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Cluster formation observed with a 4π detector and the question of entropy production in high energy nuclear collisions

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Abstract:

4π data taken with the Plastic Ball show that the cluster production in relativistic nuclear collisions depends on the size both of the produced cluster and the participant volume. Therefore values of entropy extracted via fragment yields are a strong function of the particle multiplicity. Many of the puzzles from single particle inclusive data of cluster production can thus be solved by 4π data.

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Models of relativistic nuclear collisions that include the equation of state of nuclear matter predict an increase in entropy for a phase transition at high nuclear density.[1] Thus it would be of great interest to extract entropy information from experimental data. Recently, it was pointed out[2] that entropy can be related to cluster production in a way that decreases logarithmically with the ratio of deuteron yield to proton yield. This has stimulated a dispute among theorists[3-8] over whether the information about the early state, inherent in this ratio, gets lost during the expansion phase or is disturbed only via second order effects, whether the deuteron and proton yields are the proper observables, how to include higher mass clusters, and finally how to compare the experimental data with theoretical calculations. Until now these studies have been limited to single particle inclusive data, which mixes together reactions of all impact parameters.

In this letter we present for the first time 4π data obtained with the Plastic Ball.[9] Due to its particle identifying features and large solid angle it is now possible to study cluster production as a function of the particle multiplicity of each event. Furthermore, the deuteron to proton ratio can be compared with the deuteron-like to proton-like ratio as suggested in ref. 5, where the following definition is given for the number of deuteron-like pairs:

$$d_{\text{like}} = n_d + \frac{3}{2}\left(n_t + n_{^3\text{He}}\right) + 3\, n_{^4\text{He}} \quad .$$

The number of proton-like particles is taken as the multiplicity of observed charges:

$$p_{\text{like}} = n_p + n_d + n_t + 2\left(n_{^3\text{He}} + n_{^4\text{He}}\right) .$$

The observed multiplicity of charged particles, M_c, is given by the same equation without the factor of 2 but with the addition of charged pions.

The Plastic Ball spectrometer covers the angular region between 9 and 160 degrees, 96% of the total solid angle. It consists of 815 detectors, where each module is a ΔE-E telescope capable of identifying the hydrogen and helium isotopes and positive pions. The ΔE counter is a 4-mm thick CaF_2 crystal and the E counter a 36-cm long plastic scintillator. Both signals are read out by a single photomultiplier tube. Due to the different decay times of the two scintillators, ΔE and E information can be separated by gating two different ADCs at different times. A detailed description is given elsewhere.[9]

For the investigation of entropy it is important to compare protons and clusters originating from the primordial interaction zone. Particles coming from the late state of the reaction or from the spectator regions are predominantly emitted with low energies.[10] An adequate way to eliminate those contributions is to apply a lower threshold of 40 MeV per nucleon to the data. Such a low energy cutoff should be incorporated into theoretical comparisons since values obtained this way for ratios of d_{like}/p_{like} are lower than those extracted from the full spectrum. Furthermore, this study is limited to data at emission angles of $9^\circ \leq \theta \leq 160^\circ$ ignoring the small yield of mainly spectator particles going into 0° to 9°.

The reactions, studied at the Berkeley Bevalac, are ^{20}Ne + Pb at 800 MeV/u and ^{40}Ca + Ca at 400 MeV/u. For the different beam-target combinations several hundred thousand events were measured with a reaction (minimum bias) trigger and with a central trigger. The reaction trigger requires that a beam particle was identified in the upstream start detector and that this particle lost some charge in a reaction with a target nucleus. The central trigger excludes events where any particles with beam velocity are emitted within a forward cone of two degrees, enriching the yield of central collisions.

Figure 1a shows the mean deuteron-to-proton ratio for Ne + Pb at 800 MeV/u averaged over many events as a function of the charged particle multiplicity M_c in the event. There is a steep rise of d/p up to a value of 0.3, indicating that the deuteron production increases relative to the protons as more nucleons are involved in the reaction. Figures 1b and 1c show for the same reaction the mean ratio of d-like to p-like particles (again averaged over many events). Notice the larger values compared with d/p. The data for a central trigger (1c) can be compared with the minimum bias data (1b). They practically overlap proving that the central trigger is not producing a special bias in the cluster production but only an enhancement of high multiplicity events. Figures 2a and 2b represent these ratios for the reaction of 400 MeV/u ^{40}Ca on Ca.

A simple straight line parameterization of the slopes of these curves for multiplicities up to ~25 for the Ca data and up to ~40 for the Ne data yields

$$800\ \mathrm{MeV/u}\ {}^{20}\mathrm{Ne} + \mathrm{Pb} \quad \begin{cases} d/p = 0.043 + 0.0051\ M_c \\ d_{\mathrm{like}}/p_{\mathrm{like}} = 0.049 + 0.0080\ M_c \end{cases}$$

$$400\ \mathrm{MeV/u}\ {}^{40}\mathrm{Ca} + \mathrm{Ca} \quad \begin{cases} d/p = 0.062 + 0.0067\ M_c \\ d_{\mathrm{like}}/p_{\mathrm{like}} = 0.10 + 0.010\ M_c \end{cases}$$

For higher multiplicities a saturation of the ratio is observed.

Can the increase in deuteron production with increasing multiplicity be understood in terms of the current models for cluster production? In the thermal model assuming chemical equilibrium[11] the ratio of d/p was independent of the size of the thermal source, and d/p as a function of M_c was expected to be constant. In the original coalescence model[12] the size of the participant volume was ignored and the coalescence volume in momentum space was taken as approximately the Fermi momentum of the deuteron. This predicted that d/p^2 as a function of multiplicity (not d/p) was expected to be constant. Jennings et al.[13] have shown the practical equivalence of the coalescence and thermal models: if one introduces into the coalescence model the volume of the deuteron in configuration space and sums over the number of particles, this produces a term proportional to the volume of the participants as in the thermal model. Recently, Sato and Yazaki[14] have formulated a model taking into account both the size of the deuteron and the volume of the participants. The coalescence radius p_o in momentum space is related to the deuteron radius r_d and to that of the participant volume r_p via

$$\frac{d_{like}}{p^2_{like}} = \frac{4\pi}{3} p_o^3 \propto \frac{1}{(r_d^2+r_p^2)^{3/2}} \quad .$$

The deuteron radius r_d is an average over the clusters used in the definition of d_{like}. For high energy p-nucleus collisions Nakai, et al.[15] found that r_p was independent of the target mass. However, we relate r_p, the radius of the participant volume, to the observed charges by

$$r_p = r_o\ (2\ p_{like})^{1/3}$$

with r_o a free parameter (since the participants are most probably not in a compact sphere). For the d_{like} to p_{like} ratio one finds

$$\frac{d_{like}}{p_{like}} \propto \frac{p_{like}}{(r_d^2+r_o^2(2p_{like})^{2/3})^{3/2}} \quad .$$

Figure 3 shows the ratio d_{like}/p_{like} as a function of p_{like}. The solid line is a fit to the data drawn with $r_d/r_o = 2.6$. By neglecting one or the other of the terms in the denominator one can obtain both limiting behaviors described above. If the volume of the deuteron were neglected the line would be horizontal; on the other hand, if the volume of the participants were neglected, the line would be linear through the origin. Therefore, to extract valuable information on entropy one has to know the variation of the cluster ratio with multiplicity and use the above equation to extrapolate to high multiplicities. Entropy values from single particle inclusive data are of little value because they integrate over all impact parameters.

Figures 1d,e,f and 2c,d show the ratio of d/p and of d_{like}/p_{like} in each event as a contour plot. Each plot contains approximately 140 000 events.

Focusing on the central trigger data (Figs. 1f and 2d), one observes a depletion of low multiplicity events as expected. A comparison of the contours in d/p versus those in d_{like}/p_{like} shows a narrower distribution for d_{like}/p_{like}, supporting the choice of these variables in the analysis. The largest ratios are almost as large as those that would be calculated by Bertsch and Cugnon[5] for zero impact parameter collisions, but it must be remembered that the 40 MeV/u cutoff has not been put in the theoretical calculation. However, these authors predict a decrease in entropy with decreasing impact parameter, which in turn would predict an increase in cluster production with increasing multiplicity, as observed in our data. In ref. 5 this increase of entropy is explained by the smearing of the participant volume by the mean free path of the nucleons, which may be equivalent to including the finite size of the deuteron. In fact, Biró et al.[7] found they had to include the volume of the deuteron in their thermal model.

In summary we have shown through the available 4π detector data the variation of the ratio of d_{like}/p_{like} particles as a function of multiplicity. This can be explained[14] by simple phase space considerations taking both the size of the deuteron cluster and the participant volume into account, which qualitatively supports a saturation for high multiplicities. These findings should explain the target-projectile mass dependence of d/p values[16], but shed serious doubts on previous entropy discussions based on single particle inclusive data (with averaging over many impact parameters) where the dependence on the relative sizes of the cluster and participant volumes cannot easily be judged. It will be interesting to see whether the ratio r_d/r_o remains constant for different target-projectile combinations. The variation with bombarding energy may yield information about compression.

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Figure Captions

Fig. 1. a,b,c

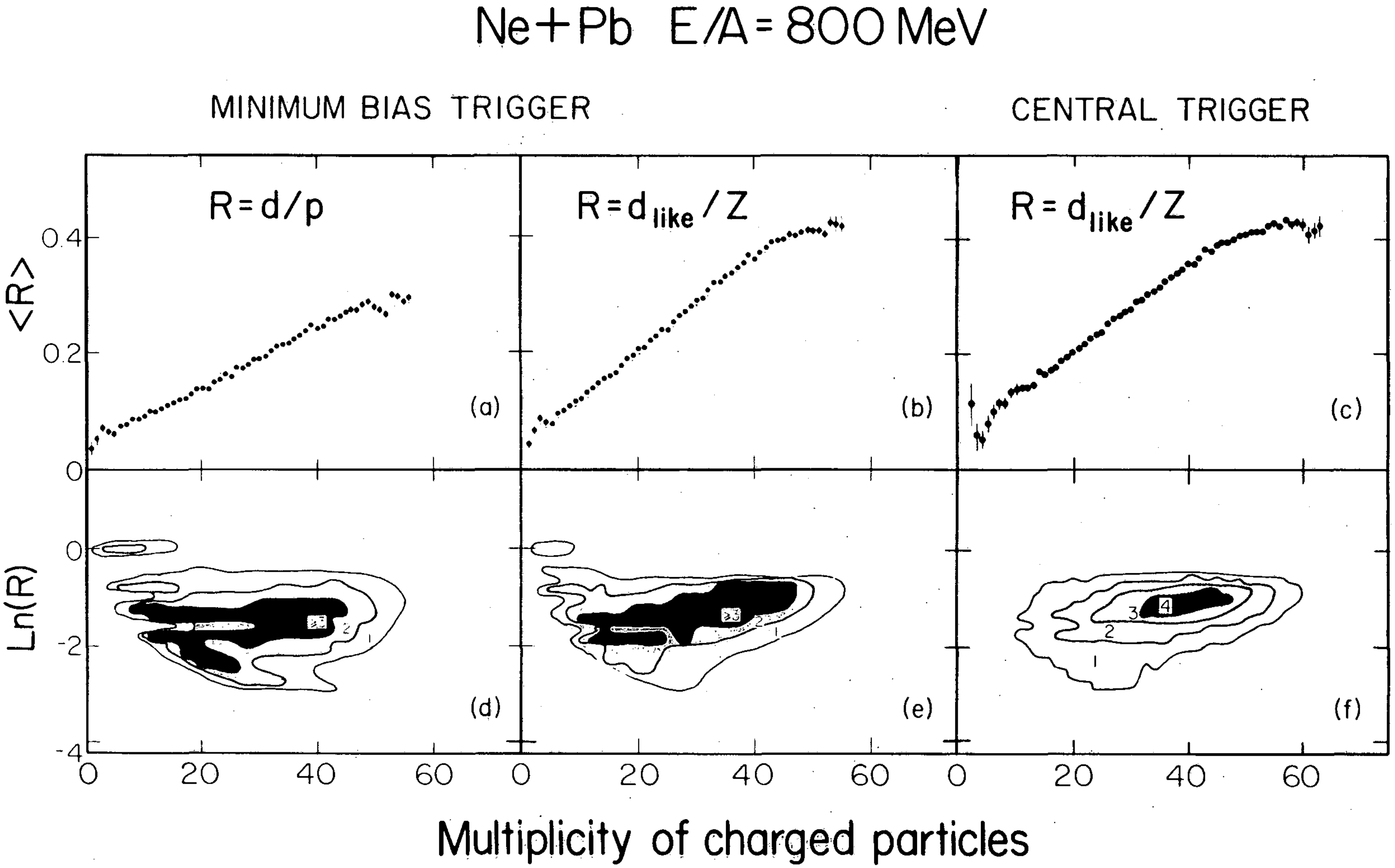
Ratio of deuteron to proton production (a) and ratio of deuteron-like to proton-like particles with two different trigger conditions (b,c) as a function of the total observed charged particle multiplicity for the reaction 800 MeV/nucleon Ne + Pb.

d,e,f

Corresponding event-by-event contour plots of the logarithm of the ratio versus charged particle multiplicity. Relative intensities are indicated by the contour lines.

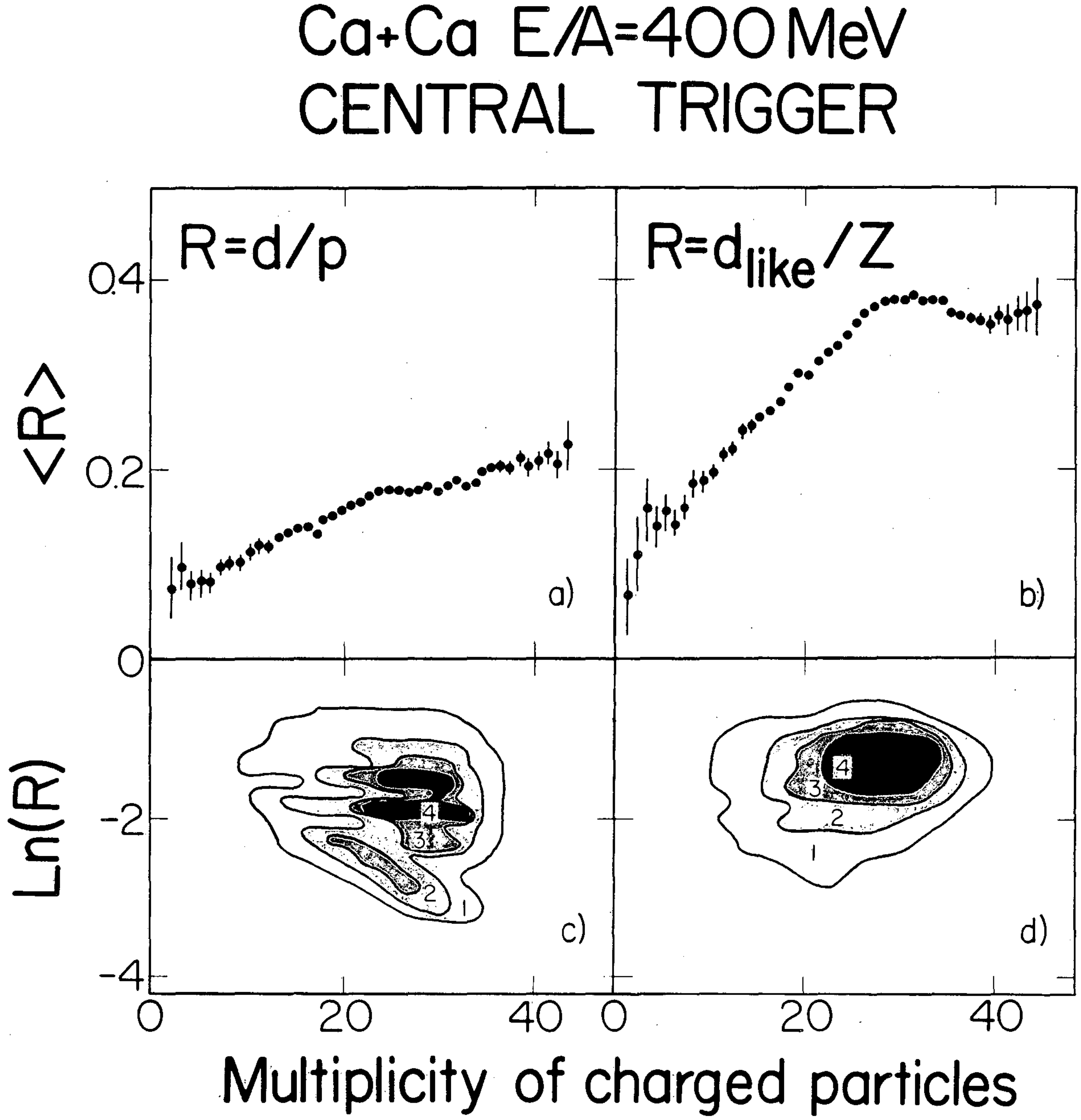
Fig. 2. Same as Fig. 1 but for the reaction 400 MeV/nucleon Ca + Ca.

Fig. 3. Ratio of the number of deuteron-like to proton-like particles as a function of the number of proton-like particles. The solid curve represents a fit to the data.



XBL 826-1438

Fig. 1



XBL 826-1433

Fig. 2

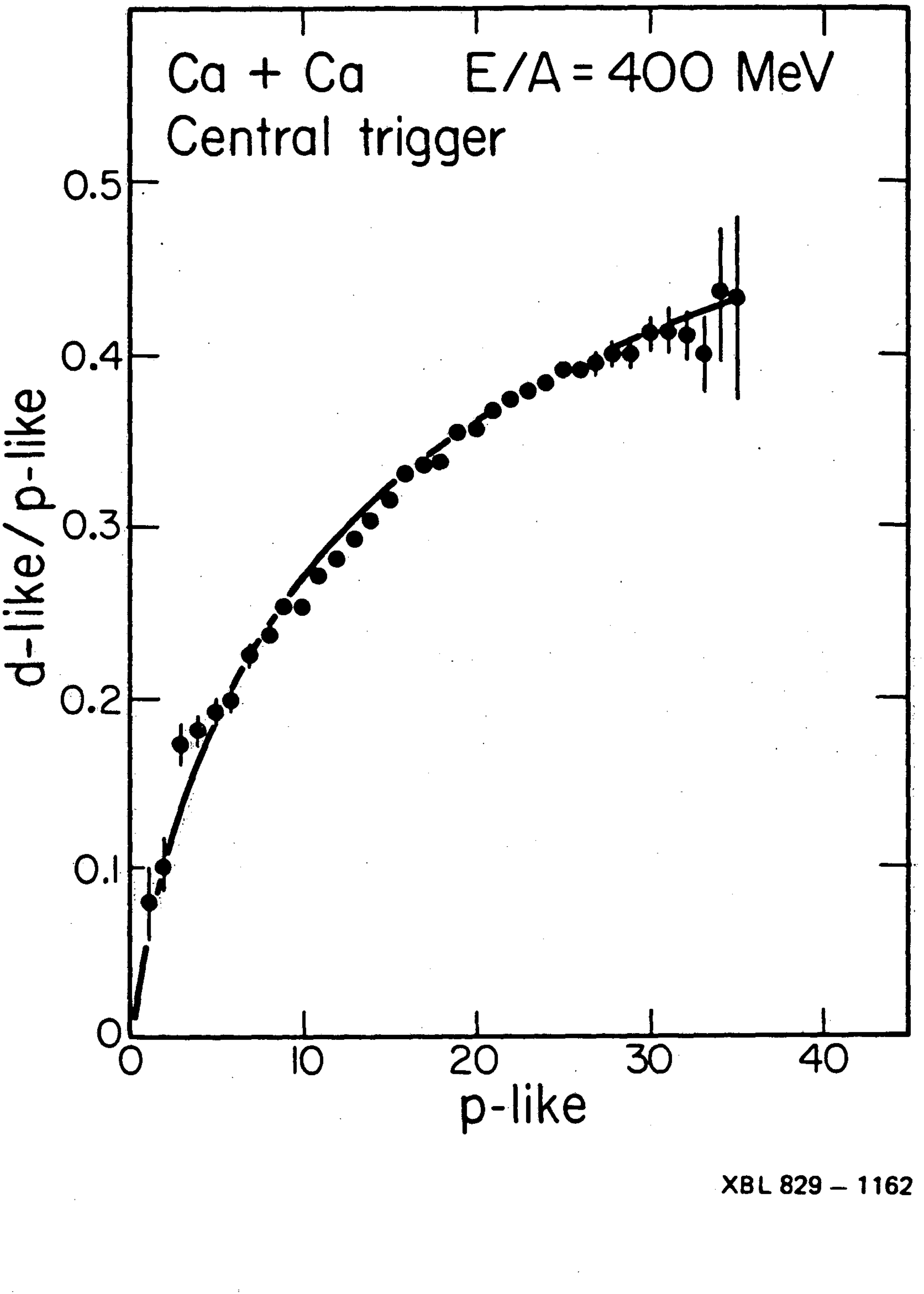

Ca + Ca E/A = 400 MeV
Central trigger
d-like/p-like
p-like
0
0.1
0.2
0.3
0.4
0.5
0
10
20
30
40
XBL 829 - 1162

Fig. 3

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