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# t/d/p Ratios in Nucleon-Nucleus and Heavy Ion Reactions - Can Entropy be Determined?

A. Fokin[1], L. Carlén[1], R. Ghetti[1], B. Jakobsson[1] J. Mårtensson[1], Yu. Murin[1], A. Oskarsson[1], C. Ekström[2], G. Ericsson[2], J. Romanski[2], E.J. van Veldhuizen[2], L. Westerberg[2], K . Nybö[5], T.F. Thorsteinsen[5], S. Amirelmi[5], M. Guttormsen[6], G. Løvhøiden[6], V. Bellini[7], F. Palazzolo[7], M.L. Sperduto[7], J.P. Bondorf[8], I. Mishustin[8], V. Avdeichikov[9], O.V. Lozhkin[10]

(CHIC Collaboration)

and W.A. Friedman[11] and K.K. Gudima[12]

[1] Department of Physics, University of Lund, Lund, Sweden

[2] The Svedberg Lab. and Dept. of Neutron Physics, University of Uppsala, Uppsala, Sweden

[3] Centre d'Etudes Nucléaires, Saclay, France

[4] Department of Physics, Chalmers Inst. of Technology, Gothenburg, Sweden

[5] Dept. of Physics, University of Bergen, Bergen, Norway

[6] Dept. of Physics, University of Oslo, Oslo, Norway

[7] INFN/LNS, University of Catania, Catania. Italy

[8] Niels Bohr Institute, Copenhagen, Denmark

[9] Joint Inst. for Nuclear Research, Dubna, Russia

[10] V.G. Khlopin Radium Inst., St. Petersburg, Russia

[11] Dept. of Physics, University of Wisconsin, Madison WI 53706, USA

[12] Inst. of applied Physics, Kishinev, Moldavie

Cosmic and Subatomic Physics
University of Lund
Sölvegatan 14
S-223 62 Lund, Sweden

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[1] Department of Physics, University of Lund, Lund, Sweden
[2] The Svedberg Lab. and Dept. of Neutron Physics, University of Uppsala, Uppsala, Sweden
[3] Centre d'Etudes Nucléaires, Saclay, France
[4] Department of Physics, Chalmers Inst. of Technology, Gothenburg, Sweden
[5] Dept. of Physics, University of Bergen, Bergen, Norway
[6] Dept. of Physics, University of Oslo, Oslo, Norway
[7] INFN/LNS, University of Catania, Catania. Italy
[8] Niels Bohr Institute, Copenhagen, Denmark
[9] Joint Inst. for Nuclear Research, Dubna, Russia
[10] V.G. Khlopin Radium Inst., St. Petersburg, Russia
[11] Dept. of Physics, University of Wisconsin, Madison WI 53706, USA
[12] Inst. of applied Physics, Kishinev, Moldavie

## Abstract

The relative yield of high energy deuterons and tritons as compared to protons have been measured in p + Kr, $^{16}O$ + Kr and $^{20}Ne$ + Ar reactions with a continuously varying beam energy up to 500(400A)MeV. The d/p or t/p ratios increase smoothly with beam energy. Statistical, (expanding)evaporation models cannot directly reproduce the high energy part of the d or t production. Models that contains nucleon-nucleon scattering, like cascade- or NMD models, can only reproduce the ratios if final-state interaction is introduced via the coalescence prescription. The coalescence radius that best fits the data is rather constant over wide beam energy intervals. Entropy can however not be directly determined from these ratios.

# 1 Introduction

Attempts to estimate both radii [1] and entropy [2] of the participant zone as by means of fragment yield ratios have been previously made. It was suggested that the entropy (S) of a finite size (mass, A) nucleus, excited to ($\epsilon^*$) less than a few tens of MeV/nucleon, can be determined from the ratio ($R_{xN}$) between the yield of a composite particle (x) and a nucleon [3]. A simple formula which relates S/A to the density of nucleons, $\rho_N$ and thus to $R_{dp}$, for an expanding Fermi-Dirac system in chemical equilibrium is,

$$S/A = 5/2 - ln(2^{2/3} < \rho_N >) = 3.95 - ln(R_{dp}) \tag{1}$$

provided that the number of protons is much larger than the number of deuterons and that heavier clusters can be neglected. Data for heavy ion collisions at 400A MeV [2], used in eq. (1) seems to vastely overestimate the entropy. The necessity to introduce additional degrees of freedom, like isospin excitations (pion production), has been discussed [4] but for energies discussed in this paper this cannot explain the large entropy determined from the t/d/p ratios. On the other hand, complete calculations, based on either hydrodynamical models [5] or statistical models [6] have been introduced, to determine the entropy. There it was shown that secondary decay plays an essential role for the S/A - $R_{dp}$ relation whereas the breakup density plays less role when kept within reasonable limits, say $\rho/\rho_o$ = 0.3 - 1.0. More recently, also the prescription of expanding systems that sequentially evaporate and/or rapidly decay (multifragmentation) has been discussed in terms of the S/A - $R_{xp}$ relation [7]. Such calculations, as well as pure evaporation calculations, microscopic- [8, 9] and mean-field calculations that contains nucleon-nucleon(NN) scattering have been confronted with our data. In the NN calculations, multinucleon clusters are produced in final-state interactions through the coalescence prescription, and we discuss in this paper how to interpret the results when comparing to the d/p and t/p data.

In the early data [2, 10, 11] from asymmetric (light projectile - heavy target) reactions at 16A MeV - 1A GeV it appeared as if an evaporative liquid-drop formalism with an assumption about global thermal equilibrium better describes the combined information from d/p, t/p and $\alpha$/p ratios than a free strongly interacting gas prescription [12]. This may be a natural consequence of the fact that low energy, light particle production is dominated by evaporation from a weakly excited target-like source. In this paper we select instead particles from the strongly interactive, highly excited part of the collisions by proper cuts in momentum-space. These data are compared to $R_{dp}$ ratios from p + Kr collisions at beam energies up to 500 MeV, which however correspond to substantially lower excitation energies, only up to 6A MeV.

The slow ramping operation at the CELSIUS storage ring with continuous data taking from the initial to the final beam energy [13] makes the data in this paper very conclusive when compared to calculations.

# 2 Experimental Details

All experimental data, presented in this paper, were collected at the CELSIUS storage ring, which can provide beams of protons up to 1360 MeV and Z/A=1/2 heavy ions up to 470A MeV with luminosities, L, up to $1 \cdot 10^{31}$ $cm^{-2}s^{-1}$ and $1 \cdot 10^{28}$ $cm^{-2}s^{-1}$ respectively. Here $L = \nu \cdot \Phi \cdot d_t$, where $\nu$ is the frequency of the circulating beam, $\Phi$ is the number of stored ions and $d_t$ is the effective target thickness, i.e. the actual thickness that the beam passes through. In our experiments, protons and fully stripped $^{16}O$ and $^{20}Ne$ ions were injected, rapidly accelerated up to the start energy($E_1$) and then stored with the gas jet target in operation while the magnets are slowly ramped [13] until the final energy($E_2$) was reached and then finally the beam was dumped. No more than a factor of three decrease in $\Phi$ is accepted. Fig. 1 gives a schematic picture of the energy and flux variation during the cycles, with lifetimes varying from 1 to 5 min.

The data presented in this work, on p, d and t, were collected in parallel with data on charged pions [13], using the same sandwich, plastic scintillator, range telescopes, whenever on-line proton rejection was not necessary for the pion registering. The 10-element telescopes were of standard CHIC construction with successively increasing scintillator thickness [14]. These telescopes were mounted outside thin windows in angular positions from 20° to 150° (Table 1). The trigger requirement is signal-above-discriminator in the first two scintillators. The stop detector is defined through a pattern unit, controlled off-line by the chain of ADC signals. Each stop detector produces a $\Delta$E-E correlation with good separation between $\pi$, p, d and t particles. Since only results on d/p and t/p ratios are included in this paper it should be pointed out that variations in the luminosity are not important and no absolute normalization is necessary. Because of the trigger requirement and of the total telescope thickness of $\sim$ 20cm we register $\sim$ 20-175 MeV protons. Normally the data that are presented contain an integer number of stop detectors. Some differences in the energy intervals appear because of the different detector thicknesses in the small volume forward telescopes and the large volume backward telescopes.

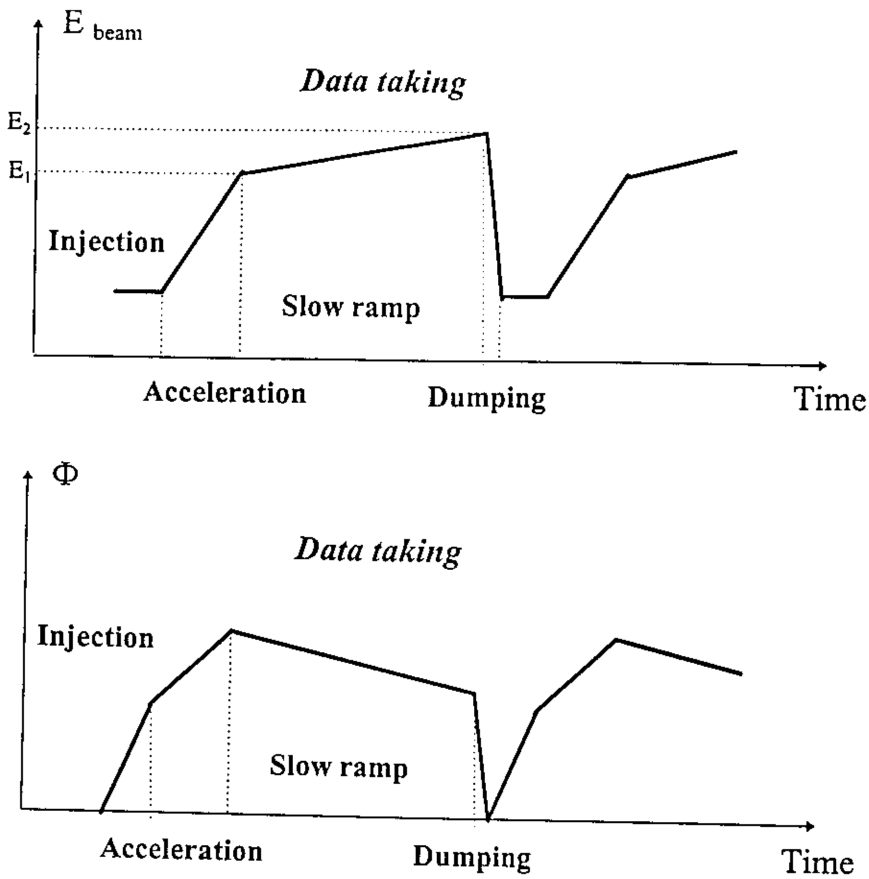


Figure 1: *Schematic representation of the beam energy and flux variation with time during one cycle of stored beam particles.*

| Reaction | Angular pos. | Beam energy |
|---|---|---|
| p + Kr | 90° | 150 - 500 MeV |
| O + Kr | 20°, 55°, 75°, 90°, 150° | 22A - 300A MeV |
| Ne + Ar | 20°, 55°, 75°, 90°, 120° | 50A - 400A MeV |

Table 1: List of reactions and detector positions.

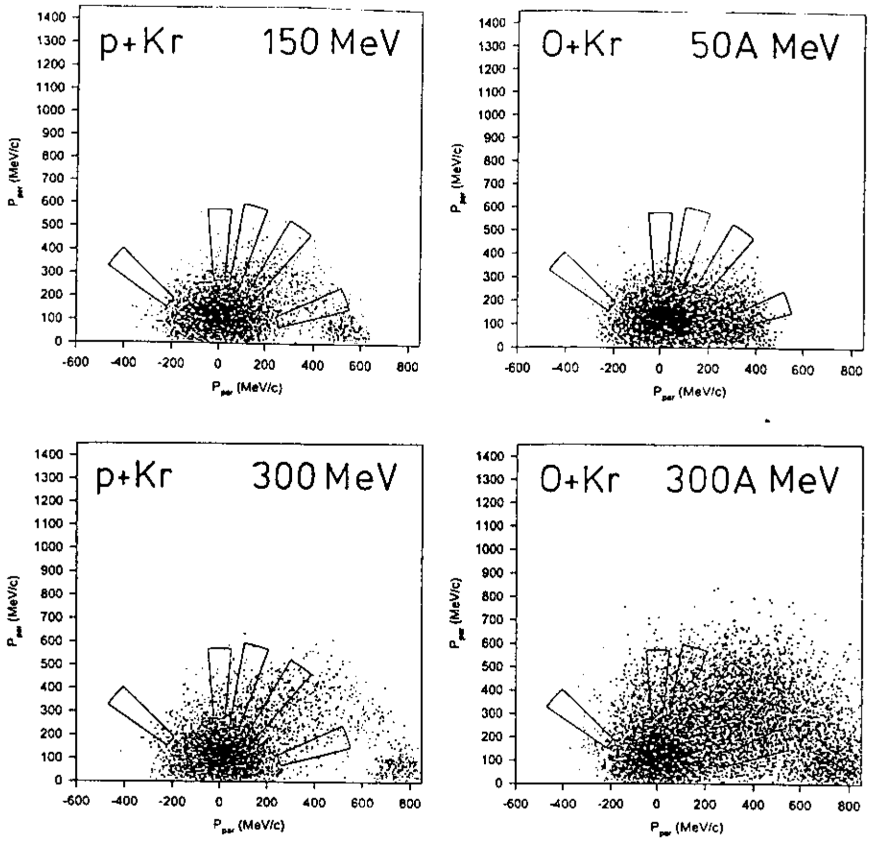


Figure 2: *NMD simulations of proton emission in various reactions and examples of the total momentum-space regions, covered by the telescopes.*

# 3 Theoretical Calculations

## 3.1 Models

The momentum-space, covered in the experiments, corresponds to emission almost exclusively from pre-equilibrium processes, i.e. knock-out or pick-up processes or early emission from hot strongly interacting regions. Hot and dense regions are chiefly produced in nucleus-nucleus reactions. Any standard three-source prescription confirms that the positions of the particle telescopes exploit the relevant momentum-space regions of pre-equilibrium particles (Fig. 2). The simulations are in this case based on the Nuclear Molecular Dynamics (NMD) model [15].

It should be noted that the impact parameter (b) is randomly selected with weight $\sim$ b in accordance with the inclusive measurements. The left hand side of Fig. 2 shows the situation in p + Kr reactions At both energies, beam-like protons and protons evaporated from the target source are well separated and not contributing very much to the selected sample. In heavy ion reactions (O + Kr, right hand side), projectile-associated protons are clearly separated from target-like protons and the intermediate source protons can be identified quite well at 300A MeV but not at 50A

MeV. The heavy-ion data we present in this paper start from 100A MeV where the pre-equilibrium source is reasonably well defined. Simulations of d and t emission, within the same prescription, show the same general emission characteristics.

The emission of light particles by evaporation from an expanding source is introduced through the model of Friedman [7]. The emission is here treated as a chain of sequential binary decay processes, where the relative decay rates are calculated by detailed balance, already proposed in the original Weisskopf prescription for evaporation[16]. These rates are influenced by the conditions associated with the expansion process. In addition secondary contributions of light particles from the decay of unstable resonances are also included. By comparing the sequential calculations to similar calculations within a microcanonical (freeze-out) approach it has been possible to define an effective volume which increases with time during the expansion and allows to estimate a time dependent entropy of the emitting system.

In addition, "reference" calculations within a classical evaporation model [17] were performed. In this case the time dependence of the entropy is neglected and complete excitation is immediately introduced. This model contains however a more detailed side-feeding prescription for the secondary decay of primary fragments that are particle instable or excited enough to decay by particle emission.

Microscopic model calculations are represented by the Dubna version of the intranuclear cascade model [8, 9]. In this model inelastic nucleus-nucleus interactions are treated as successive quasi-free two-particle collisions described by a set of coupled relativistic kinetic equations of Boltzmann type. The description of the mean-field evolution is simplified in the sense that the scalar nuclear potential, defined by the local Thomas-Fermi approximation, remains the same throughout the collision, while the potential well depth is changed according to the number of knocked-out nucleons [9]. This procedure allows one to take into account nuclear binding and Pauli blocking. This simplified prescription is relevant for hadron-nucleus and peripheral nucleus-nucleus collisions, where no large disturbance on the mean-field is expected, but it is questionable for violent, central hevy ion collisions.

After completing the cascade stage of the reaction, light particles may be emitted both from equilibrium and non-equilibrium states of excited residual nuclei at a subsequent stage of the interaction. Pre-equilibrium emission is here taken into account within the exciton model [18].

We also performed mean-field calculations, for the case of d/p in Ne + Ar collisions, within the Nuclear Molecular Dynamics (NMD) Model [15] and we will return to these results in section 4.2.

## 3.2 Coalescence

In any independent particle description, final-state interactions for creating deuterons may be prescribed via the coalescence process. In this prescription, the deuteron cross section is given by the product of the square of the nucleon cross section and the probability to to find a proton and a neutron close enough in momentum-space,

$$\frac{d^3\sigma_d}{dp^3} = (\frac{4\pi}{3}\frac{\gamma p_o^3}{\sigma_r}) \cdot (\frac{d^3\sigma_N}{dp^3})^2 \qquad (2)$$

where $\gamma$ is the Lorenz factor of the beam. The coalescence radius, $p_o$, is either predefined as an effective interaction range, varying from 90 MeV/c to 115 MeV/c for protons to alpha particles or empirically determined from d/p$^2$ radii to be larger, $\sim$ 190 MeV/c. In more elaborate calculation, $(d^3\sigma_N/dp^3)^2$ must be replaced by $(d^3\sigma_p/dp^3) \cdot (d^3\sigma_n/dp^3)$ and the proper n/p weigh of the emitting system should also be introduced. The coalescence prescription has had certain success in explaining composite particle emission data.

In cascade models a direct use of the coalescence prescription for d and t production at the proper freeze-out time has been introduced [9]. In the NMD model, these particles are produced directly, if nucleons are close enough in configuration space. Very few high energy deuterons and tritons can, however, be produced this way and therefore coalescence is introduced as final-state interaction. In the next chapter we will return to this formalism, when comparing data to calculations.

# 4 Experimental Results

## 4.1 Proton-Nucleus Collisions

Fig. 3, shows the measured d/p ratio (histograms) for high energy particle emission at 90$^o$ in the p + Kr reaction from 150 MeV to 500 MeV. Typical statistical errors are presented on a few points only in this figure and in the forthcoming ones. The lower histogram contains protons and deuterons in the same velocity or energy/nucleon bin and their position in the $p_{||}$ - $p_\perp$ plane (Fig. 2) could therefore easily be identified (p $\geq$ 240 MeV/c). The upper histogram represents particles with the same total kinetic energy (E) which is more natural when comparing to expected Maxwellian sources, $\sim \sqrt{E} \cdot exp(-E/T)$.

In order to determine the entropy, from (1), the total yield from the source is required. This is not possible from these data but if the $90^o$ emission is representative, the apparent S/A values decrease from 9 to 7 when the high energy cut is made and from 6.5 to 6 for the high energy/nucleon cut. This confirms the strong overestimation of entropy, when determined this way.

In both samples the d/p ratio increases monotoneously with beam energy which agrees with all standard prescriptions for composite particle production. The cascade approach presents this increase quite properly if deuteron production from final-state coalescence is accepted. In order to describe the very high energy production of deuterons, introduced through the energy per nucleon cut, the coalescence radius in momentum space ($p_o$) must be given a somewhat larger value than 90 MeV/c, which was originally introduced from comparison with heavy ion collision data [2, 9] The value required for p + Kr data seems to be 110 - 120 MeV/c and it does not seem to depend on the beam energy at all in the interval 150 MeV - 500 MeV. If we include also lower energy deuterons (upper histogram), some target evaporation will certainly be included and it appears as if a lower $p_o$ must be introduced in this case. It should however be stressed that an additional introduction of a "convergence" criterion, $\vec{r_{ij}}/\vec{v_{ij}} \leq 0$, in the definition of a coalescence cluster, gives the proper reduction of the d/p level as shown by the dashed curve. If this criterion is to be introduced for the high velocity cut, one should, however, expect an even larger $p_o$, 130 - 140 MeV/c.

The fact that high energy particles, that were selected, must come from early emission processes is further stressed by the "reference" QMD calculations. Without introducing coalescence, the d/p ratio falls much below the data, but after its introduction, somewhat arbitrarily at > 200 fm/c, it is possible to obtain good agreement with the experimental data over the whole beam energy region also in the QMD prescription.

A comparison to pure statistical models, like the EES model, requires the emission source to be pre-defined. For p + Kr collisions the obvious first choice of such a source, in thermal and chemical equilibrium, would be the compound nucleus with excitation energy 2 - 6 MeV/nucleon. The part of the available energy that is used for collective expansion is for obvious reasons very small in this case and therefore the emission should follow quite well an evaporative scenario. This is confirmed by the EES calculations that we performed for p + Kr between 150 and 500 MeV, but the results provide a d/p ratio for particles with E > 30 MeV is vastely overestimated, whereas the corresponding ratio for E/A > 30 MeV is somewhat underestimated. This shows the difficulties in explaining the high energy deuterons, that were selected in the experiment, solely by thermal emission processes.

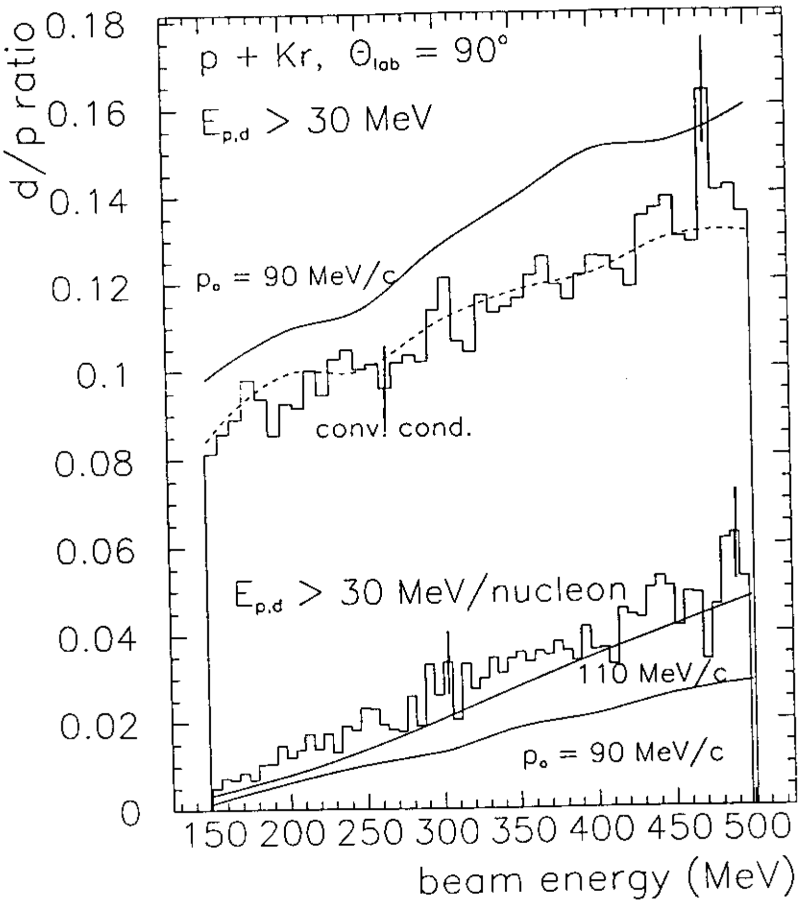


Figure 3: *High energy d/p ratio in p + Kr collisions.*

This conclusion is further confirmed by the "reference" calculation with the classical SIMON evaporation code[17]. It shows the same vaste overprediction for the E > 30 MeV ratios but almost no deuterons with energy > 30 MeV/nucleon are produced so again the ratio is underpredicted for such very high velocity cut-off. The general conclusion from the comparison to statistical calculations is therefore that non-equilibrium, early emission processes must be introduced to explain the d/p data.

## 4.2 Nucleus-Nucleus Collisions

d/p ratios from heavy ion collisions are presented as histograms in Fig. 4. The lack of data in the O + Kr case below ~ 70A MeV beam energy appears because of problems with the acquisition veto signal for the forward telescopes. For the backward telescopes, data points could be extracted down to beam energies of ~ 30A MeV but there we omit the region 30A - 70A MeV due to low statistics of deuterons. In the Ne + Ar data the lack of deuteron statistics sets in at 100A MeV. The slightly different particle energy/nucleon intervals in forward and backward telescopes appear due to somewhat different detector thicknesses. First we stress that even if the possibilities to compare these data to those from other experiments, they do agree well wherever possible. One example, taken from a comparison to the Ar + Ca data of Jacak et al. [19], shows 70° d/p ratios at 92A MeV of 0.17 and at 137A MeV of 0.25 where our

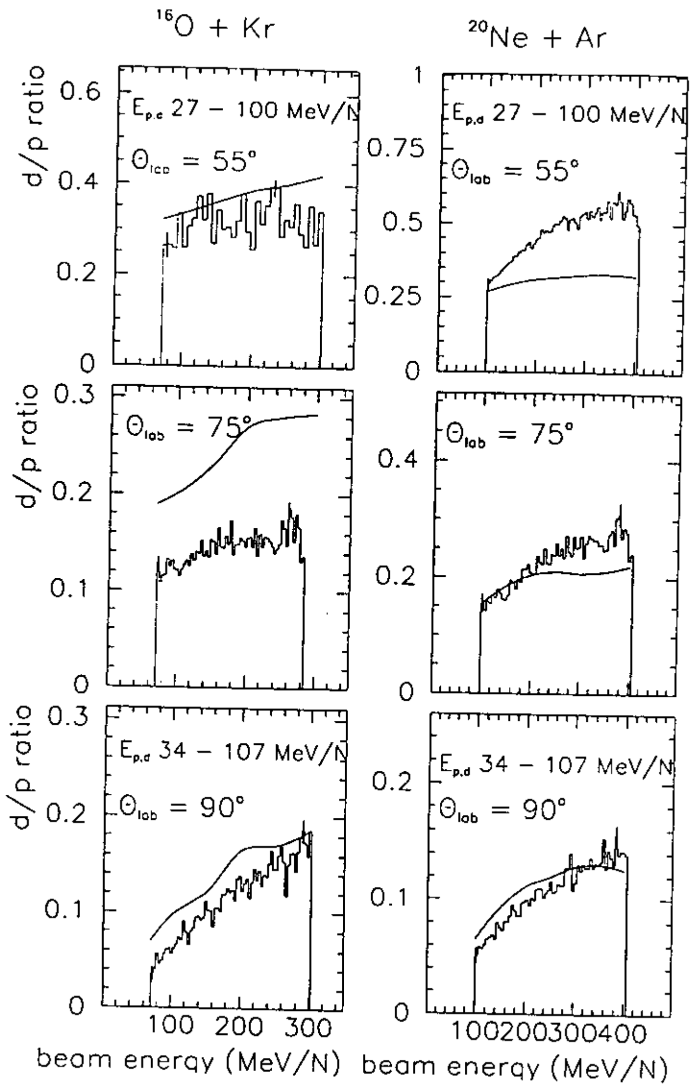


Figure 4: *High energy d/p ratio in O + Kr and Ne + Ar collisions.*

Ne + Ar ratios (75°) are 0.14 and 0.19. When comparing data from the two reactions in Fig. 4, O + Kr and Ne + Ar, one must of course consider the different degree of asymmety. In any participant-spectator prescription the emission systems should have different velocities in the laboratory system and furthermore there may be some different (small) contribution at forward angles from the projectile-like source at the smaller beam energies (see Fig. 2). After considering this, it can be concluded that both reactions show the same smooth increase of the d/p ratio with beam energy and the same decrease of the d/p level with increasing emission angle.

EES calculations must be given inital source parameters. Only for sources near thermal equilibrium with excitation energies < 10 MeV/nucleon will there be decay through evaporation. At high excitation, the model provides a monotonically expanding source with cluster formation down to low densities, $\sim 0.1\rho_o$. In view of the three-source picture (see Fig. 2), the dominating source of high energy deuterons and tritons should be the participant with some possible contribution from highly excited target sources. EES calculations for the Ne + Ar case confirm this source selection and indeed also the very wide distribution of excitation energy when looking at inclusive data. Actually, complete fusion with full stopping provides $\epsilon^*$ from 20 to 90 MeV/nucleon. Once source parameter distributions in $\epsilon^*$ and A are chosen for a given beam energy the EES calculations reproduce the experimental d/p and t/d ratios to about the same level as the cascade calculations plus coalescence. Again it is obvious that the high energy composite particles we select in this experiment represent pre-equilibrium emission which also is confirmed by "reference" calculations from the pure evaporative calculations with the SIMON [17] code which can hardly produce any deuterons with E > 27 MeV/nucleon.

We now turn back to the cascade calculations + coalescence and present in Fig. 4 as curves the d/p ratios calculated with a coalescence radius of $p_o$ = 90 MeV/c. The general tendency is in agreement with data but there are discrepancies. The angular dependence is not perfect (75° data) in the O + Kr data and the beam energy dependence is weaker than the data for forward emission in the Ne + Ar reaction. Possibly the latter discrepancy can be accounted for by an increasing contribution from the projectile-like source with decreasing beam energy. It is however obvious that there is no dramatic difference in $p_o$, 90±30 MeV/c, between p - nucleus and nucleus - nucleus collisions and no dramatic change of this parameter with increasing beam energy.

Next, t/p ratios are presented in Fig. 5. In the two examples there is again a velocity cut-off introduced, corresponding to an energy/nucleon of 27 MeV/A. This is a very high velocity cut-off for tritons and there is now an even stronger beam energy dependence than for d/p ratios. A comparison between the d/p and t/d ratio is made in the lower figures. The coalescence principle, as prescribed by formula (2), predicts the same ratios if $p_o$ is taken to be constant. One natural deviation from this may come from the summation over spin if spin coupling is strong,

$$R_{dp}/R_{td} = (2S_d+1)^2/(2S_p+1)(2S_t+1) = 9/4 \qquad (3)$$

Actually this factor is close to the one obtained in the cascade+coalescence calculations (curves in Fig. 5) and also well reproduced by the O + Kr data, at least for beam energies a bit above the very threshold of high energy composite particles. The cascade calculations are however overpredicting the t/d ratio for O + Kr by about the same factor as for the d/p ratio (see Fig. 4) and in Fig. 5 both calculated curves have been multiplied by 0.6. For the 55°, Ne + Ar ratios the calculations rather underpredict the d/p ratio (no renormalization in Fig. 5) but in this case the t/d ratio comes out in good agreement with data. Possibly, the n/p of the emitting system, discussed in section 3.2 can account for a part of the non-consistency between d/p and t/d ratios. It should again be noticed that the $p_o$ radius is 108 MeV/c for tritons, while 90 MeV/c is kept for deuterons, following the original tuning [9] from higher

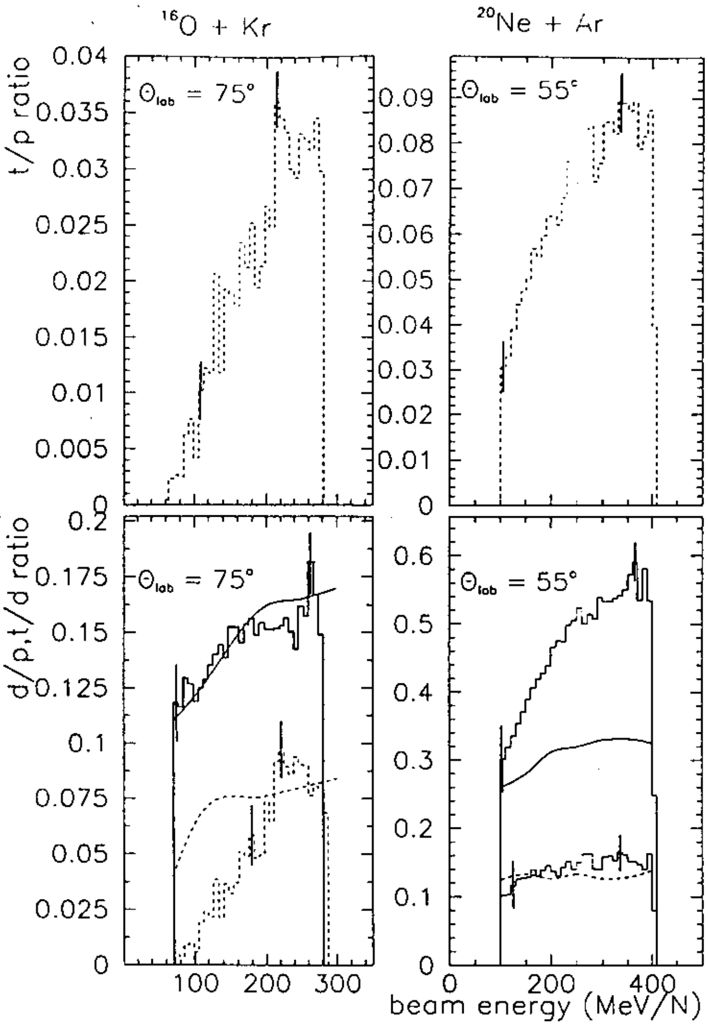


Figure 5: *t/p, d/p and t/d ratios for particles emitted with enery 27 - 107 MeV/nucleon at 75° (O + Kr) and at 55° (Ne + Ar). The curves represent the cascade+coalescence calculations with standard values for* $p_o$.

energy heavy ion collisions. The general conclusion from all t/d/p ratios is, however, that although the overall agreement between the cascade+coalescence calculations and the data is reasonable, details in angular and beam energy dependencies are not reproduced very well. It should again be stressed that with the proper choice of the source $\epsilon^*$ and A distributions, the EES calculations predict e.g. a d/p ratio of 0.3 for the Ne + Ar reaction at 300A MeV and a corresponding t/d ratio of $\sim$ 0.1, which follow the cascade predictions well. Of course no coalescence is introduced in the EES case.

With respect to selected momentum-space and statistics we believe that the backward data in the Ne + Ar reaction contain the best and most clean example of pre-equilibrium (hot source) emission. These data may be chosen to select among emission mechanisms or to fine-tune the coalescence radius. In Fig. 6 such d/p data are presented (note that the binning is different from Fig. 4) together with a) the cascade+coalescence calculations with $p_{o,d}$ = 80, 90 and 100 MeV/c (lower-, mid- and

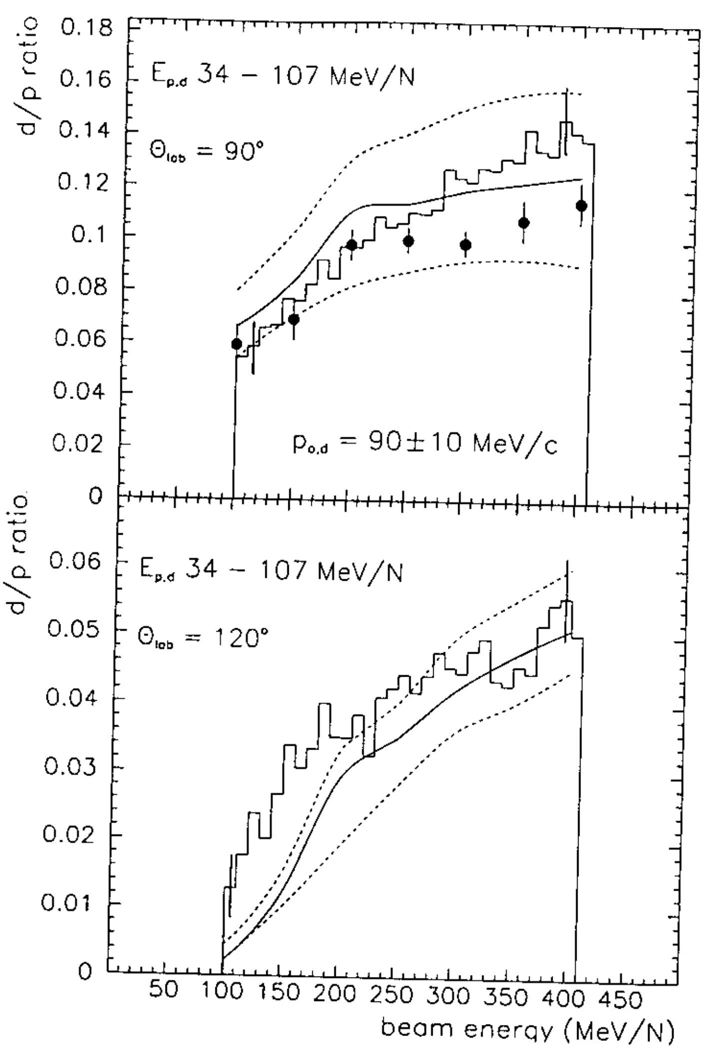


Figure 6: *d/p ratios for particles emitted with energy 34 - 107 MeV/nucleon at 90° and 120° from Ne + Ar reactions. The curves represent the cascade+coalescence calculations with* $p_o$ *= 90 MeV/c (solid) and 80, 100 MeV/c (dashed). The points represent NMD + coalescence calculation with* $p_o$ *= 90 MeV/c.*

upper curves in both figures) and b) the NMD + coalescence calculations with $p_{o,d}$ = 90 MeV/c (points in upper figure). From both data and calculations it appears as if there is a change in the d/p - beam energy relation at around 200A MeV pointing towards some change in the emission mechanism. This is most clearly seen in the 120° data where it appears also to be difficult to explain both the low and high beam energy part with the same coalescence radius. Apart from this deviation, it appears as if a coalescence radius of $p_{o,d} = 90 \pm 10$ MeV/c, well reproduce the emission of fast deuterons. The comparison to NMD + coalescence shows about the same degree of agreement with data as the cascade approach. This reflects of course the fact that both these models describe singles spectra of protons and neutrons equally good.

## 5 Conclusions

We have shown that the yields of high energy deuterons and tritons increase smoothly as a function of beam energy both in p-nucleus and nucleus-nucleus collisions. Entropy cannot directly be determined from t/d/p ratios. No standard statistical model, assuming thermal equilibrium, can reproduce these ratios since the particles are of pre-equilibrium origin. Microscopic and mean-field+NN models are equally successful in reproducing these data. Also the EES model, with proper source distribution input, can account for the nucleus - nucleus collision data to the same degree but it is less successful in explaineing the p - nucleus data. In the first two kinds of models, inclusion of coalescence as some kind of final-state interaction is necessary. The coalescence radius is surprisingly constant with beam energy and no big differences between p - nucleus and heavy ion collisions are found. Some indications exist that the emission process - or at least the nucleon density - changes in heavy ion collisions at around 200A MeV.

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