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Abstract

Two particle azimuthal correlations have been used to extract reaction plane dispersion free triple differential cross sections for d, t, and α particles for the mid-central collisions of $^{84}Kr+^{197}Au$ at E/A=35, 55 and 70 MeV. Both experimental measurements and extrapolations from lower incident energies

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suggest that rotational flow disappears at E/A≈100 MeV for light charged particles and that reaction plane dispersions introduce large uncertainties in extracting the disappearance of rotational flow.

Ideally, a complete description of the dynamics of heavy ion reaction can be achieved through measurements of invariant triple differential cross sections[1-9]. In reality, the experimentally extracted reaction planes suffer from significant uncertainties due to dispersion of the particles used in the reaction plane reconstruction. Despite intense effort, few measurements of triple differential cross sections free of reaction plane dispersions exist[8]. Recently, a new method has been proposed to extract single particle triple differential azimuthal distributions from two particles azimuthal correlation functions[10]. In this brief report, this method is applied to the $^{84}Kr +^{197} Au$ reactions.

Measurements with ^{84}Kr ions at beam energies of E/A=35, 55, and 70 MeV were performed with beams from the K1200 cyclotron of the National Superconducting Cyclotron Laboratory of Michigan State University ($NSCL/MSU$). Measurements at E/A=100 MeV were performed at the Laboratoire National SATURN at Saclay. The emitted charged particles were detected with the combined MSU Miniball[11]/Washington University Miniwall 4π phoswich detector array. Unit charge resolution up to Z=10 was routinely achieved for particles that transversed the fast plastic scintillator. Details of the experiments can be found in reference [12].

The triple differential distributions[6,8] depend strongly on impact parameters. Following refs. [12], we assumed that the charged particle multiplicity N_c detected in Miniball array depends monotonically upon the impact parameter

$$\hat{b} = \frac{b}{b_{\max}} = \left[\int_{N_C(b)}^{\infty} dN_C \cdot P\left(N_C\right)\right]^{1/2} \tag{1}$$

Here, $P(N_c)$ is the probability distribution for the charged particle which exhibit a rather structureless plateau and a near-exponential falloff at the highest multiplicities. The reduced impact parameter, $b/b_{\max}$, assumes values of 1 ($N_c = 4$) for the most peripheral collisions and 0 for the most central collisions. In the present work, a mid central gate of $0.3 < b/b_{\max} < 0.7$ is applied. This gate was chosen as a compromise to keep enough statistics to construct two particle correlation functions and to have reasonable anisotropy to study rotational flow which vanishes at $b = 0$. To minimize the effect of transverse flow, a rapidity gate of

$-0.5 < y/y_{cm} < 0.5$ is also applied to the data where y is the rapidity of the emitted particle and y_{cm} is the center-of-mass rapidity of the system.

To avoid the complexicities in determining the reaction planes, two particle correlations have been used to extract the energy where sideward or rotational flow disappears[13]. The azimuthal correlation function is defined as

$$C(\Delta\phi) = \frac{N_{corr}(\Delta\phi)}{N_{uncorr}(\Delta\phi)} \tag{2}$$

where $\Delta\phi$ is the relative azimuthal angle between the two particles; $N_{corr}(\Delta\phi)$ and $N_{uncorr}(\Delta\phi)$ are the distribution of the coincident fragment pairs and uncorrelated fragment pairs from different events, respectively. Figure 1 shows the $\alpha - \alpha$ correlation functions for $^{84}Kr +^{197} Au$ at E/A=35, 55, 70 and 100 MeV. At low energy where the mean field interaction dominates, charged particles are emitted mainly in the reaction plane[5-8], and the correlations exhibit the typical V shape which flattens with increasing incident energies. The slight asymmetries occurring between $\Delta\phi = 0°$ and $\Delta\phi = 180°$ may come from collective flow, Coulomb repulsion as well as recoil. These effects become more dominant with increasing incident energies. At E/A=100 MeV, the correlation function no longer exhibits a minimum at $\Delta\phi = 90°$, but rather shows an enhancement at $\Delta\phi = 180°$.

In the past, the correlations have been fit with a Fourier series with the expression [10,13,14]

$$C(\Delta\phi) \propto 1 + \lambda_1 \cos(\Delta\phi) + \lambda_2 \cos(2\Delta\phi) \tag{3}$$

where λ_1 and λ_2 can be treated as fit parameters to the data. The solid lines in Figure 1 show the quality of the fit. In this expression, λ_2 represents the rotational flow in the reaction plane. Table I lists all the fit values of λ_1 and λ_2 for $d-d$, $t-t$, and $\alpha-\alpha$ correlations. The magnitudes of λ_1 are very small (similar values of λ_1 were obtained by applying either the gates $y/y_{cm} < 0$ or $y/y_{cm} > 0$) due to the absence of measurable transverse flow for $Kr + Au$ reactions below E/A=100 MeV[15]. Thus the effect of λ_1 will be neglected in the present study.

The left hand panels of Figure 2 show the incident energy dependence of λ_2 for $d-d$, $t-t$ and $\alpha-\alpha$ azimuthal correlation functions. λ_2 decreases with incident energy and vanishes around E/A=100 MeV. Apriori, one does not know the exact functional dependence of λ_2 on the incident energy. The data points seem to deviate from a simple linear function as shown by the dashed lines which are the least square fits to the data[16].

If the two particles used in the azimuthal correlations are emitted independent of each other in the same event, the correlation function, $C(\Delta\phi)$, can be described by the convolution of single particle azimuthal distributions, $P(\phi)$[7, 8]

$$C(\Delta\phi) = \int_0^{2\pi} P(\phi)P(\phi+\Delta\phi)d\phi \tag{4}$$

Empirically, the single particle distribution $P(\phi)$ can be described by a function similar to Equation 3[9,10],

$$P(\phi) \propto 1 + a_1\cos(\phi) + a_2\cos(2\phi) \tag{5}$$

Combining Eq. 3, 4, and 5, one obtains a relationship between a_i and λ_i.

$$a_i = \sqrt{}(2\lambda_i) \tag{6}$$

In the right panel of Figure 2, a_2^{true} from equation 6 are plotted as solid points. The data points at 100 MeV where the values of λ_2 are very small, have not been included since Coulomb forces between two alpha particles will always force λ_2 to be slightly positive even if the distribution is isotopic. If linear fits are applied to the extracted values of a_2^{true} (solid lines) for incident energies of E/A=35, 55 and 70 MeV, $E(a_2^{true}=0))$ are 98±5 MeV, 106±5 MeV and 96 ± 4 MeV for d, t and α particles respectively.

From Eqs. 5 and 6, one can construct the triple differential cross-sections from the experimentally measured two-particle azimuthal correlation functions. The solid lines in Figure 3 shows the "true" single particle azimuthal distributions $P(\phi) \propto 1+\sqrt{}(2\lambda_2)\cos(2\phi)$ for d, t and α particles at E/A=35, 55 and 70 MeV. The distributions are normalized to 1 at $\phi = 0°$. For comparison, the experimental azimuthal distributions (open points) were obtained using the reaction planes constructed by the momentum tensor method described in ref. [8]. The same impact parameter and rapidity gates used in the two-particle correlation functions have been applied to these data. Data at E/A=100 MeV are not shown here due to problems associated with extracting the reaction planes at this energy. Study of $Au + Au$ reactions suggests that squeezeout effects from repulsive nucleon-nucleon interactions start to dominate around E/A=100 MeV and the reaction planes determined from the momentum tensor method are not correct[17]. A detailed description of squeeze out effects at high incident energy is beyond the scope of this short report.

At low energies, the experimental azimuthal distributions show a fairly small anisotropy while the true azimuthal distributions are relatively sharp. The difference between experimental (open circles) and true azimuthal distributions (solid lines) shown in Figure 3 are so large that the reaction plane dispersions can not be neglected. To quantify the reaction plane dispersions, the dashed lines are the fits of Eq. 5 to the data. The fit values of a_2^{expt} for d, t, and α particles are plotted as open points in the right panel of Figure 2. If the experimental determined reaction planes are close to the true reaction planes as in the case of low energy fission reactions [18], then $a_2^{expt} \approx a_2^{true}$. However, for the present study, a_2^{true} (solid circles) are much larger than a_2^{expt} . If linear fits are applied to the extracted values of a_2^{expt} (dashed lines), $E(a_2^{expt} = 0)$ are 82 ± 5 MeV, 78 ± 5 MeV and 76 ± 4 MeV for d, t and α particles respectively, about 20 MeV lower than $E(a_2^{true} = 0)$ for light charge particles. Since $E(a_2^{expt} = 0)$ and $E(a_2^{true} = 0)$ should be the same, the 20 MeV discrepancies indicate that the errors associated with the reaction plane dispersions when extracting the energy where rotational flow disappears are large possibly because the linear functional form used to extract $E(a_2^{expt} = 0)$ is wrong.

To quantify the reaction plane dispersions, $< \cos(2\Delta\phi) >$can be defined as:

$$< \cos(2\Delta\phi) >= \frac{a_2^{expt}}{a_2^{true}} \qquad (7)$$

These values are listed in Table II. In general $2\Delta\phi$ is large suggesting that reaction planes are poorly determined from the detected particles. As expected, the dispersion $(2\Delta\phi)$

increases with increasing incident energies.

In summary, we have extracted triple differential cross-sections for d, t and α particles using two particle correlation functions. As these cross-sections are free from reaction plane dispersions, they can be compared directly with transport model calculations such as BUU and QMD. We have also examined the reaction plane dispersion and its effects on extracting the energy where rotational flow disappears. The results suggest that correction for reaction plane dispersions are very important to extract such values from single particle azimuthal distributions.

Acknowledgments

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FIGURES

FIG. 1. Alpha-alpha azimuthal correlations for $^{84}Kr +^{197}Au$ reactions at E/A=35, 55, 70 and 100 MeV. See text for detailed gating conditions.

FIG. 2. Left panels : Coefficients λ_2 of Eq. 3 plotted as a function of incident energies. Right panels: a_2^{expt} (open points) and a_2^{true} (solid circles) as function of incident energy for d, t and α particles.

FIG. 3. Single particle azimuthal distributions: Solid points are the data; dashed lines are fits to data according to Eq. 5 and solid lines are true azimuthal distributions from Eq. 4 and 6.

TABLES

TABLE I. λ_1 and λ_2 from particle - particle correlation in Kr + Au system.

E_{lab}/A		35 MeV	55 MeV	70 MeV	100 MeV
d-d	λ_1	-0.012±0.005	-0.017±0.003	-0.017±0.004	-0.011±0.005
	λ_2	0.025±0.005	0.023±0.002	0.0099±0.003	0.003±0.005
t-t	λ_1	-0.016±0.005	-0.034±0.005	-0.013±0.004	-0.014±0.007
	λ_2	0.065±0.004	0.027±0.003	0.023±0.002	0.011±0.006
α-α	λ_1	-0.018±0.003	-0.012±0.002	-0.017±0.003	-0.030±0.003
	λ_2	0.069±0.003	0.028±0.002	0.018±0.003	0.0045±0.002

TABLE II. Reaction plane dispersion in Kr + Au system

E_{lab}/A		35 MeV	55 MeV	70 MeV
d-d	$< cos(2\Delta\phi) >$	0.21±0.04	0.12±0.04	0.083±0.04
	$2\Delta\phi$	77.7±3	83.2±3	85.3±3
t-t	$< cos(2\Delta\phi) >$	0.19±0.03	0.13±0.04	0.061±0.03
	$2\Delta\phi$	79.7±2	82.4±2	86.5±2
α-α	$< cos(2\Delta\phi) >$	0.19±0.02	0.12±0.03	0.065±0.02
	$2\Delta\phi$	78.9±2	83.3±2	86.3±2

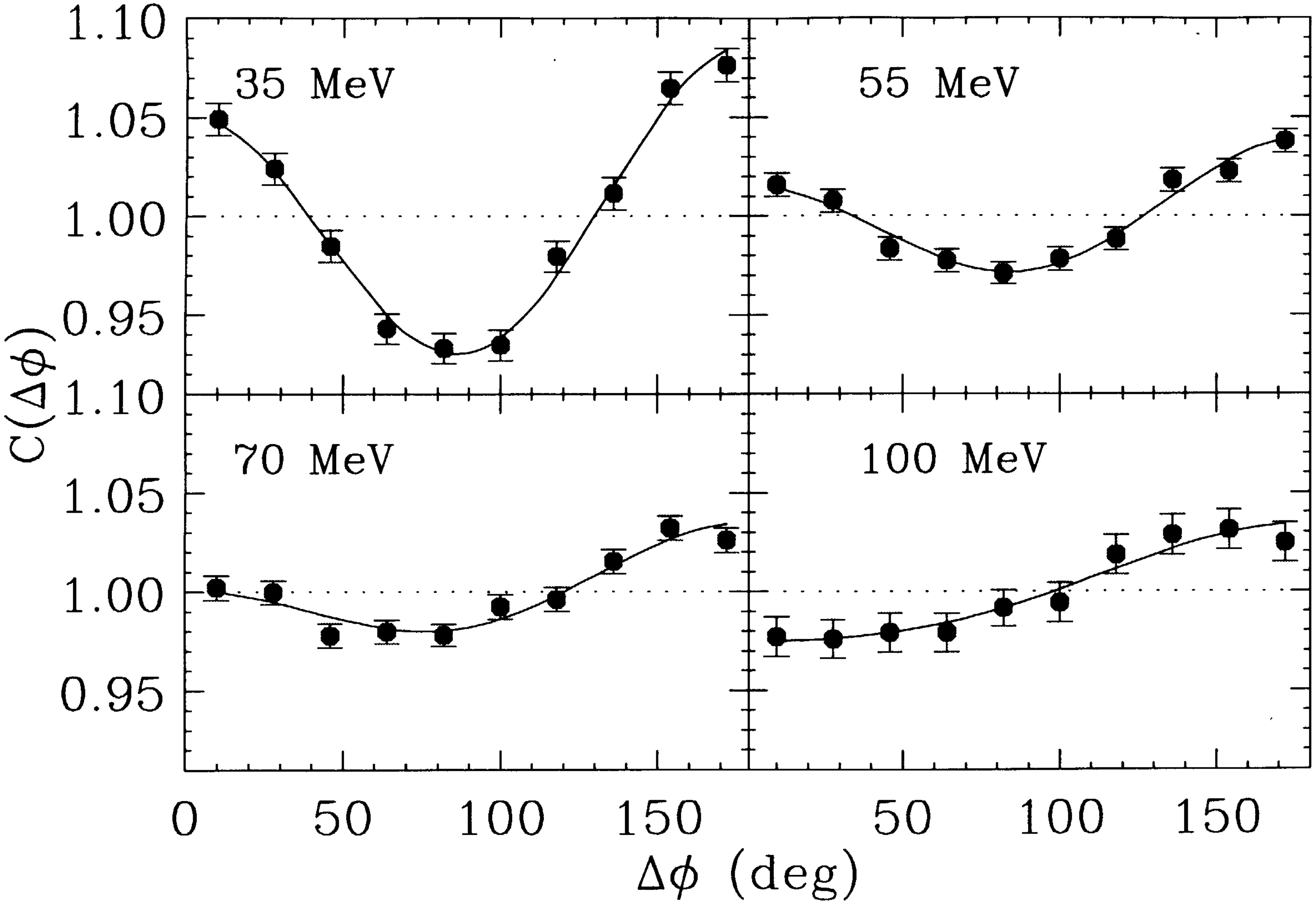
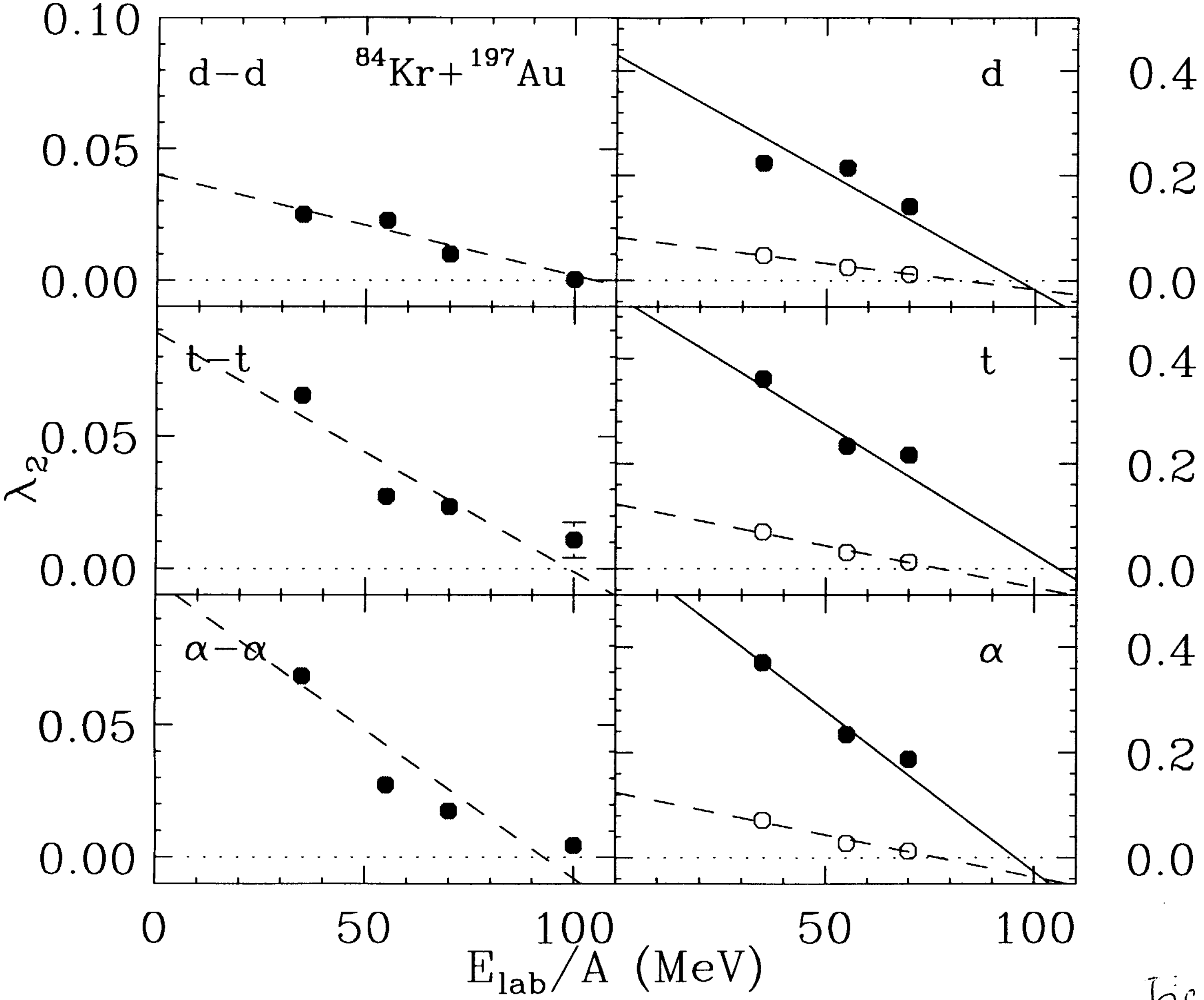

35 MeV
55 MeV
70 MeV
100 MeV
C(Δφ)
1.10
1.05
1.00
0.95
0
50
100
150
Δφ (deg)

Fig 1



d–d
^{84}Kr+^{197}Au
d
t–t
t
α–α
α
λ_2
0.10
0.05
0.00
0.05
0.00
0.05
0.00
0.4
0.2
0.0
0.4
0.2
0.0
0.4
0.2
0.0
0
50
100
50
100
E_{lab}/A (MeV)

fig 2

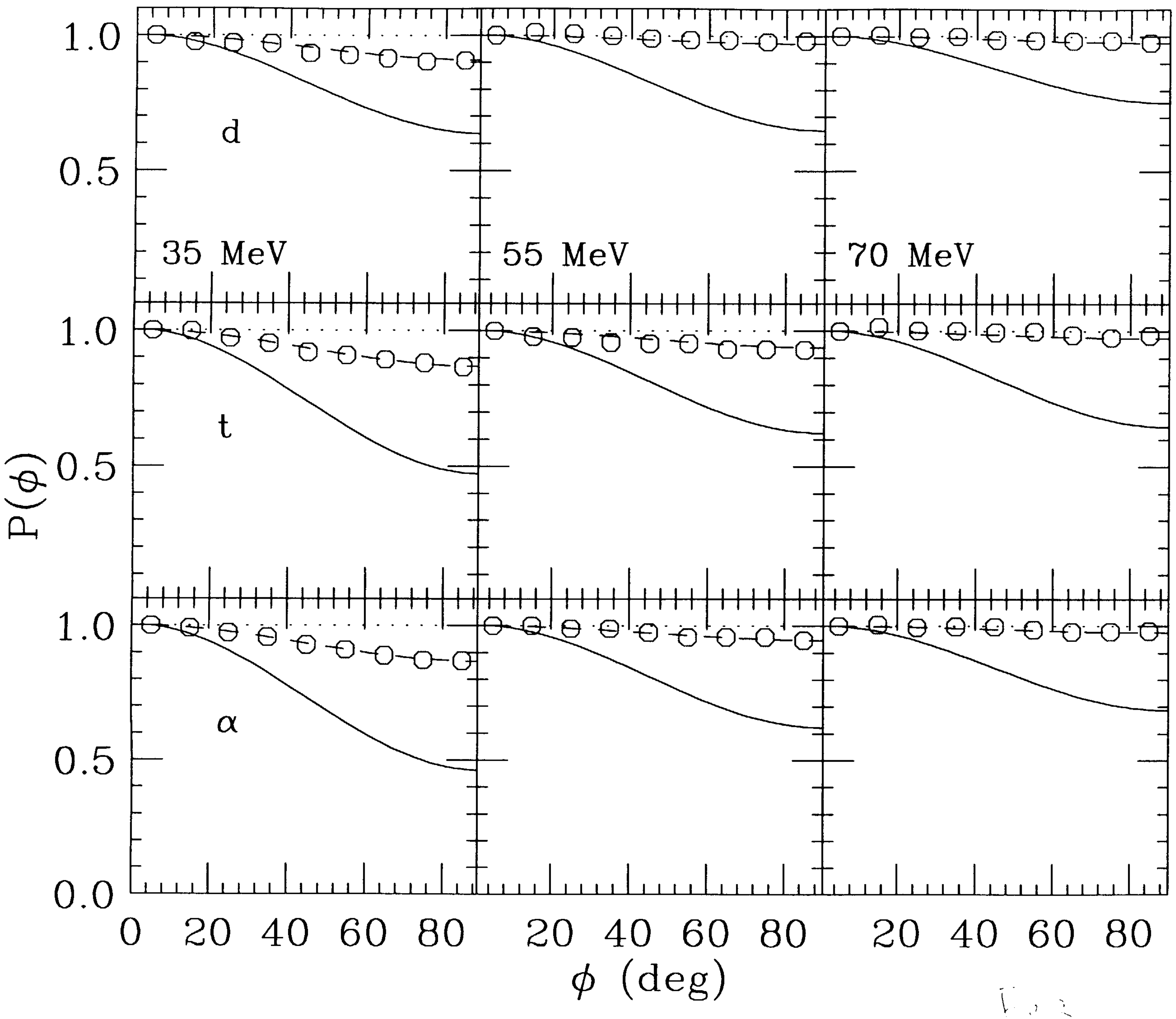


Fig 3