The pioneering studies in ref. hint to the transition between liquid and gaseous phases of nuclear matter. The nuclear temperature as the crucial observable was derived from the isotope thermometer based on double yield ratios (see below). This thermometer is assumed to be sensitive to the local temperature at the particle freeze-out. Meanwhile, the critical behaviour has been established in various heavy-ion collisions involving medium and heavy mass nuclei. Whereas the underlying Statistical Multifragmentation Model was successful in this mass region it is open whether the statistical nature of fragmentation processes can be seen and classified in small many-body systems. Therefore, temperature measurements in light nuclei with tested isotope thermometers are highly desirable.

A search for reliable isotope thermometers in proton induced collisions \( p + X \rightarrow \text{IMF}(3 \leq Z \leq 14) + X \) at beam momentum from 80 to 250 GeV/c was recently performed in ref. where it was established that such thermometers show a characteristic behaviour that is independent of the reaction type. Encouraged by this finding we have analysed the data available from inclusive measurements of 1 GeV proton interactions with various target nuclei. The data taken into consideration were obtained in some independent experimental projects performed at the external proton beam of the PNPI synchrocyclotron Gatchina.

(i) One experiment was addressed to Light Charged Particle (LCP) detection at backward angles. The basic tool was a lens spectrometer with a momentum resolution of \( \Delta p/p \approx 2.5\% \) within the dynamical range from 0.25 to 0.75 GeV/c. This spectrometer was installed at \( \Theta_{lab}=109^\circ \) and \( 156^\circ \) with respect to the beam axis. TOF measurements allowed to separate the hydrogen isotopes obtained from proton collisions with various targets from \( ^6\text{Li} \) to lead. Differential cross sections were obtained from the kinetic energy spectra extrapolated by fits with a Maxwell functional form. For the first time, we attend to the yields of hydrogen isotopes and employed the thermometer based on the double-ratio \((^2\text{H}/^3\text{H})/(^1\text{H}/^2\text{H})\). Thus, it became possible to determine the temperature of \( ^6\text{Li} \) as the smallest probe. Hitherto, the hydrogen isotope yields have casted doubt on usefulness as thermometer since different nonequilibrium processes may contribute to these yields. Such contributions should be suppressed under our kinematical conditions and we consider the hydrogen yields as an adequate tool for temperature measurements.

(ii) The second data set to be analysed involves Intermediate Mass Fragments (IMF):

\[
p(1\text{GeV})+(\text{Be,C},^{58}\text{Ni}, \text{Ag},^{238}\text{U})\rightarrow \text{IMF}(Z \geq 2) + X
\]

As the incident energy was kept fixed at 1 GeV we expect that target-spectator fragmentation contributes mainly to the observables. In distinction from heavy-ion collisions the influence of compression and collective motion on the fragment abundancies and on the related temperatures is supposed to be minimized. IMF production was studied in \( p+\text{Ag, Au and U collisions} \) at \( \Theta_{lab}=60^\circ \) and \( 120^\circ \) with a setup consisting of the above mentioned magnetic lens spectrometer combined with a \( \Delta E-E \) telescope. The energy resolution of the \( \Delta E \)-detector ( \( \approx 50 \) keV) allowed to separate isotopes of fragments from helium to boron. Absolute cross sections were obtained by integration of the inclusive energy spectra approximated by a moving source fit and angular integration using the expression \( d\sigma/d\Omega = c_1 + c_2 \cdot \cos \Theta_{lab} \). We included into this analysis additional differential cross sections at \( \Theta_{lab}=60^\circ \) of fragments produced in 1 GeV proton collisions with \( ^{48}\text{Ti}, \, ^{58}\text{Ni}, \, ^{64}\text{Ni}, \, ^{112}\text{Sn} \) and \( ^{124}\text{Sn} \).
targets have been registered with an experimental setup consisting of two TOF-E spectrometers installed at \( \Theta_{lab}=30^\circ \) and \( 126^\circ \) with respect to the beam axis \([1]\). The basic detectors in each arm were twin Bragg Ionization Chambers combined with Parallel Plate Avalanche Counters. This setup, in general described in ref. \([12]\), allowed to measure the low energy part of the kinetic energy distributions of the fragments below \( \simeq 30 \) MeV. This part of the fragment spectrum, well reproduced by a moving-source fit with one exponential slope, is expected to represent mainly the equilibrated component. From the inclusive differential and absolute cross sections measured in the mentioned experiments we derived isotopic yield ratios.

The method of temperature evaluation from isotopic abundances ref. \([2]\) is related to five assumptions summarized in ref. \([13]\). The most important one is the selection of fragments emitted from a single and equilibrated source. These conditions are assumed to be fulfilled rather well at 1 GeV incident energy if the emission from the target spectator is considered. Experimentally, detection in backward direction and (or) registration of fragments with low kinetic energies should satisfy these requirements. According to ref. \([3]\) the temperature can be obtained from the relation

\[
T_{app} = \frac{B}{ln(a \cdot R)} \tag{1}
\]

where the double ratio \( R = R_1/R_2 \) is defined by the isotope yields \( Y \)

\[
R_1 = Y(A_i,Z_i)/Y(A_j+\Delta A,Z_i+\Delta Z)
\]

\[
R_2 = Y(A_j,Z_j)/Y(A_j+\Delta A,Z_j+\Delta Z)
\]

which is valid if the fragments with mass \( A_i, A_j \) and nuclear charge \( Z_i, Z_j \) are produced in their ground states. Each combination of \( (R, a, B) \) in equation (1) terms a "thermometer" which allows to find the absolute or relative temperature related to the fragment formation. The numerator \( B \) in equation (1) is determined by the binding energies \( BE \)

\[
B = BE(A_i,Z_i) \cdot BE(A_i+\Delta A,Z_i+\Delta Z)
\]

\[
- BE(A_j,Z_j) + BE(A_j+\Delta A,Z_j+\Delta Z).
\]

The magnitude \( a \) includes the spin degeneration factor and mass numbers of the considered isotopes. The intrinsic nuclear temperature is proportional to the temperature measured by means of relation (1) up to 5-7 MeV as shown in ref. \([14]\). We selected pairs with the same \( \Delta A = \Delta Z = 1 \) where the influence of the chemical potentials cancels out. The choice of pairs with \( \Delta A = 1, \Delta Z = 0 \) was made to minimize the influence of Coulomb barriers onto the yields.

The relation (1) must be modified for "sequential decays", i.e. if particle decays from higher lying states of the same and other isotopes contributes to the yields. In the special case of thermometers selected by \( B \geq 10 \) MeV an empirical correction for sequential decays was published in ref. \([3]\)

\[
\frac{1}{T_{app}} = \frac{1}{T_o} + \frac{ln(\kappa)}{B} \tag{2}
\]

where \( T_o \) is the unknown intrinsic equilibrium temperature. The correction factor \( \kappa \) is defined by \( R_{app} = \kappa \cdot R \) where \( R_{app} \) is the measured double isotope yield ratio and \( R \) the corresponding one for isotopes produced at equilibrium. The sensitivity of the thermometers improves with increasing \( B \) reducing relative errors. In the limit where \( B \) becomes equal or less the intrinsic temperature appreciable contributions from sequential decays may affect the yields \([13]\).

In figs.1–3 we present the dependence of \( T_{app} \) on the target mass number \( A_T \) as obtained by individual thermometers. Hereby, neither selection criterion \( B \geq 10 \) MeV nor correction for sequential decays were applied to avoid the first instance detailed discussions about it.

Fig. 1 shows the results obtained with the LCP thermometer \( \langle \hat{^2}H/\bar{^2}H \rangle/\langle \hat{^1}H/\bar{^2}H \rangle \) for two angles. One can see that \( T_{app} \) is nearly a constant over the target mass region \( 6 \leq A_T \leq 208 \) for \( \Theta = 109^\circ \) (top of fig.1). Since this behaviour is also established by IMF thermometers (see below) we cannot confirm the former doubts about the utility of the ratio \( Y(p)/Y(d) \) (ref.\([3]\)). But the temperatures which are derived from the hydrogen yields at \( \Theta = 156^\circ \) (lower part of fig.1) show some increase toward smaller \( A_T \). We guess that an admixture of the \( \Delta \) isobaric state becomes apparent in the used differential cross sections. Fits performed with a Maxwell-Boltzmann distribution including a Breit-Wigner contribution evidence this enhancement for the smallest \( A_T \) but the error bars become larger.

We plot the temperatures obtained by He and IMF yields as function of \( A_T \) in fig. 2. Additional data given in fig. 3 confirm the finding observed in fig.1 and 2. Whereas IMF thermometers provide constant temperatures, some dependence on \( A_T \) is observed if we make use of the ra-
the drawn errors are overestimated
ters is demonstrated in the top panel of fig.4. Although
incident energy. The behaviour of individual thermome-
since contributions from this process are
valid in a multifragmentation scenario cannot be applied
not exceed 15%. Alternative correction methods, e.g. [16],
≃
Y
where the primary yields
ing
∆
T
emperatures obtained from He and IMF pairs includ-
Fig. 2. Temperatures obtained from He and IMF pairs including
ω
1
−
ω
2
/\ Z
A
−
1

He and IMF thermometers (ΔA=1, ΔZ=0)

He and IMF thermometers (ΔA=1, ΔZ=0)

Fig. 3. Temperatures obtained from IMF pairs including combi-
with one thermometer is repeated by each of the other
ones. Such property hints to a real physical effect. In the
lower panel we present the mean averages of the above
values in order to compare with other available data. The
following features of fig.4 are worth to discuss:
(i) All temperatures which have been corrected for sequen-
tial decays by using equation (2) almost coincide at each
target mass number \( A_T \). Only the thermometer which
explores the double ratio \( ^{11}\text{B}/^{12}\text{B} \) overesti-
mates the temperature in the case of the target nuclei \( \text{Au} \)
and \( \text{U} \).
(ii) The temperatures which have been derived from the
differential cross sections at \( \Theta_{lab}=60^\circ \) are larger in com-
parison with those obtained from production cross sec-
tions. Enhanced temperatures in forward direction and
strong variations in the thermometers with \( ^3\text{He}/^4\text{He} \) ra-
tios were also reported in ref. [17].
(iii) Further, we observe pronounced structures in the tem-
peratures. These irregularities are related to fragments
from the target nuclei \( ^{48}\text{Ti},^{58}\text{Ni},^{64}\text{Ni},^{112}\text{Sn} \) and
\( ^{124}\text{Sn} \) which were studied to search for the influence of various nucleon
composition on the fragmentation process. The authors of
this investigation [14] stressed that the yields of fragments
(except \( ^4\text{He} \)) normalized to the geometrical cross section
depend mainly on the \( N/Z \) ratio. We presume from this
observation that the fluctuations of the temperature usu-

1 The errors drawn in figs.1–4 were obtained by simulations
where the primary yields \( Y_i \pm \Delta Y_i \) were treated as Gaussian
distributions with \( \langle Y_i \rangle \) and \( \sigma_i = \Delta Y_i \). Such procedure provides
dependable but enlarged errors \( \Delta T_i \), because it takes not into
account that systematic errors are to be reduced in the ratios
\( Y_i/Y_{i+1} \) if they are taken from the same experiment.
Fig. 4. Corrected temperatures $T_o$ as function of $A_T$. Open circles: data from measurements at $\theta_{lab}=60^{\circ}$. Top panel: individual thermometers are connected by dashed lines, solid lines connect $T_o$ evaluated from isotope production cross sections (black dots). Lower panel: mean average of the above 4 thermometers, same denotations.

Fig. 4. Corrected He thermometers ($\Delta A=1, \Delta Z=0$)

(iii) The temperatures obtained from the ratios of cross sections show a smooth but weak dependence on the target mass $A_T$. The most pronounced increase with decreasing $A_T$ was observed only for the thermometers which include the ratio $^3$He/$^4$He (see fig. 4). Above all, we attribute this slope to the variation of the inherent nucleon composition of the target nuclei. Double ratios involving heavier isotopes provide temperatures which are nearly independent on the target mass (see figs. 2–3) within the error bars. Although hints to this behaviour were already found in refs.18,17 one may doubt the universal validity of temperature measurements by double isotope ratios. Therefore, we accomplished an independent test of this method using data from an other physical process. For this purpose, yields of isotopes from hydrogen to boron registered in the spontaneous and thermal-neutron induced ternary fission,16,17,20, were processed by the same procedure as applied to them from fragmentation at 1 GeV. The used thermometers show a consistent behaviour resulting in significant lower temperatures of $\langle T_{app}\rangle \simeq 1$ MeV. Remark that fission neutron spectra are well reproduced by a temperature of $\simeq 0.7$ MeV.21

Summarizing, we analyzed inclusive data obtained in 1 GeV proton interactions with various target nuclei employing different isotope thermometers. We found that even uncorrected thermometers which involve pairs with $B \leq 10$ MeV provide "stable" results which may be suitable for relative temperature measurements. The weak dependence of the temperatures from the target mass $A_T$ suggests speculations about a unique thermodynamical behaviour whereby the dimensions of the nuclear systems may be changed to a large extent.

Acknowledgments This work was supported by the German Ministry of Education and Research (BMBF) under contract RUS-622-96 and by the Russian Foundation for Fundamental Research Grant No. 95-02-03671.

References

1. J.Pochodzalla et al., Phys. Rev. Lett. 75, 1040 (1995)
2. S.Albergo et al., Nuovo Cimento 89, 1 (1985)
3. V.Serfling et al., ALADIN collaboration, GSI 98-06, Darmstadt 1998
4. J.Bondorf et al., Phys. Rep. 257, 133 (1995)
5. A.S.Botvina and D.H.E.Gross, Phys. Rev. C 58, R23 (1998)
6. M.B.Tsang et al., Phys. Rev. Lett. 78, 3836 (1997)
7. M.N.Andronenko et al., Preprint LNPI No. 698 (1981), Preprint LNPI No. 830 (1983), Preprint LNPI No. 951 (1984) and Pisma ZhETF 37 446 (1983)
8. S.Shlomo et al., Phys. Rev. C 55, R 2155 (1997)
9. E.N.Volnin et al., Preprint LNPI No. 101 (1974)
10. E.N.Volnin et al., Phys. Rev. Lett. B 55, 409 (1975) and E.N.Volnin, PhD thesis, Leningrad 1975.
11. L.N.Andronenko et al., Preprint PNPI No. 2217 (1998) and Preprint PNPI No. 2321 (1999)
12. L.N.Andronenko et al., Nucl. Instr. Meth. A 312 467 (1992)
13. M.Milazzo et al., Phys. Rev. C 58 953 (1998)
14. H.Xi et al., Phys. Rev. C 59, 1567 (1999)
15. L.N.Andronenko et al., in Proceedings of the 7th International Conference on Clustering Aspects of Nuclear Structure and Dynamics, Rab, 1999 to be edited by Z.Basrak et al., (World Scientific,Singapore)
16. J.P.Bondorf et al., Phys. Rev. C 58, R27 (1998)
17. V.E.Viola et al., Indiana State University IUCF-40007-116, 1998 (unpublished)
18. A.S.Botvina et al., Nucl. Phys. A 475 663 (1987)
19. A.A.Vorobyov et al., Phys. Lett. B 30 332 (1969), Phys. Lett.B 40 102 (1972)
20. T.Krogulski et al., Nucl. Phys. A 128 219 (1969)
21. H.R.Bowman et al., Phys. Rev. 126 2110 (1962)

2 A forthcoming paper is in progress.