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Short note

Peculiarities of isotopic temperatures obtained from p + A collisions at 1 GeV

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Abstract. Nuclear temperatures were extracted from fragment yields obtained in inclusive measurements of p+A collisions at 1 GeV. All thermometers based on double-isotopic yield-ratios provide temperatures $T \simeq 4$ MeV nearly independent on the target mass.

PACS. 25.40.-h Nucleon-induced reactions – 25.40.Ve Other reactions above meson production threshold (energies > 400 MeV) – 25.40.Sc Spallation reactions

The pioneering studies in ref. [1] aim to prove 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 [2] (see below). This thermometer is assumed to be sensitive to the local temperature at the particle freeze-out [3]. Meanwhile, the critical behaviour of nuclear matter has been established in various heavy-ion collisions involving medium and heavy mass nuclei. However, it is open whether the statistical nature of fragmentation processes can be seen and classified in small many-body systems [4]. Therefore, reliable temperature measurements in light nuclei with tested isotope thermometers are highly desirable.

A search for those isotope thermometers in *proton* induced collisions $\mathrm{p + Xe \to IMF}(3 \leq Z \leq 14) + \mathrm{X}$ at beam momentum from 80 to 350 GeV/c was recently performed in ref. [5] 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 several experimental projects performed at the external proton beam of the PNPI synchrocyclotron in Gatchina.

i) One experiment was addressed to Light Charged Particle (LCP) detection at backward angles [6,7]:

$$\mathrm{p(1GeV)} \;+\; (^{6}\mathrm{Li}, {}^{7}\mathrm{Li}, \mathrm{Be}, \mathrm{C}, \mathrm{Al}, {}^{58}\mathrm{Ni}, \mathrm{Ag}, \mathrm{Pb}) \\ \to \mathrm{LCP}(Z = 1) + \mathrm{X}.$$

The basic tool was a lens spectrometer with a momentum resolution of $\Delta p/p \simeq 2.5\%$ within the dynamical range from 0.25 to 0.75 GeV/c. This setup was installed at $\Theta_{\mathrm{lab}} = 109°$ and 156° with respect to the beam axis. TOF measurements allowed to separate the hydrogen isotopes produced in these reactions. 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 $(^{2}\mathrm{H}/^{3}\mathrm{H})/(^{1}\mathrm{H}/^{2}\mathrm{H})$. Thus, it became possible to determine the temperature of ^{6}Li as the smallest probe. Hitherto, there was reason to doubt the usefulness of hygrogen isotope yields as thermometer since different nonequilibrium processes may contribute to these yields. Such contributions should be suppressed under our kinematic conditions and we consider the hydrogen yields as an adequate tool for temperature measurements.

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

$$\mathrm{p(1GeV)} \;+\; (\mathrm{Be}, \mathrm{C}, {}^{58}\mathrm{Ni}, \mathrm{Ag}, \mathrm{Au}, {}^{238}\mathrm{U}) \\ \to \mathrm{IMF}(Z \geq 2) + \mathrm{X}.$$

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 abundances and on the related temperatures [8] may be neglected.

IMF production was studied in p+Ag, Au and U collisions at $\Theta_{\mathrm{lab}} = 60°$ and 120° [9] using a setup consisting of the above mentioned magnetic lens spectrometer combined with a $\Delta E - E$ telescope. The energy resolution of the ΔE-detector ($\simeq 50$ keV) allowed to separate isotopes of

fragments from helium to boron. Absolute cross-sections were obtained by integrating the inclusive energy spectra approximated by a moving source fit and using the angular dependence $\mathrm{d}\sigma/\mathrm{d}\Omega = c_1 + c_2 \cdot \cos\Theta_{\mathrm{lab}}$. In addition, we included in this analysis differential cross-sections at $\Theta_{\mathrm{lab}} = 60°$ of fragments produced in 1 GeV proton collisions with ^{48}Ti, ^{58}Ni, ^{64}Ni, ^{112}Sn and ^{124}Sn [10].
iii) Isotopically separated fragments from ^{9}Be and ^{12}C targets were registered with a setup consisting of two TOF-E spectrometers installed at $\Theta_{\mathrm{lab}} = 30°$ and 126° with respect to the beam axis [11]. The basic detectors in each arm were twin Bragg Ionization Chambers combined with Parallel Plate Avalanche Counters. This setup, in detail 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 of the spectrum. 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 [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. We assume that this condition is rather well fulfilled 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.[2] the temperature can be obtained from the relation

$$T_{\mathrm{app}} = \frac{B}{\ln(a \cdot R)}\ , \tag{1}$$

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

$$R_1 = Y(A_i, Z_i)\,/\,Y(A_i + \Delta A, Z_i + \Delta Z),$$
$$R_2 = Y(A_j, Z_j)\,/\,Y(A_j + \Delta A, Z_j + \Delta Z).$$

The parameter a includes the spin degeneration factor and mass numbers of the considered isotopes. Equation (1) 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

$$\begin{aligned} B = {} & BE(A_i, Z_i) - BE(A_i + \Delta A, Z_i + \Delta Z) \\ & - BE(A_j, Z_j) + BE(A_j + \Delta A, Z_j + \Delta Z). \end{aligned}$$

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.

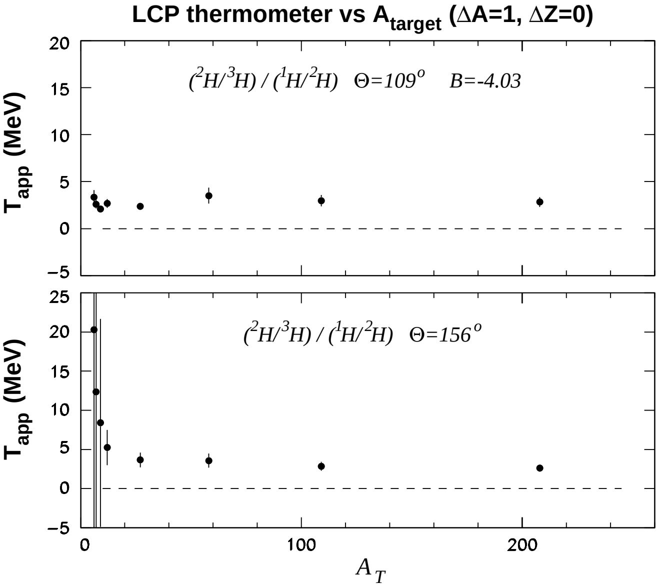

Fig. 1. Apparent temperatures obtained from hydrogen isotopes as a function of the target mass number A_{T}.

The relation (1) must be modified for "sequential decays", *i.e.* if particle decays from higher-lying states of the same and other isotopes contribute to the yields. An empirical correction for such decays was given for the special case of thermometers selected by $B \geq 10$ MeV [5]

$$\frac{1}{T_{\mathrm{app}}} = \frac{1}{T_{\mathrm{o}}} + \frac{\ln(\kappa)}{B}, \tag{2}$$

where T_{o} is the unknown intrinsic equilibrium temperature. The correction factor κ is defined by $R_{\mathrm{app}} = \kappa \cdot R_{\mathrm{o}}$ where R_{app} is the measured double isotope yield ratio and R_{o} the corresponding one for isotopes produced at equilibrium. The sensitivity of the thermometers improves with increasing B that reduces 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. For the time being, neither selection criterion $B \geq 10$ MeV nor correction for sequential decays were applied to avoid detailed discussions about it.

Figure 1 shows the results obtained with the LCP thermometer $(^{2}\mathrm{H}/^{3}\mathrm{H})/(^{1}\mathrm{H}/^{2}\mathrm{H})$ for two angles. At $\Theta_{\mathrm{lab}} = 109°$ the temperature T_{app} is nearly constant within $6 \leq A_{\mathrm{T}} \leq 208$ (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. [2]). The lower part of fig. 1 shows temperatures which are derived from the differential cross-sections of hydrogen isotopes measured at $\Theta = 156°$. With regard to the light target nuclei Li, Be and C the Δ-isobaric state contributes (up to $\simeq 20\%$) to the differential cross-section as shown in ref. [7]. In

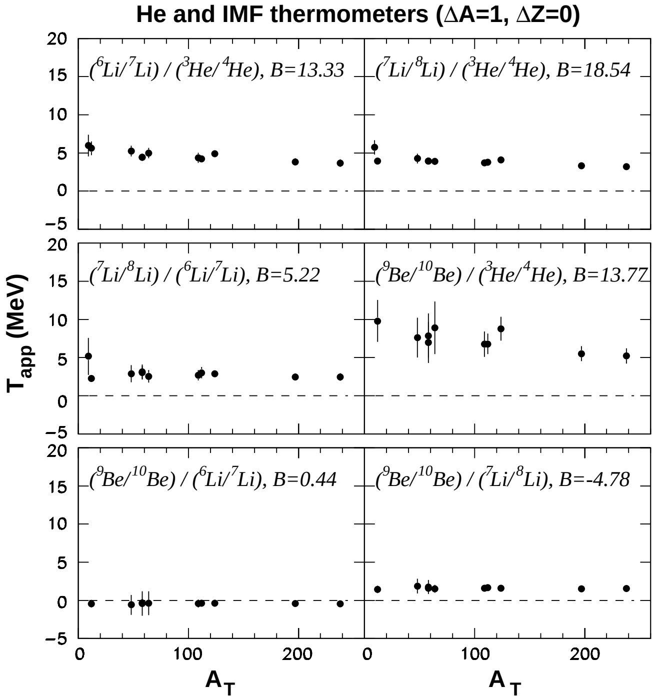

Fig. 2. Temperatures obtained from He and IMF pairs including $\Delta A = 1$, $\Delta Z = 0$ as function of A_{T}.

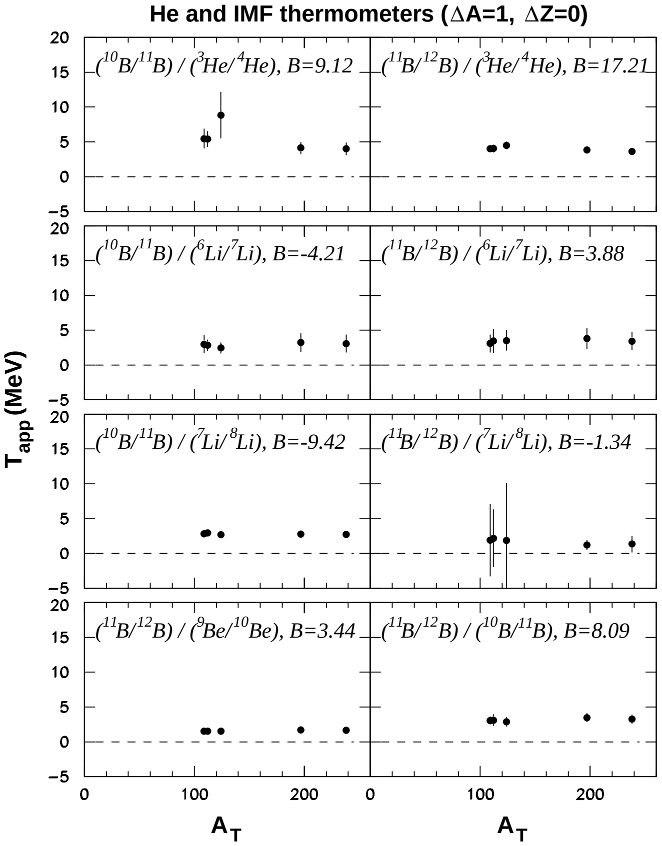

Fig. 3. Temperatures obtained from IMF pairs including combinations of boron isotopes with those of He, Li and Be.

order to eliminate this non-negligible contribution we performed additional fits combining a Maxwell-Boltzmann distribution with a Breit-Wigner term as substitute of the Δ-isobar. In spite of this correction the qualitative behaviour is conserved, *i.e.* an increase of T_{app} at $A_{\mathrm{T}} \leq 10$ cannot be excluded. But the errors are too large to draw a final conclusion.

We plot the temperatures obtained from 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 ratio ^{3}He/^{4}He. A comparison of temperatures derived from double ratios with $\Delta A = 1$, $\Delta Z = 0$ with those of $\Delta A = 1$, $\Delta Z = 1$ shows that they are equal within the error bars apart from some larger fluctuations. The observed agreement of the studied thermometers exhibits that possibly each one is suitable for relative temperature measurements without the hitherto introduced limitation $B \geq 10$ MeV. For a given thermometer the influence of sequential decays seems to be independent from the origin of the excited primordial fragments. This behaviour is rather surprising since the target mass number (or the volume of the fragmenting nuclei, respectively) changes by a factor of nearly 25. Under the same conditions, the *single* ratios of isotope yields show a pronounced dependence on $N_{\mathrm{T}}/Z_{\mathrm{T}}$, ref. [15].

Next we converted the above values T_{app} on the basis of relation (2) into intrinsic temperatures T_{o} as far as the correction factors for sequential decay κ [14] were available. The mean correction amounts to $\simeq 5\%$ but does not exceed 15%. Alternative correction methods, *e.g.* [16], valid in a multifragmentation scenario cannot be applied since contributions from this process are $\leq 5\%$ at 1 GeV incident energy. The behaviour of thermometers including isotopic pairs with ^{3}He/^{4}He ($B \geq 10$ MeV) is demonstrated in the top panel of fig. 4. Although the drawn errors are overestimated [1] the same trend was observed for all considered thermometers. In the lower panel we present the mean averages of the above values in order to compare with other available data. Some features of fig. 4 are worth to discuss. The first comments are related to T_{o} in the top panel:

i) All temperatures which have been corrected for sequential decays by using eq. (2) almost coincide at each target mass number A_{T}. Only the thermometer which exploits the ratio ^{11}B/^{12}B overestimates the temperature in the case of the target nuclei Au and U.

ii) The temperatures which have been derived from the differential cross-sections at Θ_{lab}=60° (open circles) are larger in comparison with those obtained from production cross-sections. Enhanced temperatures in forward

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[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 ΔT_{app} because it does not take 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.

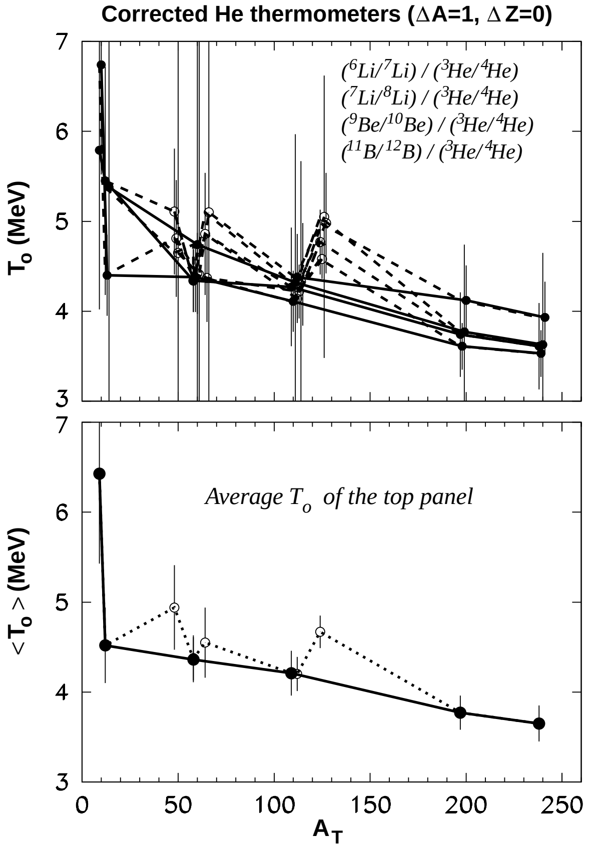

Fig. 4. Corrected temperatures T_o as function of A_T. Open circles: data from measurements at $\Theta_{lab} = 60°$. Top panel: individual thermometers are connected by dashed lines, solid lines connect T_o evaluated from isotope production cross-sections (black dots). Lower panel: mean average of the above 4 thermometers, same denotations.

direction and strong variations in thermometers which involve ^{3}He/^{4}He ratios were also reported in [17].

The second comments are addressed to the averages $\langle T_o \rangle$ plotted in the lower panel.

iii) We observe pronounced structures in the temperatures obtained from fragment yields at $\Theta_{lab} = 60°$ for ^{48}Ti, ^{58}Ni, ^{64}Ni, ^{112}Sn and ^{124}Sn targets (open circles). These data [10] are characterized by the low cut-off in the measured kinetic energy distributions and small corrections for the missing part of the spectra to obtain energy integrated yields. Regardless of the indicated errors fig. 4 shows a common systematic trend to higher temperatures with increasing ratio N/Z of the target. The isotopically separated targets ^{58,64}Ni and ^{112,124}Sn form such groups which look like fluctuations within a limited range of A_T but probably they are caused by different N/Z ratios of the fragmenting nuclei.

iv) If we consider the full range of A_T instead of a limited one, the opposite tendency dominates: the nuclear temperature decreases weakly with increasing A_T. We mention that the same dependence was also found at $E_p = 8$ and 12 GeV [18]. The temperatures which include the ratio ^{3}He/^{4}He show the most pronounced decrease with increasing A_T. This behaviour seems to be related to the exceptional properties of ^{4}He which were attributed to a predominant production by evaporation [10]. But double ratios involving heavier isotopes provide temperatures which are nearly independent of the target mass within the error bars (see figs. 2–3). We mention that the average temperature $\langle T_o \rangle \simeq 4$ MeV was obtained from cross-sections (lower panel, black dots) in the range A_T under consideration. Although hints to nearly constant temperatures were already found in refs. [5,17,18] one may doubt the universal validity of temperature measurements basing on 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 [19,20], were processed by the same procedure as applied to those from fragmentation at 1 GeV (a forthcoming paper is in progress). The used thermometers resulted in significant lower temperatures of $\langle T_{app} \rangle \simeq 1$ MeV which are consistent with the temperature of 1.1 ± 0.2 MeV [21] derived from the neutron spectrum accompanying ternary fission of ^{252}Cf.

Summarizing, we analyzed inclusive data obtained in 1 GeV proton interactions with various target nuclei employing different isotope thermometers. We found that even thermometers which involve pairs with $B < 10$ MeV provide "stable" results which may be suitable for relative temperature measurements. The weak dependence of the temperatures on the target mass A_T suggests speculations that in nearly all considered targets the fragmentation process is governed by the same thermodynamical properties.

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