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AZIMUTHAL DISTRIBUTIONS OF FISSION FRAGMENTS AND α-PARTICLES EMITTED IN THE REACTIONS $^{36}Ar + ^{238}U$ AT E/A = 20 AND 35 MeV AND $^{14}N + ^{238}U$ AT E/A = 50 MeV

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Abstract

Azimuthal correlations between coincident fission fragments and a-particles were measured for the reactions $^{36}Ar+^{238}U$ at E/A=20 and 35 MeV and $^{14}N+^{238}U$ at E/A=50 MeV. At all energies, coplanar emission is enhanced. The azimuthal distributions for fission fragments and u-particles are decoupled using a simple parametrization. Both azimuthal distributions are highly anisotropic at lower incident energies: these anisotropies decrease with energy. At the highest incident energies, energetic a-particles emitted at large traverse momenta appear to be more suited to tag the orientation of the entrance channel reaction plane.

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Intermediate energy nucleus-nucleus collisions exhibit a subtle interplay between mean-field and nucleon-nucleon-collision dynamics. At low incident energies, the mean field is largely attractive. As a consequence, light particles are predominantly emitted to negative deflection angles in the entrance channel reaction plane [1-6]. With increasing energy, individual nucleon nucleon collisions are less hindered by the Pauli exclusion principle and the azimuthal distributions of the emitted particles should become more isotropic. A number of measurements [1-6] are in qualitative agreement with such expectations. To be more quantitative, however, one must locate the entrance channel reaction plane experimentally and know how accurately it has been determined. Well calibrated techniques for determination of the orientation of the reaction plane are also essential for measurements of triple differential cross sections [7], $\sigma(E,\theta,\phi)$, and for transverse flow analyses [8].

In order to explore the distribution of particles in and out of the reaction plane and to explore techniques for reaction plane determination, we have investigated correlations between coincident fission fragments and α-particles emitted in the reactions $^{36}Ar+^{238}U$ at E/A=20 and 35 MeV and $^{14}N+^{238}U$ at E/A=50 MeV. The experiment was performed with beams from the K500 cyclotron of Michigan State University. A $^{238}UF_4$ target of 400 $\mu g/cm^2$ areal density was used. Charged particles were detected with 96 plastic CsI(Tl) phoswich detectors of the "Dwarf-Ball-Wall" array developed at Washington University [9], which has an angular coverage of about 85% of 4π. Fission fragments were detected with two X-Y-position sensitive multiwire detectors [10] covering angular ranges of θ_1=36°-116° for ϕ=0±10° and θ_2=39°-89° for ϕ=180±30°. Further details of the experimental setup can be found in refs. [11,12]. In order to reduce contributions from peripheral collisions, all data were filtered by requiring that the linear momentum transfer to the fissioning nucleus be larger than one fifth of the projectile momentum.

The left hand panels of Fig. 1 show the azimuthal distribution, $Y_{\alpha}^{ff}(\phi_{\alpha})$, of α-particles emitted at θ_{α}=70° and with energy E_{α}=46-70 MeV in coincidence with two fission fragments. (Azimuthal correlations presented in this report are normalized to an average value of unity.) Consistent with previous observations [1], these particles are preferentially emitted in the fission plane. For the decay of residues with large angular momenta, the fission plane closely correlated with the entrance channel reaction plane (which is perpendicular to the semiclassical entrance channel orbital angular momentum vector) [1]. In order to extract the azimuthal anisotropies, $R_{\alpha}^{ff}= Y_{\alpha}^{ff}(\phi_{\alpha}=0°)/Y_{\alpha}^{ff}(\phi_{\alpha}=90°)$, we have fitted the azimuthal distribution with a simple functional form: $Y_{\alpha}^{ff}(\phi_{\alpha}) \propto \exp(-\kappa\sin^2\phi_{\alpha})$. Examples of such fits are shown by the dot-dashed curves in the left hand panels of Fig. 1. The extracted anisotropies are shown on the right hand side of Fig. 1, as a function of α-particle kinetic energy, $\langle E_{\alpha}\rangle$, for θ_{α}=70° (top panel), and as a function of emission angle, θ_{α}, for E_{α}=46-70 MeV (bottom panel). The most pronounced azimuthal asymmetries are observed for high energy α-particles emitted at large angles with respect to the beam axis, $\theta_{\alpha}\approx$70°-90°. The enhanced emission of α-particles in the fission plane becomes less pronounced with increasing projectile velocity.

Decreasing values of R_{α}^{ff} correspond to less enhanced emission in the entrance channel reaction plane, for fission fragments, α-particles, or both. In order to assess the degree to which emission is enhanced in the entrance channel reaction plane, we have fitted the measured correlations with the parametrizations used in refs. [1,4]. These parametrizations, given below, are chosen solely because they provide flexible and satisfactory parametrizations of the experimental data. The probability distribution, $P(\Phi)$, for the angle Φ between the entrance channel scattering plane and the fission plane was parametrized as [1]

$$P_f(\Phi) \propto \exp[-C\sin^2\Phi] \ . \tag{1}$$

Semiclassically, $C=\hbar^2J^2\sin^2\theta_f/2T_fI_{eff}$, where J, T_f, and I_{eff} are the angular momentum, temperature, and effective moment of inertia of the fissioning nucleus, and θ_f is the emission angle of the fragment. For heavy ion induced fission at high angular momenta, the effective moments of inertia are larger than expected from the transition state model [13]. In addition, preequilibrium emissions cause large uncertainties of the properties of the fissioning nucleus. Thus we treat C as an adjustable parameter. The emission of α-particles was described using an expression for the emission from an ideal gas of temperature T, rotating with angular velocity $\vec{\omega}$ perpendicular to the reaction plane, and moving with a velocity v_o parallel to the beam axis [1,4]:

$$P_\alpha(E_\alpha,\theta_\alpha,\phi_\alpha-\Phi) \propto \sqrt{(E_\alpha-V_c)E_s}\ \frac{J_1(iK)}{iK}\exp(-E_s/T). \tag{2}$$

Here, $E_s=E_\alpha-V_c+E_o-2\sqrt{E_o(E_\alpha-V_c)}\cos\theta_\alpha$, $K=\frac{R\ \omega}{T}\sqrt{2m_\alpha(E_s-(E_\alpha-V_c)\sin^2\theta_\alpha\sin^2(\phi_\alpha-\Phi))}$, and $E_o=\frac{1}{2}m_\alpha v_o^2$; J_1 denotes the first-order Bessel function; E_α, m_α, θ_α and

ϕ_α are the energy, mass, polar and azimuthal angles of the emitted particle. For comparison to measurements, one must sum over all possible orientations of the reaction plane [1]. Accordingly, the correlations between coincident fission fragments and α-particles are given by:

$$Y_\alpha^{ff}(E_\alpha,\theta_\alpha,\phi_\alpha) \propto \int_0^{2\pi} d\phi \; P_f(\phi) \; P_\alpha(E_\alpha,\theta_\alpha,\phi_\alpha-\phi) \; . \qquad (3)$$

Three calculated correlations between α-particles and fission fragments, $Y_\alpha^{ff}(\phi_\alpha)$, are shown by the solid, dashed, and dotted curves in the left hand panels of Fig. 1. The parameters used for these calculations are listed in Table 1. The similarity between these curves, which are nearly degenerate in the figure, illustrates the considerable ambiguities that remain concerning the relative widths of the α-particle and fission fragment distributions. These ambiguities arise because wider fission distributions, $P_f(\phi)$, can be compensated by narrower α-particle distributions, $P_\alpha(E_\alpha,\theta_\alpha,\phi_\alpha-\phi)$, without significant effect on the α-fission correlation. In order to reduce these ambiguities, one may explore the azimuthal correlation function for two α-particles detected in coincidence with two fission fragments:

$$C_{\alpha\alpha}^{ff}(\theta_1,\phi_1,\theta_2,\phi_2) \propto Y_{\alpha\alpha}^{ff}(\theta_1,\phi_1,\theta_2,\phi_2)/Y_\alpha^{ff}(\theta_1,\phi_1)Y_\alpha^{ff}(\theta_2,\phi_2) \; . \qquad (4)$$

The top panel of Fig. 2 illustrates that such a correlation function removes much of the parameter ambiguity which existed in the description of $Y_\alpha^{ff}(\phi_\alpha)$. Rather than fit a large number of α-α correlation functions measured with moderate statistical accuracy, we have constructed averaged α-α azimuthal distributions, $\langle Y^{ff}_{\alpha\alpha}(\Delta\Phi)\rangle$, defined by:

$$\langle Y^{ff}_{\alpha\alpha}(\Delta\Phi)\rangle \propto \sum_{i\neq j} Y^{ff}_{\alpha\alpha}(\theta_1,\Phi_i,\theta_2,\Phi_j)\varepsilon_{ij}(\Delta\Phi) \;/\; \sum_{i\neq j}\varepsilon_{ij}(\Delta\Phi) \ , \qquad (5)$$

where $\varepsilon_{ij}(\Delta\Phi)=1$ for $\Delta\Phi=|\Phi_i-\Phi_j|\pm30^\circ$ and $\varepsilon_{ij}(\Delta\Phi)=0$ otherwise. The summation in Eq. 5 is performed over all detectors i and j which are located at the polar angles θ_1 and θ_2, respectively. Averaged azimuthal α-α distributions, shown in the three lower panels of Fig. 2, largely remove the parameter ambiguities which existed in the description of the α-fission correlations of Fig. 1. The dotted, dashed and solid curves represent calculations for the averaged azimuthal distributions using the same parameter values as in Fig. 1 and taking the individual detector locations into account according to Eq. 5. The solid curves in Figs. 1 and 2 represent calculations with an optimum choice of parameters. These calculations also reproduce the other overall trends of the data well, including the energy and angular dependences shown by the solid lines in the right hand panels of Fig. 1.

Additional insight can be gained by examining the distributions P_α and P_f for α particles and fission fragments which provide the best description of the experimental data. The left hand panels of Fig. 3 show azimuthal distributions for α-particles (top) and fission fragments (bottom) calculated from the optimum parameters for the three reactions. Both fission and α-particle emission become less concentrated in the reaction plane as the projectile energy is increased. Emission out of the reaction plane appears to increase more rapidly for fission than for energetic α-particles. The origin of the broadening in the fission distributions is not clear. Broader fission azimuthal distributions could arise from more compact or hotter fission transition states. Recent measurements of the multiplicities of pre- and post-fission neutrons from intermediate energy heavy ion reactions suggest however that fission occurs at a rather low temperature during the final stages of these reactions [14]. Misalignments of the residue angular momentum caused by prefission light particle emission may significantly broaden the fission azimuthal distribution. Energetic α-particles, emitted with large transverse momenta during an earlier stage of the reaction, remain strongly aligned in the reaction plane and therefore could be a trigger of choice for tagging the entrance channel reaction plane.

The upper right hand panel in Fig. 3 shows the calculated angular dependence of the ratio, R_α, of α-particles emitted in ($\Phi=0^\circ$) over out ($\Phi=90^\circ$) of the entrance channel reaction plane. The largest azimuthal anisotropies are observed for large emission angles, $\theta_\alpha \approx 70^\circ-90^\circ$. Enhanced randomization of the particle momenta with increasing energy is apparent as is qualitatively expected from microscopic models [15]. The lower right hand panel shows the calculated ratio, $R_{\alpha\alpha}=Y_{\alpha\alpha}(\Delta\Phi=0^\circ)/Y_{\alpha\alpha}(\Delta\Phi=90^\circ)$, for azimuthal correlations between two α-particles of energies above 45 MeV, when one α-particle is detected at $\theta_1=70^\circ$ and the other α-particle is detected at the polar angle θ. The calculated azimuthal α-α correlations decrease strongly with projectile velocity, a trend which has been previously observed [2,4,5,16].

In summary, we have investigated azimuthal correlations between α-particles and coincident fission fragments. A simple parametrization has been used to extract the degree to which fission and α-particle emission are enhanced in the entrance channel reaction plane. Both emission patterns become broader as the projectile velocity increases. The most pronounced azimuthal anisotropies are observed for energetic α-particles emitted at large angles, 70°-90°; these particles appear to be particularly well suited to tag the orientation of the entrance channel reaction plane.

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Table 1: Parameters used for the calculations shown in Figs. 1-2.

Reaction	E/A (MeV)	v_o/c †	T (MeV) *	Rω/c	C	curve
$^{36}Ar+^{238}U$	20	0.08	4.0	0.04	5.0	dotted
$^{36}Ar+^{238}U$	"	"	"	0.05	3.1	solid
$^{36}Ar+^{238}U$	"	"	"	0.06	2.5	dashed
$^{36}Ar+^{238}U$	35	0.13	6.0	0.05	2.9	dotted
$^{36}Ar+^{238}U$	"	"	"	0.06	2.0	solid
$^{36}Ar+^{238}U$	"	"	"	0.07	1.8	dashed
$^{14}N+^{238}U$	50	0.16	7.5	0.05	1.3	dotted
$^{14}N+^{238}U$	"	"	"	0.065	1.1	solid
$^{14}N+^{238}U$	"	"	"	0.08	0.9	dashed

† Extracted from ref. [17].

* In accordance with ref. [4], this parameter was taken as 0.6 times the slope parameter extracted by a non-rotating moving source analysis of the kinetic energy spectrum of the emitted particle.

Figure Captions:

Fig. 1: Left hand panels: Azimuthal correlations, Y_{α}^{ff}, between fission fragments and α-particles of energy E_{α}=46-70 MeV, emitted at θ_{α}=70°. Right hand panels: In- over out-of-plane ratio, R_{α}^{ff}, for coincident fission fragments and α-particles. The top panel shows the dependence of R_{α}^{ff} on the kinetic energy of α-particles emitted at θ_{α}=70°; the bottom panel shows the dependence of R_{α}^{ff} on the emission angle for α-particles with E_{α}=46-70 MeV. Open circles, solid points, and open squares show data for the reactions $^{36}Ar+^{238}U$ at E/A=20 and 35 MeV and $^{14}N+^{238}U$ at E/A=50 MeV, respectively. The solid, dashed, dotted, and dot-dashed lines depict calculations described in the text.

Fig. 2: Top panel: α-α correlation function, $C_{\alpha\alpha}^{ff}$ (eq. 4), measured in coincidence with two fission fragments for the $^{36}Ar+^{238}U$ reaction at E/A=35 MeV; the α-particles were detected at the polar angles θ_1=42° and θ_2=63° and the azimuthal angles Φ_1=104° and $\Phi_2=\Phi_1+\Delta\Phi$. Lower panels: Average azimuthal distributions of α-particles, $\langle Y_{\alpha\alpha}^{ff}\rangle$ (eq. 5), for the reactions indicated. The solid, dashed and dotted lines depict calculations described in the text.

Fig. 3: Left hand panels: Azimuthal distributions, defined with respect to the reaction plane and calculated with the optimum set of parameters for α-particles with E_{α}=46-70 MeV and θ_{α}=70° (top) and fission fragments (bottom). Right hand panels: In- over out-of-plane ratio as a function of emission angle for single α-particle distributions with respect to the

reaction plane (top) and for azimuthal two-α-correlation functions as a function of the relative angle of emission (bottom).

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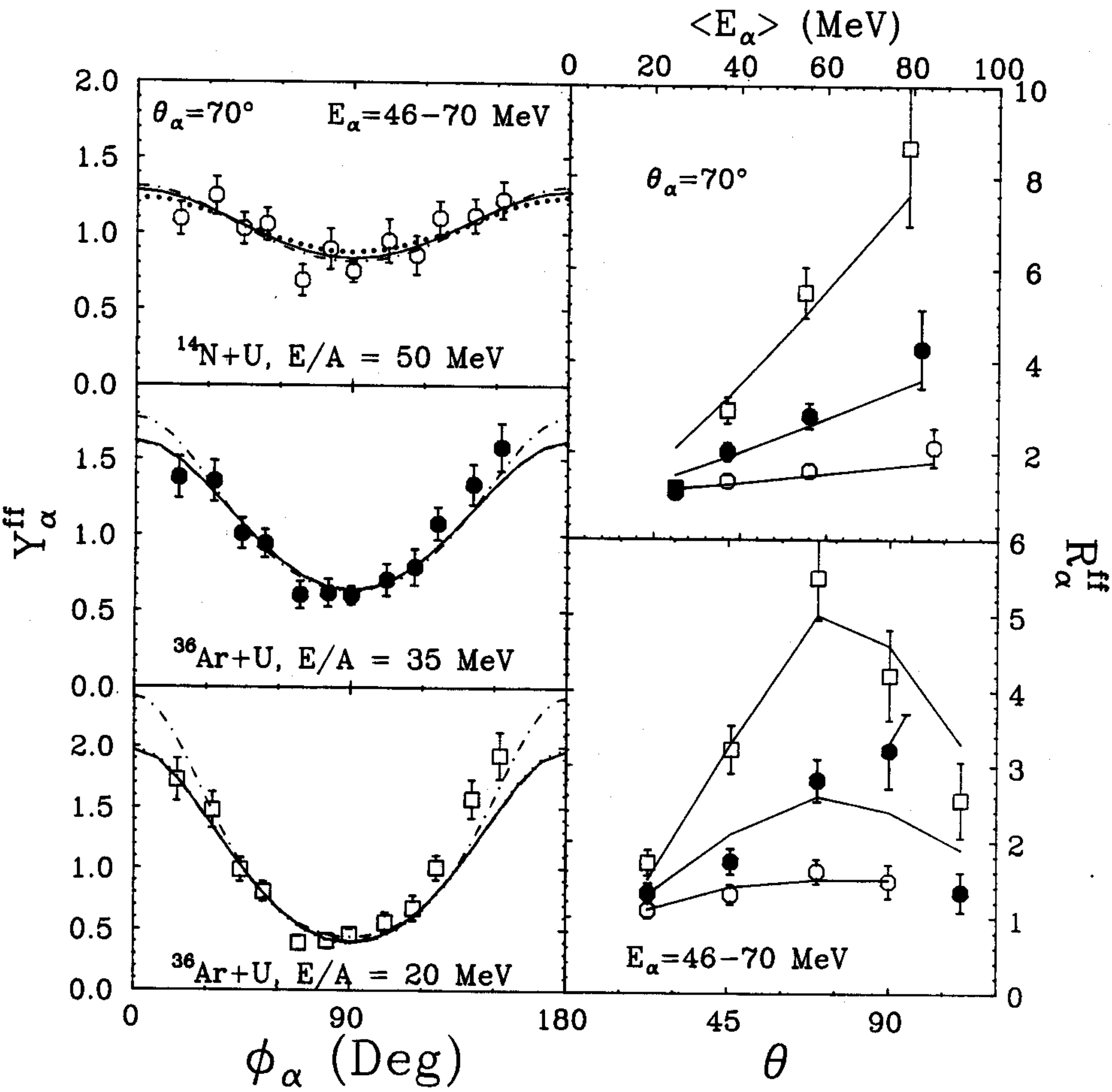


Fig. 1:

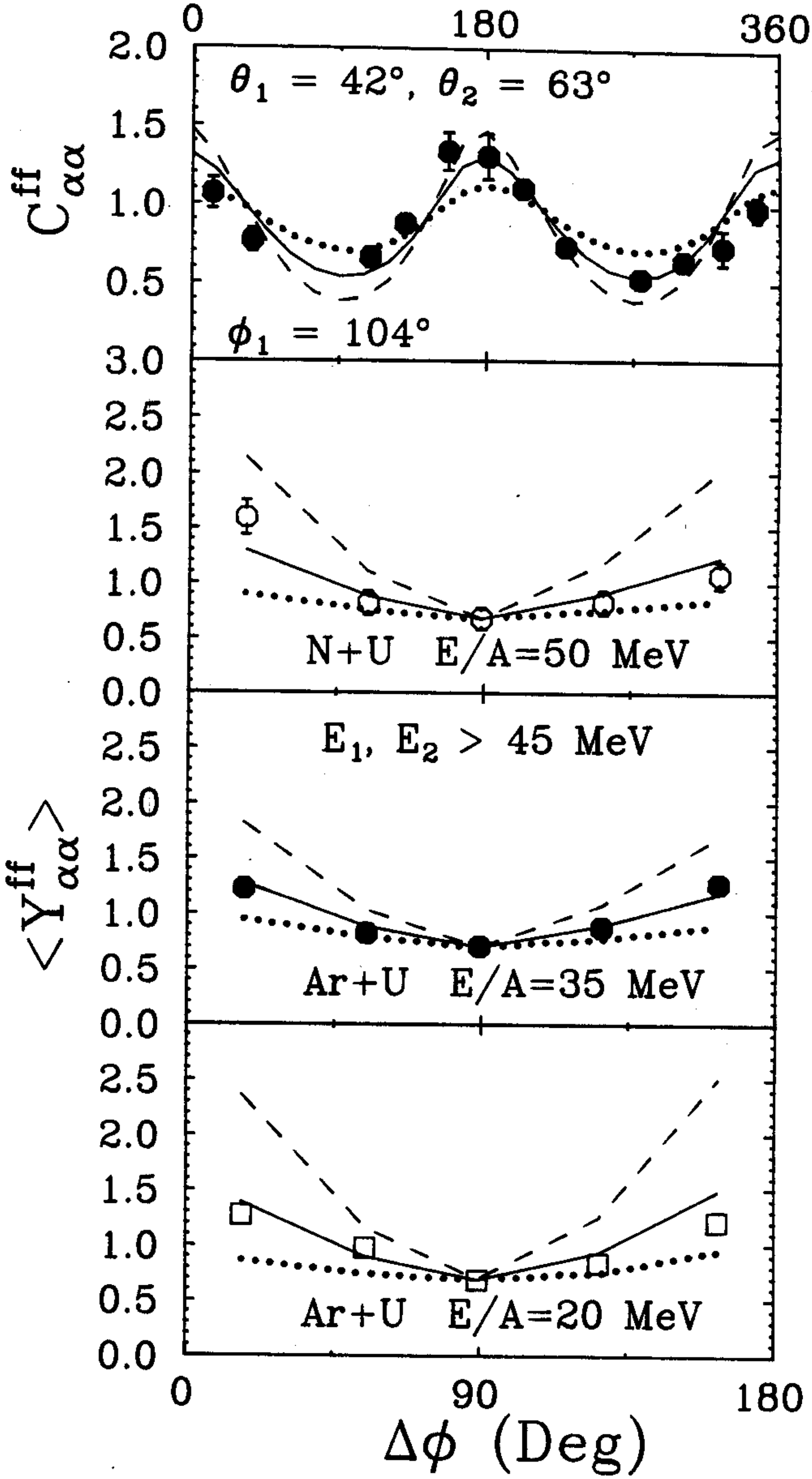
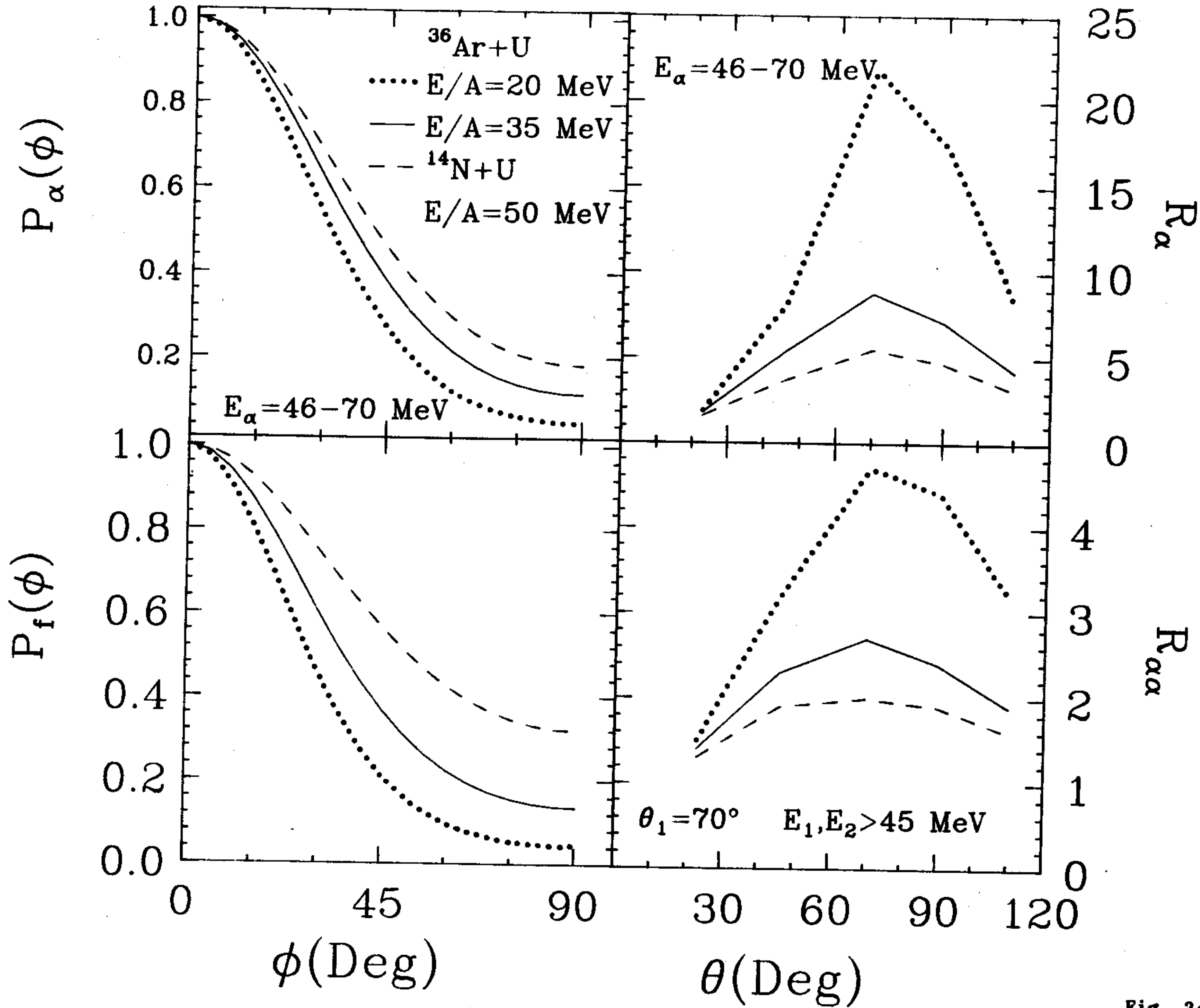

0
180
360
2.0
1.5
1.0
0.5
3.0
$C^{ff}_{\alpha\alpha}$
θ_1 = 42°, θ_2 = 63°
ϕ_1 = 104°
2.5
2.0
1.5
1.0
0.5
0.0
N+U E/A=50 MeV
E_1, E_2 > 45 MeV
$\langle Y^{ff}_{\alpha\alpha} \rangle$
Ar+U E/A=35 MeV
Ar+U E/A=20 MeV
0
90
180
$\Delta\phi$ (Deg)

Fig. 2:



$P_\alpha(\phi)$
$P_f(\phi)$
R_α
$R_{\alpha\alpha}$
^{36}Ar+U
E/A=20 MeV
E/A=35 MeV
^{14}N+U
E/A=50 MeV
E_α=46–70 MeV
E_α=46–70 MeV
θ_1=70°
E_1,E_2>45 MeV
1.0
0.8
0.6
0.4
0.2
0.0
0
45
90
30
60
120
25
20
15
10
5
4
3
2
1
ϕ(Deg)
θ(Deg)

Fig. 3: