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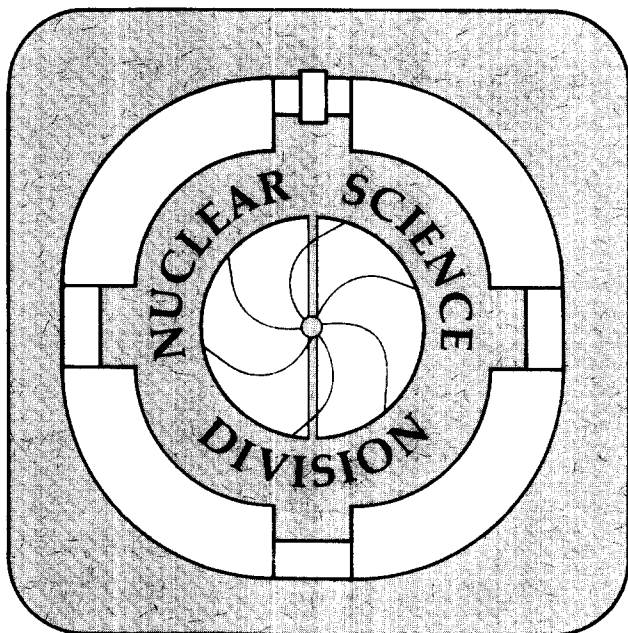
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## Evidence for the Reducibility of Multifragment Emission to an Elementary Binary Emission In Xe-Induced Reactions

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**Abstract:** Multifragmentation for  $^{129}\text{Xe}$ -induced reactions on several targets ( $\text{natCu}$ ,  $^{89}\text{Y}$ ,  $^{165}\text{Ho}$ ,  $^{197}\text{Au}$ ) has been studied at  $E/A = 40, 50$  and  $60$  MeV. The probability of emitting  $n$  intermediate mass fragments is shown to be binomial at each transversal energy and reducible to an elementary binary probability  $p$ . For each target and at each bombarding energy,  $p$  shows a thermal behavior as demonstrated by linear Arrhenius plots. A nearly universal linear Arrhenius plot is observed at each bombarding energy, independent of target.

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In the last several years, experimental studies have succeeded in isolating and characterizing what appear to be true multifragmentation sources formed in reverse kinematics intermediate energy heavy-ion reactions[1-3]. In these experiments, the excitation energy of the source  $E^*$ , was estimated kinematically from the parallel source velocity assuming an incomplete fusion picture[4-6]. The relative probabilities for detecting  $n$  intermediate mass fragments (IMFs,  $3 \leq Z \leq 20$ ) were obtained as a function of the excitation energy  $E^*$ . These excitation functions were found to be independent of the specific target and even of the bombarding energy. This decoupling between entrance and exit channel is a necessary condition for statistical decay. In one analysis[3], a linear dependence was observed for the natural logarithms of the branching ratios of  $n$ -body decay as a function of  $E^{*-1/2}$  (Arrhenius plots). Since nuclear temperature is proportional to  $E^{*1/2}$  in the Fermi gas model, this linear dependence indicated a statistical energy dependence of the  $n$  IMFs emission probabilities.

For the reactions  $^{36}\text{Ar} + ^{197}\text{Au}$  at bombarding energies of  $E/A = 80$  and  $110$  MeV[7, 8], it has been observed recently that, at any given transversal energy, the probabilities of emitting  $n$  IMFs are binomially distributed[9], and that it is possible to extract an elementary one-fragment emission probability  $p$  according to the binomial distribution:

$$P_n^m = \frac{m!}{n!(m-n)!} p^n (1-p)^{m-n}. \quad (1)$$

In a sequential decay interpretation, the parameter  $m$  represents the number of chances the system has to emit an inert fragment with fixed binary decay probability  $p$ . These elementary probabilities were extracted and shown to have a thermal dependence of the type  $p = e^{-B/T}$  as demonstrated by their linear Arrhenius plots[9]. The parameter  $B$  is the barrier associated with a given decay channel under consideration, and  $T$  is the temperature of the emitting system.

The above observation that multifragmentation is reducible to single-fragment emission is striking and leads us to explore whether this reducibility occurs in other intermediate energy

heavy-ion reactions. In this letter, we search for evidence of the reducibility of the  $n$  IMFs emission probability  $P_n$  to an elementary binary decay probability  $p$  in the  $^{129}\text{Xe}$ -induced reactions described below.

The experiment was performed at the K1200 Cyclotron of the National Superconducting Laboratory at Michigan State University.  $^{129}\text{Xe}$  beams of  $E/A = 40, 50$  and  $60$  MeV were used to bombard several targets ( $^{\text{nat}}\text{Cu}$ ,  $^{89}\text{Y}$ ,  $^{165}\text{Ho}$ ,  $^{197}\text{Au}$ ). Reaction products ( $Z = 1 - 54$ ) were detected with a multidetector system consisting of the MSU Miniball phoswich array[10] and the LBL forward array[11]. The combined detector system covered a large fraction of the available solid angle (89% of  $4\pi$ ). The Miniball (171 phoswich detectors) was used to identify charged particles with  $Z = 1 - 20$  emitted between  $16^\circ$  and  $160^\circ$  with respect to the beam axis. At forward angles, from  $2^\circ$  to  $16^\circ$ , charged particles with  $Z = 1 - 54$  were detected by the 16 Si-Si-Plastic telescopes of the LBL array. Representative detection thresholds for the Miniball and the LBL array were  $E/A = 2, 3, 4$  MeV for  $Z = 3, 10, 18$  and  $E/A = 6, 13, 21, 27$  MeV for  $Z = 2, 8, 20, 54$ , respectively.

In order to extract  $p$  experimentally, we need to know the excitation energy of the event, or at least a quantity proportional to it. Following reference [9], we assume the transversal energy ( $E_t = \sum E_i \sin^2 \theta_i$ , where  $E_i$  and  $\theta_i$  are the kinetic energy and the laboratory angle of each fragment respectively) to be proportional to the excitation energy. More specifically, we assume  $E_t = K(E_{\text{beam}}, A_P, A_T)E^*$ , where  $E^*$  is the excitation energy of the source and  $K$  is the proportionality constant that depends on the bombarding energy  $E_{\text{beam}}$ , the mass of the projectile  $A_P$  and the mass of the target  $A_T$ .

Since we do not have an ideal detector, we need to estimate the effect of the detection efficiency  $\epsilon$ , on the extracted values of  $p$ . The observed binary decay probability  $p_{\text{obs}}$  is the product of the true decay probability  $p_{\text{true}}$  and the detection efficiency  $\epsilon$ . We have considered only the geometric efficiency and neglected effects due to energy thresholds, multiple hits, etc. in

our estimation of  $\varepsilon$ . Since the resulting  $\varepsilon$  is approximately constant for our device, the observed excitation function will still be well described by a binomial distribution (with  $p$  replaced by  $p_{obs}$ ).

For  $^{129}\text{Xe}$ -induced reactions on  $^{nat}\text{Cu}$ ,  $^{89}\text{Y}$ ,  $^{165}\text{Ho}$ , and  $^{197}\text{Au}$  targets at bombarding energies of  $E/A = 40, 50$  and  $60$  MeV, we have measured the probability  $P_n$  of emitting  $n$  IMFs as a function of the transversal energy  $E_t$ .  $P_n$  is defined as:

$$P_n = \frac{N(n)}{\sum N(n)}, \quad (2)$$

where  $N(n)$  is the number of events with  $n$  IMFs. To compare with the results of the  $^{36}\text{Ar} + ^{197}\text{Au}$  reactions[9], we first study the reactions of  $^{129}\text{Xe} + ^{197}\text{Au}$  at three bombarding energies. The excitation functions  $P_n$  are plotted in Fig. 1b for  $n=0$  to  $n=9$ , together with the solid lines generated from the binomial distribution in Eq. 1. The input values  $p$  and  $m$  in Eq. 1 are extracted from the mean  $\langle n \rangle$  and the variance  $\sigma^2$  of the IMF multiplicity distributions using the binomial relations:  $\langle n \rangle = mp$ , and  $\sigma_n^2 = \langle n \rangle (1 - p)$ . Excellent agreement between the experimental  $n$  IMFs emission probabilities (symbols) and the binomial calculations (curves) for the entire  $E_t$  range is observed for values of  $n$  up to 9 at all three bombarding energies. This remarkable agreement means that the probability  $P_n$  is indeed binomial and can be reduced to an elementary binary probability  $p$ .

To investigate the temperature dependence of the elementary probability,  $1/p$  is plotted (using a log scale) as a function of  $E_t^{-1/2}$  in Fig. 1a for the  $^{129}\text{Xe} + ^{197}\text{Au}$  reactions. A linear dependence is observed for all three bombarding energies similar to the pattern observed previously in  $^{36}\text{Ar} + ^{197}\text{Au}$  reactions at  $E/A = 80$  &  $110$  MeV[9]. The solid lines are linear fits to the data. The linearity of these plots clearly illustrates the "thermal" nature of  $p$  over the measured  $E_t$  range.

We can also extract  $p$  "differentially" from the ratio of any pair of excitation functions  $P_n/P_{n+1}$  as given below:

$$\frac{1}{p} = \frac{P_n^m}{P_{n+1}^m} \frac{m-n}{n+1} + 1. \quad (3)$$

The values of  $p$  obtained "differentially" using Eq. 3 can be compared with those calculated "integrally" from the mean and the variance of the IMF multiplicity. Fig. 2 shows that the differentially determined values of  $p$  up to  $n=4$  collapse onto the straight lines from Fig. 1a for all three bombarding energies. The observed consistency between the two different methods of extracting  $p$  confirms the binomial nature of  $P_n$  and the thermal dependence of  $p$ . For  $n > 4$  (data not shown), good agreement is observed at large transversal energy ( $E_t > 400$  MeV) although scattering about the fitted line occurs at small transversal energy due to poor statistics.

At this point we consider the reactions with lighter targets. Fig. 3 shows the excitation functions for  $^{129}\text{Xe}$ -induced reactions on  $^{\text{nat}}\text{Cu}$ ,  $^{89}\text{Y}$ , and  $^{165}\text{Ho}$  targets at  $E/A = 40$  MeV. These excitation functions have been truncated at a chosen upper limit of  $E_t$  to exclude 0.1% of the total integrated yield at the tail of the  $E_t$  distribution. The increase in the upper limit of  $E_t$  from 600 MeV ( $^{\text{nat}}\text{Cu}$ ) to 960 MeV ( $^{165}\text{Ho}$ ) is consistent with the increase of the available energy in the center of mass frame from 1700 MeV ( $^{\text{nat}}\text{Cu}$ ) to 2900 MeV ( $^{165}\text{Ho}$ ) under the assumption that  $E_t$  is proportional to excitation energy.

Interestingly, the excitation functions are almost identical for all three targets over the entire range of the transversal energy. This prompts one to compare the extracted values of  $p$  and  $m$ . A most remarkable result is that the Arrhenius plots for different targets collapse onto a nearly universal line, and the binomial parameter  $m$  is also independent of the target mass as shown in Fig. 4. Target independence was also observed by others in the excitation functions for emission of  $n$  IMFs[1, 3] and in the dependence of the average IMF multiplicity on the total charged particle multiplicity[12]. We observe a similar independence when the average IMF multiplicity is plotted as a function of  $E_t$ .

For  $^{\text{nat}}\text{Cu}$  and  $^{89}\text{Y}$ , the target mass is smaller than that of the  $^{129}\text{Xe}$  projectile, and the observed target independence is consistent with the picture of incomplete fusion[5, 6]. In this

picture, the source for multifragmentation is the incomplete fusion product formed when the heavier  $^{129}\text{Xe}$  projectile picks up various amounts of mass from any lighter target. In other words, this source can be characterized mainly by the amount of mass transfer, and the reactions depend relatively little on the actual nature of the target. For the heavier  $^{165}\text{Ho}$  and  $^{197}\text{Au}$  targets, the observed target independence seems to imply a similar mass transfer to the  $^{129}\text{Xe}$  projectile. This picture is contrary to the conventional incomplete fusion mechanism and remains an unresolved puzzle.

The extracted values of  $p$  and  $m$  in Fig. 4 are used to generate the curves shown in Fig. 3. The excellent agreement between the data and binomial calculations for the IMF distribution demonstrates the binomial nature of  $P_n$  and its reducibility to  $p$  independent of the specific target. In addition,  $^{129}\text{Xe}$ -induced reactions at the two higher bombarding energies ( $E/A = 50$  and  $60$  MeV) show a similar target independence.

In conclusion, we have studied the production of intermediate mass fragments for  $^{129}\text{Xe}$ -induced reactions on  $^{\text{nat}}\text{Cu}$ ,  $^{89}\text{Y}$ ,  $^{165}\text{Ho}$ , and  $^{197}\text{Au}$  targets at  $E/A = 40, 50$  and  $60$  MeV. The IMF multiplicity distributions as a function of the transversal energy are well described by a binomial distribution characterized by a single binary event probability  $p$ . The thermal nature of  $p$  and its target independence are illustrated by the nearly universal linear Arrhenius plot observed at a given bombarding energy. These results demonstrate that the reducibility of  $n$  IMFs emission probability to  $p$  is wide-spread in intermediate energy heavy-ion reactions, implying that multifragmentation is empirically reducible to single-fragment emission. At higher excitation energies, the probability for light charged particle emission should increase dramatically and one should observe a decrease in the IMF emission probability. It would be interesting to investigate heavy-ion reactions at higher bombarding energies to verify whether reducibility and the thermal nature of  $p$  are also observed in these reactions.



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## Figure Captions

Fig. 1 For the  $^{129}\text{Xe} + ^{197}\text{Au}$  reactions: a) (left column) the reciprocal of the binary decay probability  $1/p$  as a function of  $E_t^{-1/2}$ ; and b) (right column) the parameter  $m$  and the probability  $P(n)$  for emitting  $n$  IMFs ( $3 \leq Z \leq 20$ ) as a function of the transversal energy  $E_t$ . The three rows correspond to different bombarding energies:  $E/A = 40$  MeV (upper);  $E/A = 50$  MeV (middle); and  $E/A = 60$  MeV (lower).

Fig. 2 For the reaction  $^{129}\text{Xe} + ^{197}\text{Au}$ , the binary decay probability  $p$  extracted "differentially" using Eq. 3 in the text is shown as a function of  $E_t^{-1/2}$ . The solid lines are linear fits to  $\log(1/p)$ , which is calculated from the mean and variance of the IMF distributions. The different symbols represent the probabilities  $p$  extracted "differentially" for the indicated values of  $n$ . The three columns correspond to different bombarding energies:  $E/A = 40$  MeV (left);  $E/A = 50$  MeV (middle); and  $E/A = 60$  MeV (right).

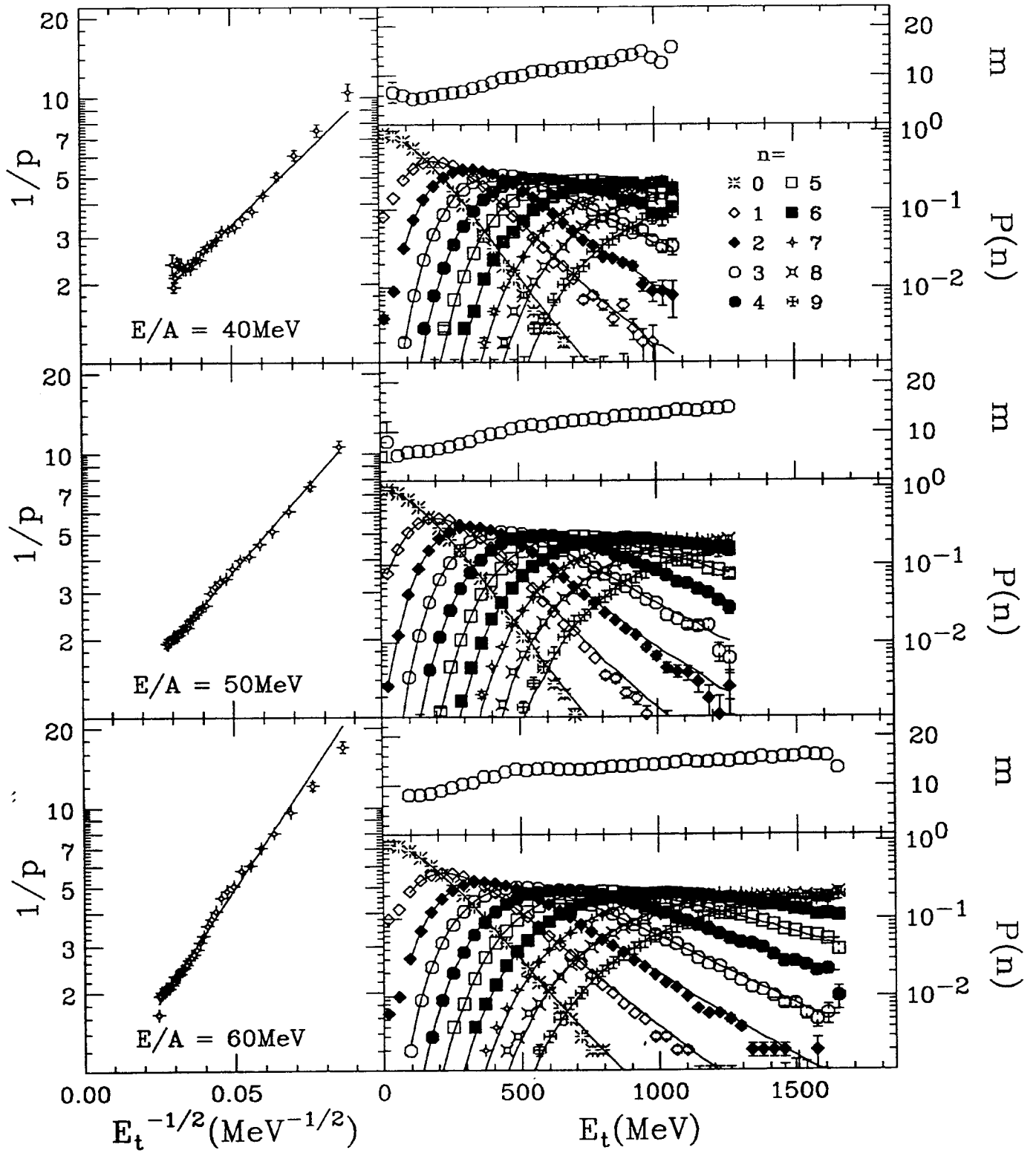
Fig. 3 The experimental probability (symbols), and the calculated probability (lines) to emit  $n$  IMFs as a function of  $E_t$  for  $^{129}\text{Xe}$ -induced reactions ( $E/A = 40$  MeV) on different targets:  $^{\text{nat}}\text{Cu}$  (lower panel),  $^{89}\text{Y}$  (middle panel) and  $^{165}\text{Ho}$  (upper panel). For number of fragments  $n = 0-10$ ,  $P(n)$  is calculated assuming a binomial distribution using values of  $m$  and  $p$  from Fig. 4.

Fig. 4 The binomial parameter  $m$  (top panel) and the reciprocal of the binary decay probability  $1/p$  (bottom panel) as a function of  $E_t^{-1/2}$  for  $^{129}\text{Xe}$ -induced reactions on different targets ( $^{\text{nat}}\text{Cu}$ ,  $^{89}\text{Y}$ ,  $^{165}\text{Ho}$ ,  $^{197}\text{Au}$ ) at  $E/A = 40$  MeV. The line is linear fit to the data.

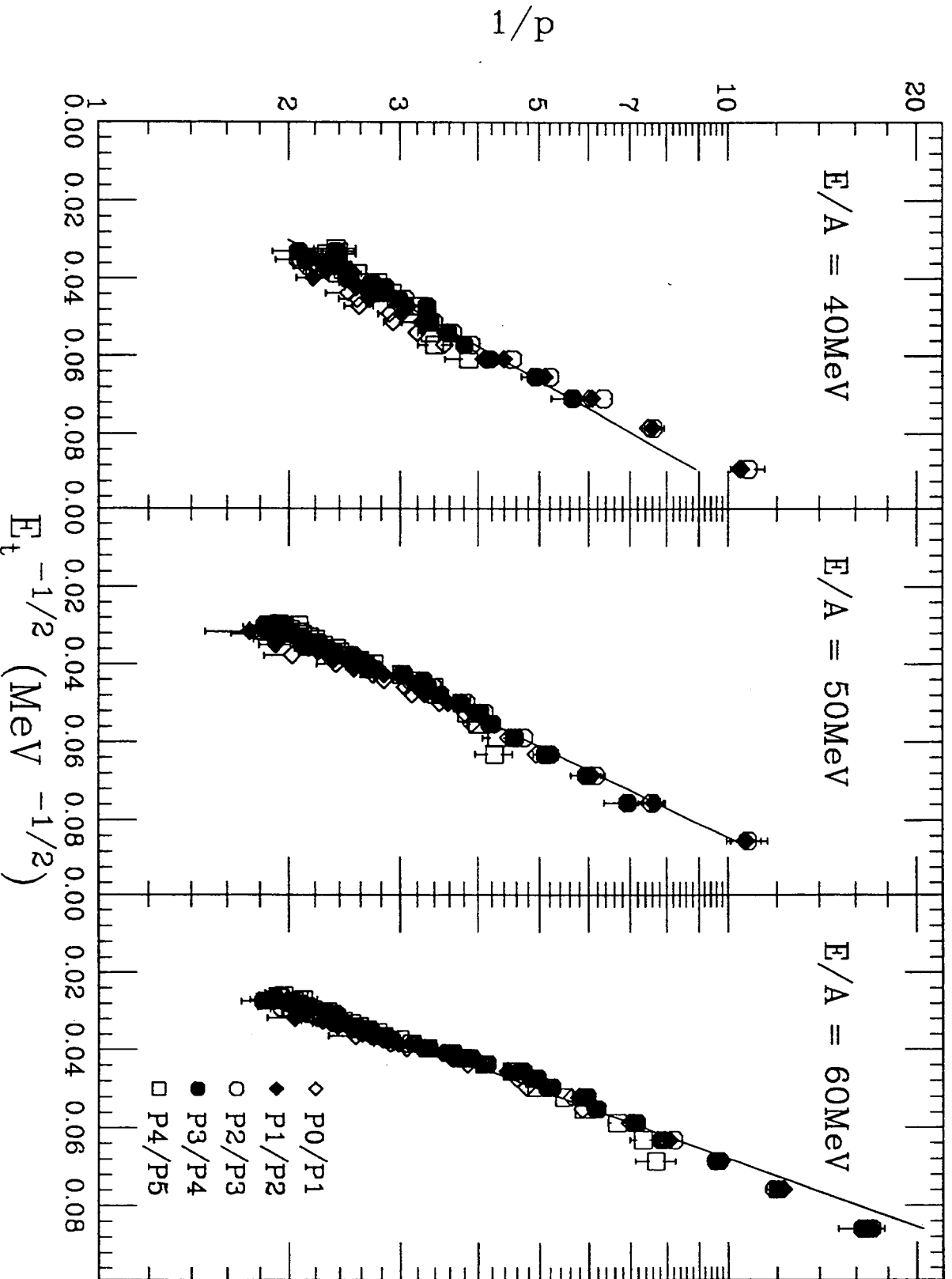
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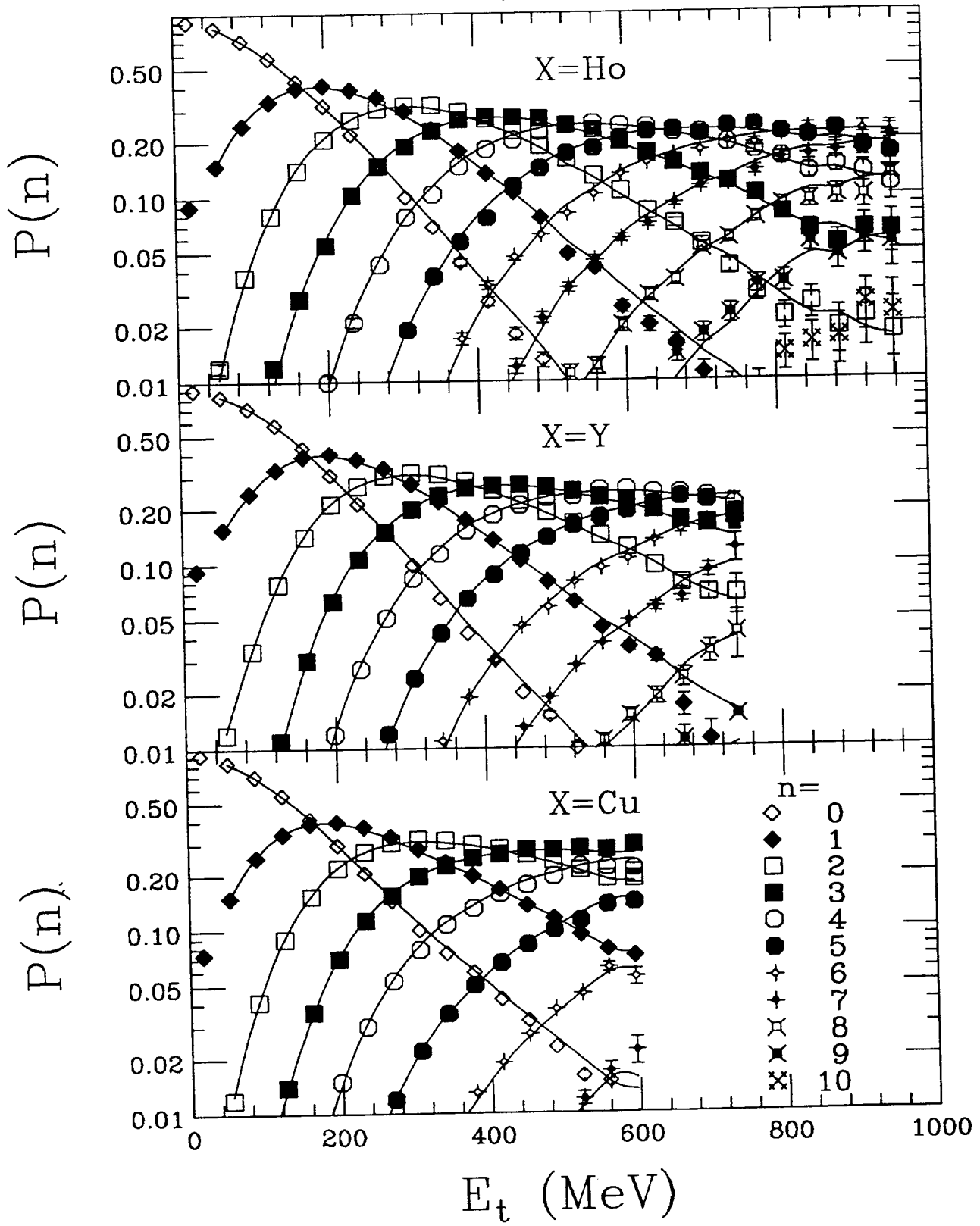
$^{129}\text{Xe} + ^{197}\text{Au}$



$^{129}\text{Xe} + ^{197}\text{Au}$



$^{129}\text{Xe} + X \quad (E/A = 40\text{MeV})$



$^{129}\text{Xe} + X$  ( $E/A = 40\text{MeV}$ )

