full reconstruction of the hot quasiprojectiles from mid-peripheral binary collisions [11]. Excellent description of the fragment observables was obtained using the model of deep-inelastic transfer (DIT) [22] for the early stage of collisions and the statistical multifragmentation model (SMM) [23] for de-excitation. The large N/Z range of quasi-projectiles allowed unique studies of the dependence of fragment observables on quasi-projectile N/Z. An increasingly inhomogeneous N/Z-distribution between light charged particles and heavier fragments was observed with increasing isospin asymmetry [19]. An exponential scaling of the isobaric ratio Y(^{3}H)/Y(^{3}He) with the quasi-projectile N/Z was observed and the temperature was extracted from the logarithmic slope [20]. In the present work we examine the isoscaling phenomenon in unique conditions of highly-selective data. Typically, the investigations of isoscaling focused on yields of light fragments with Z=2-8 originating from de-excitation of massive hot systems produced using reactions of mass symmetric projectile and target at intermediate energies [14, 15, 16] or by reactions of high-energy light particle with massive target nucleus [17]. In a recent article [18], we report the investigations of isoscaling using the heavy residue data from the reactions of 25 MeV/nucleon ^{86}Kr projectiles with ^{124}Sn,^{112}Sn and ^{64}Ni, ^{58}Ni targets. Here we present the investigation of the isoscaling phenomenon on the full sample of fragments emitted by the hot thermally equilibrated quasi-projectiles with mass A=20-30.

A thermally equilibrated system undergoing statistical decay can be, within grand-canonical approach, characterized by a yield of fragments with neutron and proton numbers N and Z [24, 25]:

$$Y(N,Z) = F(N,Z)\exp[B(N,Z)/T]\exp(N\mu_n/T + Z\mu_p/T) \quad (1)$$

where $F(N,Z)$ represents contribution due to the secondary decay from particle stable and unstable states to the ground state; μ_n and μ_p are the free neutron and proton chemical potentials; $B(N,Z)$ is the ground state

*Electronic address: fyzimarv@savba.sk

binding energy of the fragment, and T is the temperature.

The ratio of the isotope yields from two different systems, having similar excitation energies and similar masses, but differing only in N/Z, cancels out the effect of secondary decay and provides information about the excited primary fragments [14]. Within the grand-canonical approximation (Eq. 1), the ratio $Y_2(N,Z)/Y_1(N,Z)$ assumes the form

$$R_{21}(N,Z) = Y_2(N,Z)/Y_1(N,Z) = C\exp(\alpha N + \beta Z) \tag{2}$$

with $\alpha = \Delta\mu_n/\mathrm{T}$ and $\beta = \Delta\mu_p/\mathrm{T}$, with $\Delta\mu_n$ and $\Delta\mu_p$ being the differences in the free neutron and proton chemical potentials of the fragmenting systems. C is an overall normalization constant. Alternatively, as introduced by Botvina et al. [17], the isoscaling can be expressed as

$$R_{21}(N,Z) = Y_2(N,Z)/Y_1(N,Z) = C\exp(\alpha' A + \beta'(N-Z)) \tag{3}$$

thus introducing the scaling parameters which can be related to the isoscalar and isovector components of free nucleon chemical potential since $\alpha' = \Delta(\mu_n + \mu_p)/2\mathrm{T}$ and $\beta' = \Delta(\mu_n - \mu_p)/2\mathrm{T}$. In this variant of isoscaling, the mass dependence is rather weak and the information is concentrated in the isoscaling parameter β'.

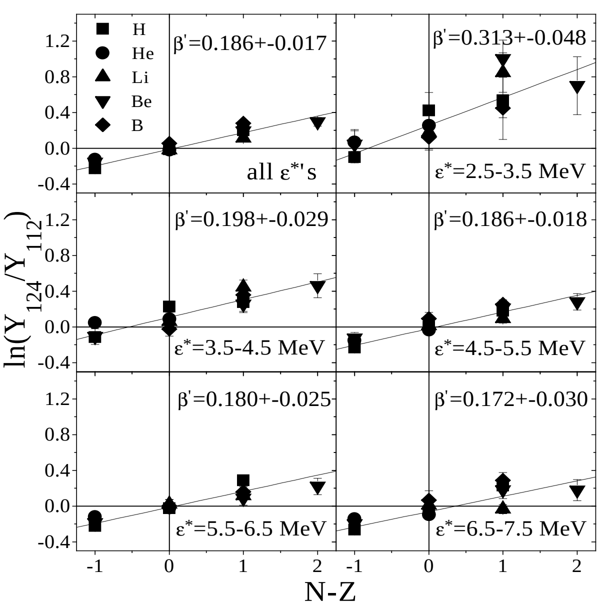

FIG. 1: The isoscaling plots from the reactions of ^{28}Si+^{124,112}Sn at 50 MeV/nucleon for the full set of isotopically resolved quasi-projectiles and for five bins of quasi-projectile excitation energy per nucleon.

In Figs. 1 and 2, we present the isoscaling data from statistical decay of hot quasiprojectiles from the reactions ^{28}Si+^{124,112}Sn at projectile energy 50 and 30 MeV/nucleon, respectively. Observed charged particles with Z≤5 have been isotopically resolved and the total observed charge was close to the charge of the projectile (Z=12-15) [10, 11]. The observed fragment data provide full information (with the exception of emitted neutrons) on the de-excitation of thermally equilibrated hot quasi-projectiles with known mass (A=20-30), charge, velocity and excitation energy [11]. In Figs. 1 and 2, the isoscaling plots are presented not only for the full data but also for five bins of excitation energy. The isoscaling occurs at both projectile energies, both for the inclusive data and for the sub-sets with different excitation energies. The slope depends on the excitation energy in a similar way as the slope of the dependence of isobaric ratio Y(^{3}H)/Y(^{3}He) on the quasi-projectile N/Z observed in [20]. On the other hand, the isoscaling parameters for individual excitation energy bins do not depend on the projectile energy and the difference of the slopes of the inclusive data is given by the different excitation energy distributions of hot quasi-projectiles at two projectile energies.

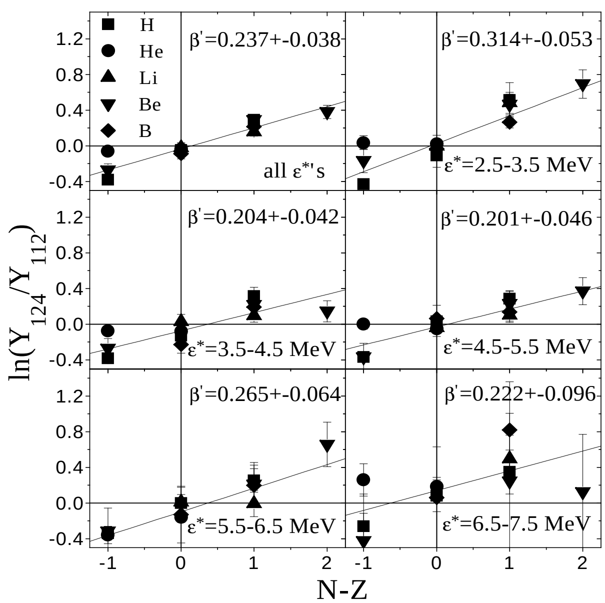

FIG. 2: As in Fig. 1 but for 30 MeV/nucleon.

In Fig. 3 are presented isoscaling plots for three selected quasiprojectiles ^{24,26,28}Al (representing the central part of quasiprojectile mass and charge distribution) in the reactions of ^{28}Si+^{124,112}Sn targets at projectile energy 50 MeV/nucleon. Isoscaling behavior is not observed which means that no memory of the entrance channel interaction leading to production of a given quasi-projectile remains and the isoscaling analysis is not sensitive to the statistical fluctuations in de-excitation. The slight hint of isoscaling in the case of ^{28}Al may be due to low statistics or due to larger uncertainty in the number of unobserved neutrons of the reconstructed neutron-rich quasiprojectile ^{28}Al caused by more intense neutron emission than for proton-rich isotopes ^{24,26}Al. A behavior similar in appearance to Fig. 3 was reported by Tsang et al. [15] using the yields of fragments with Z=3-8 from the reaction of ^{16}O with ^{197}Au, ^{208}Pb targets at projectile energy 20 MeV/nucleon [26], measured at 40°. There, the absence of isoscaling behavior suggests that the sample of original prefragments is independent of the target isospin asymmetry, what for such inclusive data suggests a geometric reaction scenario such as breakup or abrasion and the observed fragments are most probably the spectator parts of the original projectile, ejected to a large laboratory angle by the recoil in the projectile breakup.

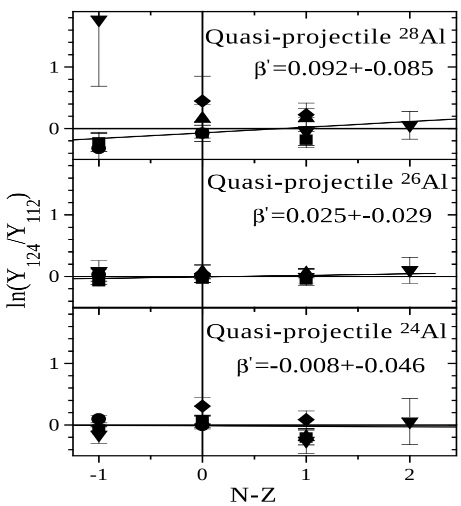

FIG. 3: The isoscaling plots from the reactions of ^{28}Si+^{124,112}Sn at 50 MeV/nucleon for three reconstructed quasi-projectiles. Symbols as in Figs. 1,2.

As suggested by Botvina et al. [17], the isoscaling parameter trends are similar to the observed double isotope ratio temperature. The temperature for the current data was studied in detail in [20] and we use the results of that work for comparison with the isoscaling parameters. In Fig. 4 we present the observable $\beta' T$, canceling out the trivial 1/T-dependence of the isoscaling parameter. In Fig. 4a we use the double isotope ratio temperature [24] from the isotopic ratios Y(^{2}H)/Y(^{3}H) and Y(^{3}He)/Y(^{4}He) and in Fig. 4b we use the temperature obtained from the slope of the dependence of Y(^{3}H)/Y(^{3}He) on the quasi-projectile N/Z (mirror nucleus temperature) [20]. Grossly, the $\beta' T$ should reflect the level of N/Z equilibration [18], which is known for the current data [11] where full N/Z-equilibration was not reached. The horizontal lines represent the estimate of the zero temperature values of $\beta' T$ of reconstructed quasi-projectiles using the known N/Z equilibration [11]. We estimate the zero temperature proton and neutron chemical potentials by the proton and neutron separation energies ($\mu_{p,n} \approx -S_{p,n}$). Similar approximation was used to extract the mirror nucleus temperature [20]. The zero temperature estimates of $\beta' T$ for all excitation energy bins are consistent with horizontal lines which is a result of the selection of quasiprojectiles with Z=12-15. Any experimental deviations from the zero temperature values of $\beta' T$ can be understood as a non-trivial dependence representing the details of de-excitation. The thick and thin lines represent the $\beta' T$ estimates with and without the correction for neutron emission from backtracing of DIT/SMM simulations [11]. The dashed/full lines represent the projectile energies 30 and 50 MeV/nucleon, respectively. The open circles/squares represent the experimental data at 30 and 50 MeV/nucleon while the full squares represent the combined data from both energies. The experimental dependences of $\beta' T$ on excitation energies indicate an initial decrease at low excitation energies (consistent with expansion of the homogeneous excited source), further they exhibit a turning-point at 4 MeV/nucleon followed by increase toward the zero temperature value at 6-7 MeV/nucleon. The trend is similar at both projectile energies independent of the method of temperature extraction and quality of the statistical sample. The existence of such a turning-point can be understood in the context of work [20], where the viability of the approximation $\mu_{p,n} \approx -S_{p,n}$ at high temperatures was supported by a possible counterbalance of two effects, namely expansion of hot nucleus (leading to a decrease of the absolute values of chemical potentials compared to the zero temperature values as indicated by a solid curve) and chemical separation into an isospin symmetric heavy fraction and an isospin asymmetric nucleon gas, leading to stronger dependence of $\mu_n - \mu_p$ of the nucleon gas (dilute phase) on N/Z of the system [1, 2] thus resulting in higher sensitivity of the observed yield ratios. Such a conclusion is supported by the inhomogeneous isospin distribution observed for the current data [19] where the isospin asymmetry of light charged particles exhibits strong sensitivity on N/Z of the quasiprojectile while the isospin asymmetry of heavier fragments is rather insensitive. The estimate of $\beta' T$ for homogeneous system was obtained assuming $\rho^{2/3}$-dependence and using the estimate of free volume (eq. 52 of ref. [23]) for each excitation energy bin from the successful DIT/SMM simulations. Since the isoscaling parameter depends directly on the free nucleon chemical potentials, the turning-point at 4 MeV/nucleon can be understood as a signal of the onset of chemical separation which reverts the decrease of the free nucleon chemical potential consistent with expansion of the homogeneous system. This is also consistent with the recent theoretical study of thermodynamical properties of finite nuclei of Sanzhur et al. [27] where the hot nucleus (at a given initial excitation energy) can expand up to the turning point where the central part begins to contract again while the increasing number of nucleons form the dilute component surrounding the dense central part. The values of the temperature characterizing the turning point in the central density for a given excitation energy reproduce well the caloric curve [20] for the data investigated here. The existence of the turning-point explains the difference of caloric curves (around 4 MeV/nucleon) obtained in [11] using double isotope ratio and mirror nucleus temperatures, former free of assumptions on chemical potentials (

the same applying to Fig. 4a) while latter using the approximation $\mu_{p,n} \approx -S_{p,n}$ (thus artificially lowering the values of $\beta' T$ around the turning-point). When estimating the density of the homogeneous system at the turning point (assuming $\rho^{2/3}$-dependence of $\beta' T$), it is consistent with theoretical estimates of the position and shape of the spinodal contour, typically at almost constant total density $0.6\rho_0$ in the wide range of asymmetries [6]. Thus, inside the spinodal region the homogeneous nuclear medium is quickly replaced by the inhomogeneous system.

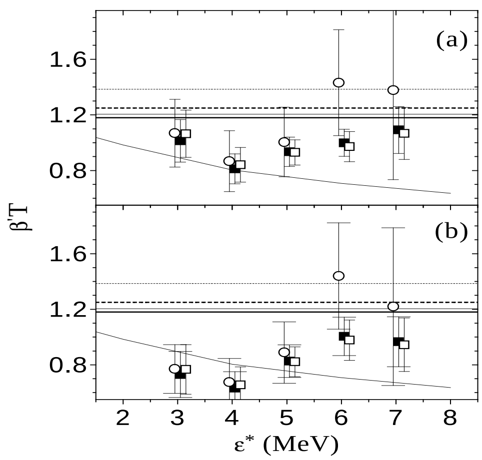

FIG. 4: The dependence of observable $\beta' T$ on relative excitation energy of the quasiprojectile. Open squares and circles show experimental data obtained using the double isotope ratio (a) and Y(^{3}H)/Y(^{3}He) slope (b) temperature at 50 and 30 MeV/nucleon, respectively. Full squares represent combined data from both energies. Full and dashed horizontal lines show estimate of $\beta' T$ obtained when assuming $\mu_{p,n} \approx -S_{p,n}$ at 50 and 30 MeV/nucleon, respectively. Solid curve represents the expected trend for homogeneous system. For details see text.

In summary, the isoscaling is investigated using the fragment yield data from fully reconstructed quasi-projectiles observed in peripheral collisions of ^{28}Si with ^{124,112}Sn at projectile energies 30 and 50 MeV/nucleon. The excitation energy dependence of the isoscaling parameter β' is observed which is independent of the beam energy. For a given reconstructed quasi-projectile produced in reactions with different targets no isoscaling is observed. Thus, the magnitude of the isoscaling is determined by the difference of initial quasi-projectile samples produced in reactions with different targets leading to different level of N/Z-equilibration. The excitation energy dependence of the observable $\beta' T$, corrected for the 1/T temperature dependence, exhibits a turning-point at 4 MeV/nucleon which can be interpreted as a signal of the onset of separation into isospin asymmetric dilute and isospin symmetric dense phase. The initial trend of expansion of the homogeneous system is reverted by the transition into an inhomogeneous system with two phases having different proton and neutron concentrations. A novel experimental information on the equation of state of the asymmetric nuclear matter is thus obtained.

We are thankful to L. Tassan-Got for his DIT code and to A. Botvina for his SMM code. This work was supported in part by the Robert A. Welch Foundation through grant No. A-1266, the Department of Energy through grant No. DE-FG03-93ER40773, and the Slovak Scientific Grant Agency through grant VEGA-2/1132/21.

[1] H. Muller and B. D. Serot, Phys. Rev. C **52**, 2072 (1995).
[2] V. M. Kolomietz et al., Phys. Rev. C **64**, 24315 (2001).
[3] B.-A. Li and C. Ko, Nucl. Phys. A **618**, 498 (1997).
[4] V. Baran et al., Phys. Rev. Lett **86**, 4492 (2001).
[5] M. Colonna et al., Phys. Rev. Lett **88**, 122701 (2002).
[6] J. Marqueron and P. Chomaz, Phys. Rev. C **67**, 41602(R) (2003).
[7] S. J. Yennello et al., Phys. Lett. B **321**, 15 (1994).
[8] H. Johnston et al., Phys. Lett. B **371**, 186 (1996).
[9] E. Ramakrishnan et al., Phys. Rev. C **57**, 1803 (1998).
[10] R. Laforest et al., Phys. Rev. C **59**, 2567 (1999).
[11] M. Veselsky et al., Phys. Rev. C **62**, 064613 (2000).
[12] F. Rami et al., Phys. Rev. Lett. **84**, 1120 (2000).
[13] H. S. Xu et al., Phys. Rev. Lett. **85**, 716 (2000).
[14] M. B. Tsang et al., Phys. Rev. Lett. **86**, 5023 (2001).
[15] M. B. Tsang et al., Phys. Rev. C **64**, 041603 (2001).
[16] M. B. Tsang et al., Phys. Rev. C **64**, 054615 (2001).
[17] A. S. Botvina, O. V. Lozhkin, and W. Trautmann, Phys. Rev. C **65**, 044610 (2002).
[18] G. A. Souliotis et al., Phys. Rev. C **68**, 24605 (2003).
[19] M. Veselsky et al., Phys. Rev. C **62**, 041605 (2000).
[20] M. Veselsky et al., Phys. Lett. B **497**, 1 (2001).
[21] F. Gimeno-Nogues et al., Nucl. Instr. and Meth. A **399**, 94 (1997).
[22] L. Tassan-Got and C. Stefan, Nucl. Phys. A **524**, 121 (1991).
[23] J. P. Bondorf et al., Phys. Rep. **257**, 133 (1995).
[24] S. Albergo et al., Nuovo Cimento A **89**, 1 (1985).
[25] J. Randrup and S. E. Koonin, Nucl. Phys. A **356**, 223 (1981).
[26] C. K. Gelbke et al., Phys. Rep. **42**, 311 (1978).
[27] A. I. Sanzhur, private communication.