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AZIMUTHAL CORRELATIONS BETWEEN LIGHT PARTICLES EMITTED IN ^{16}O INDUCED REACTIONS ON ^{12}C AND ^{197}Au AT 400 MeV

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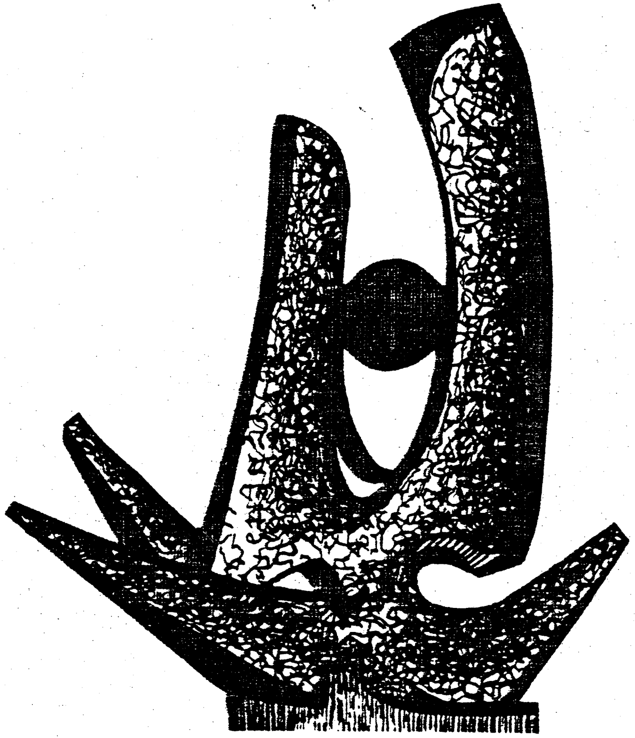

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Azimuthal correlations between light particles emitted in ^{16}O induced reactions on ^{12}C and ^{197}Au at 400 MeV *)

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Abstract

Azimuthal correlations between light particles emitted to polar angles of 40 and 70 degrees with respect to the beam axis were measured for ^{16}O induced reactions on ^{12}C and ^{197}Au at 400 MeV. Coincident light particles are preferentially emitted in a plane which contains the beam axis. For reactions on ^{12}C, coincident light particles are preferentially emitted to opposite sides of the beam axis. These correlations may be understood in terms of the phase space constraints imposed by momentum conservation on systems with finite number of nucleons. For reactions on ^{197}Au, on the other hand, preferential emission of coincident deuterons and tritons to the same side of the beam axis may be caused by the shadowing of preequilibrium particles by the adjacent cold spectator nuclear matter.

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For intermediate energy nuclear collisions, particle emission prior to the attainment of full statistical equilibrium of the emitting nucleus is expected to provide information about the early stages of the reaction. The global trends of single particle inclusive cross sections can be rather well described in terms of the concept of local statistical equilibrium [1-3]. Recent results from two-proton correlation measurements at small relative momenta are consistent with the emission of energetic light particles from a localized region of high excitation [4]. Because of shadowing [5-7] by the surrounding cold spectator matter, emission from such a localized region of high excitation is expected to be left-right asymmetric. In order to search for the possible existence of shadowing effects, we have measured azimuthal angular correlations of light particles emitted in ^{16}O induced reactions on ^{12}C and ^{197}Au at 400 MeV.

The experiment was performed at the Holifield Heavy-Ion Research Facility of Oak Ridge National Laboratory. ^{12}C and ^{197}Au targets of 2.5 and 9.7 mg/cm^2 areal density were bombarded with ^{16}O ions of 400 MeV incident energy. Prescaled singles and coincident light particles (p,d,t) were detected using seven telescopes with solid angles between 13 and 40 msr. Three of these telescopes were mounted at the polar angles measured with respect to the beam axis of θ = 40°, 70°, and 130° and the azimuthal angle of 0°; the remaining four telescopes were positioned at the polar angles of θ = 40°, 70°, 130°, and 160°; their azimuthal angle was varied between 50° and 180°. Absolute cross sections, accurate to 10%, were obtained from the integrated beam current, the target thickness, and the solid angles of the telescopes. Energy calibrations accurate to 3% were obtained by measuring the energies of recoil protons backscattered from a Mylar target by a 200-MeV ^{16}O beam.

Figure 1 shows the inclusive energy spectra of protons, deuterons, and tritons detected at θ = 40° and 70°. For reactions induced on ^{197}Au, estimated upper limits for emission from the compound nucleus are shown by the solid lines in the left hand part of the figure. These estimates were obtained by assuming that the energy spectra measured at θ =160° are entirely due to isotropic evaporation from the compound nucleus. The energy spectra at 40° and 70° are clearly dominated by non-compound emission processes. For reactions on ^{12}C, on the other hand, the shapes of the energy spectra are consistent with evaporation from the compound nucleus.

In order to reduce systematic errors, the azimuthal correlation is defined by the ratio of the coincidence cross-section divided by the singles cross-sections $\sigma_{xy}/\sigma_x\sigma_y$. Contributions from compound nucleus decay were reduced by applying a low energy threshold of 36 MeV in computing the cross-sections. Figure 2 shows the azimuthal correlations of two coincident light particles emitted at θ = 40° and 70°. For reactions on ^{197}Au, coincident light particles are preferentially emitted in a plane which contains the beam axis, (Fig.2a). Similar observations were made [8] for ^{14}N induced reactions on ^{197}Au at 420 MeV. It was shown [8] that non-compound light particles are preferentially emitted in the entrance channel reaction plane (defined as the plane which contains the beam axis and which is perpendicular to the semiclassical orbital angular momentum vector for the relative motion between the projectile and target nuclei). These observations could be described by assuming the superposition of a collective motion in the reaction plane on the random motion of the individual nucleons. To corroborate this point, we have performed schematic calculations corresponding to emission from a rotating moving source [8]

$$\frac{d^2M_x}{dE_x d\Omega_x}(E_x,\theta_x,\phi_x) = \text{Const.}\ (E_x E_{cm})^{\frac{1}{2}}\ e^{-E_{cm}/T}\ \frac{J_1(iB_x(E_{cm}-E_x\sin^2\theta_x\sin^2\phi_x)^{\frac{1}{2}})}{iB_x(E_{cm}-E_x\sin^2\theta_x\sin^2\phi_x)^{\frac{1}{2}}} \tag{1}$$

where $\frac{d^2M_x}{dE_x d\Omega_x}$ is the differential multiplicity for the emission of the light particle x. Alternatively, purely translational motion may be parameterized by assuming emission from two sidewards deflected sources

$$\frac{d^2M_x}{dE_x d\Omega_x} = \frac{d^2M_{x+}}{dE_x d\Omega_x} + \frac{d^2M_{x-}}{dE_x d\Omega_x} ,$$

where

$$\frac{d^2M_{x\pm}}{dE_x d\Omega_x}(E_x,\theta_x,\phi_x)=\text{Const}\cdot E_x^{1/2} \exp\{-[E_x+E_o-2E_x^{1/2}E_o^{1/2}(\cos\theta_x\cos\theta_o \pm \sin\theta_x\sin\theta_o\cos\phi_x)]/T\} \qquad (2)$$

In eqs. 1 and 2, J_1 denotes the first order Bessel function, $B_x=(2m_x)^{1/2}R\omega/T$; $E_{cm}=E_x+E_o-2(E_x\ E_o)^{1/2}\cos\theta_x$; $E_o=\frac{1}{2}m_x v_o^2$; $E_{lab}=E_x+E_c$, m_x, θ_x, and ϕ_x are the energy, mass, polar angle and azimuthal angle of the emitted particle; R,ω,v_o and T are the radius, angular velocity, translational velocity and the temperature of the source. The parameter E_c is introduced to correct for Coulomb repulsion from the target. Equations 1 and 2 parameterize the single particle distributions for a fixed orientation of the entrance channel reaction plane where ϕ_x = 0° or 180° corresponds to emission in the entrance channel reaction plane. Single particle spectra are obtained after averaging over the orientation of this plane.

$$\frac{d^2\sigma_x}{d\Omega_x dE_x}(E_x,\theta_x,\phi_x) = \text{Const}\cdot \int_o^{2\pi} d\Phi \frac{d^2M_x}{dE_x d\Omega_x}(E_x,\theta_x,\phi_x+\Phi) \qquad (3)$$

To compare with the experimental azimuthal correlation, the singles and coincidence cross-sections are given by

$$\sigma_x = \text{Const}\cdot\int_o^{2\pi} d\Phi \int_{E_x^{min}}^{E_x^{max}} dE_x \frac{d^2M_x}{dE_x d\Omega_x}(E_x,\theta_x,\phi_x+\Phi) \qquad (4)$$

and

$$\sigma_{xy} = \mathrm{Const}\cdot\int_{0}^{2\pi} d\Phi \int_{E_x^{\min}}^{E_x^{\max}} dE_x \int_{E_y^{\min}}^{E_y^{\max}} dE_y \cdot \frac{d^2M_x}{dE_x d\Omega_x}(E_x,\theta_x,\phi_x+\Phi)\frac{d^2M_y}{dE_y d\Omega_y}(E_y,\theta_y,\phi_y+\Phi) \qquad (5)$$

respectively.

The calculations with the rotating source parameterization are shown by the dashed curves in Fig.1 and the solid curves in Fig.2a; they were performed with the parameters T=5.6 MeV, v_o=0.09c, E_c=10 MeV, and Rω=0.1c. The calculations for two sidewards deflected sources are shown by the dot-dashed curves in Fig.1 and the dashed curves in Fig.2a; they were performed with the parameters T=6 MeV, v_o=0.12c, E_c=10 MeV, and θ_o =35°. Both of these schematic calculations can reproduce the overall trends of the azimuthal correlations rather well. Momentum conservation and nuclear shadowing effects are expected to affect the relative magnitude of the coincidence cross sections corresponding to coincident particle emission to the same (ϕ=0°) and to opposite (ϕ=180°) sides of the beam axis where ϕ denotes the relative azimuthal angle of the two particles. Since these effects are not incorporated in the simple parameterizations of eqs. 1 and 2, the relative magnitudes of these cross-sections are not reproduced.

In contrast to reactions on ^{197}Au, there is a clear enhancement for the emission of two coincident light particles to opposite sides of the beam axis for reactions on ^{12}C, see Fig.2b. These correlations may be understood in terms of the phase space constraints imposed by momentum conservation [9]. (Because of the small size of the colliding nuclei, shadowing effects are expected to be negligible.) In order to illustrate the effect of momentum conservation, we performed schematic calculations [9] for a source of A_s=28 nucleons and temperature T=7.1 MeV moving with the velocity of the compound nucleus, v_o=0.13c. In these calculations it is assumed that the momentum P_x of the emitted particle with mass number A_x changes the mean velocity of the second particle by $\Delta v_o=A_xP_x/m_x(A_s-A_x)$, i.e. the entire residual source is assumed to recoil to conserve total linear momentum. As is shown by the solid lines on the right hand side of Fig.1 and in Fig.2b, these schematic calculations reproduce the overall trends of the data rather well indicating that the preferential emission of coincident light particles to opposite sides of the beam axis may be explained in terms of the phase space constraints imposed by momentum conservation on finite nucleon systems. The influence of these constraints becomes more pronounced with increasing mass of the detected light particles.

The ratios $\sigma_{xy}(\phi=180°)/\sigma_{xy}(\phi=0°)$ of the coincidence cross sections for emission to opposite sides divided by the cross-sections for emission to the same side of the beam axis are given in Fig.3. For reactions on ^{197}Au, this ratio decreases with increasing mass of the two coincident light particles, in striking contrast to the strong increase measured for reactions on ^{12}C. The dot-dashed and dashed lines in the figure illustrate the effects due to momentum conservation for momentum conserving subsets consisting of A_s=28 and A_s=40,60,90,213 nucleons, respectively. For these calculations, particles were assumed to be emitted with Maxwellian distributions corresponding to a temperature of T=7.1 MeV and initial mean velocity parallel to the beam axis of v_o=0.13c (dot-dashed line) and v_o=0.11c (dashed lines). (The parameters for the source consisting of A_s=28 nucleons are identical with the parameters used for the calculation shown in Fig. 2b.)

Qualitatively, our observations might be explained in terms of the competing effects caused by shadowing and momentum conservation. If preequilibrium emission originates from a localized region of high excitation, absorption or rescattering by the adjacent spectator nuclear matter will enhance emission to the same side of the beam axis. Momentum conservation, on the other hand, will favor emission to opposite sides of the beam axis. Whether coincident light particles are preferentially emitted to the same or to opposite sides of the beam axis will depend on the relative magnitude of these two opposing effects. Absorptive effects are expected to be more pronounced for the emission of composite light particles than for the emission of nucleons. This is in qualitative agreement with the trends measured for reactions on ^{197}Au where it is observed that coincident protons have a slight preference to emerge at opposite sides of the beam axis, whereas coincident composite light particles have a slight preference to emerge at the same side of the beam axis.

In summary, we have measured the azimuthal angular correlations between light particles emitted at $\theta=40°$ and 70° with respect to the beam axis for ^{16}O induced reactions on ^{12}C and ^{197}Au at 400 MeV incident energy. For reactions on ^{12}C, the observed preferential emission of two coincident light particles to opposite sides of the beam axis may be understood in terms of the phase space constraints imposed by momentum conservation on systems with finite number of nucleons. For reactions on ^{197}Au, non-compound light particles are preferentially emitted in a plane containing the beam axis. This is consistent with an ordered motion in a direction perpendicular to the entrance channel orbital angular momenta which is superimposed onto the random motion of the individual light particles [8]. The small enhancements for the emission of two coincident protons to opposite sides of the beam axis and for the emission of two composite light particles to the same side of the beam axis may be interpreted in terms of the competition of momentum conservation effects and absorptive (shadowing) effects. The tentative identification of these effects provides further evidence for the emission of preequilibrium light particles from localized regions of high excitation.

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Figure Captions

Fig. 1. Inclusive light particle cross sections measured for ^{16}O induced reactions on ^{197}Au (left hand side) and ^{12}C (right hand side) at 400 MeV incident energy. For reactions on ^{197}Au, estimated upper limits for contributions from compound nucleus evaporation are shown by the solid lines. The solid, dashed and dot-dashed curves are explained in the text.

Fig. 2. Azimuthal angular correlations between coincident light particles emitted at θ =40° and 70° with respect to the beam axis for ^{16}O induced reactions on ^{197}Au (a) and ^{12}C (b) at 400 MeV incident energy. A low energy threshold of 36 MeV was applied. See text for detailed explanation of solid and dashed curves.

Fig. 3. Ratio of cross sections corresponding to emission of coincident light particles to opposite sides divided by the emission to the same side of the beam axis for ^{16}O induced reactions on ^{12}C (open points) and ^{197}Au (full points) at 400 MeV incident energy. The dashed and dot-dashed curves illustrate the effects of momentum conservation for systems with finite number of nucleons. The calculations are explained in the text.

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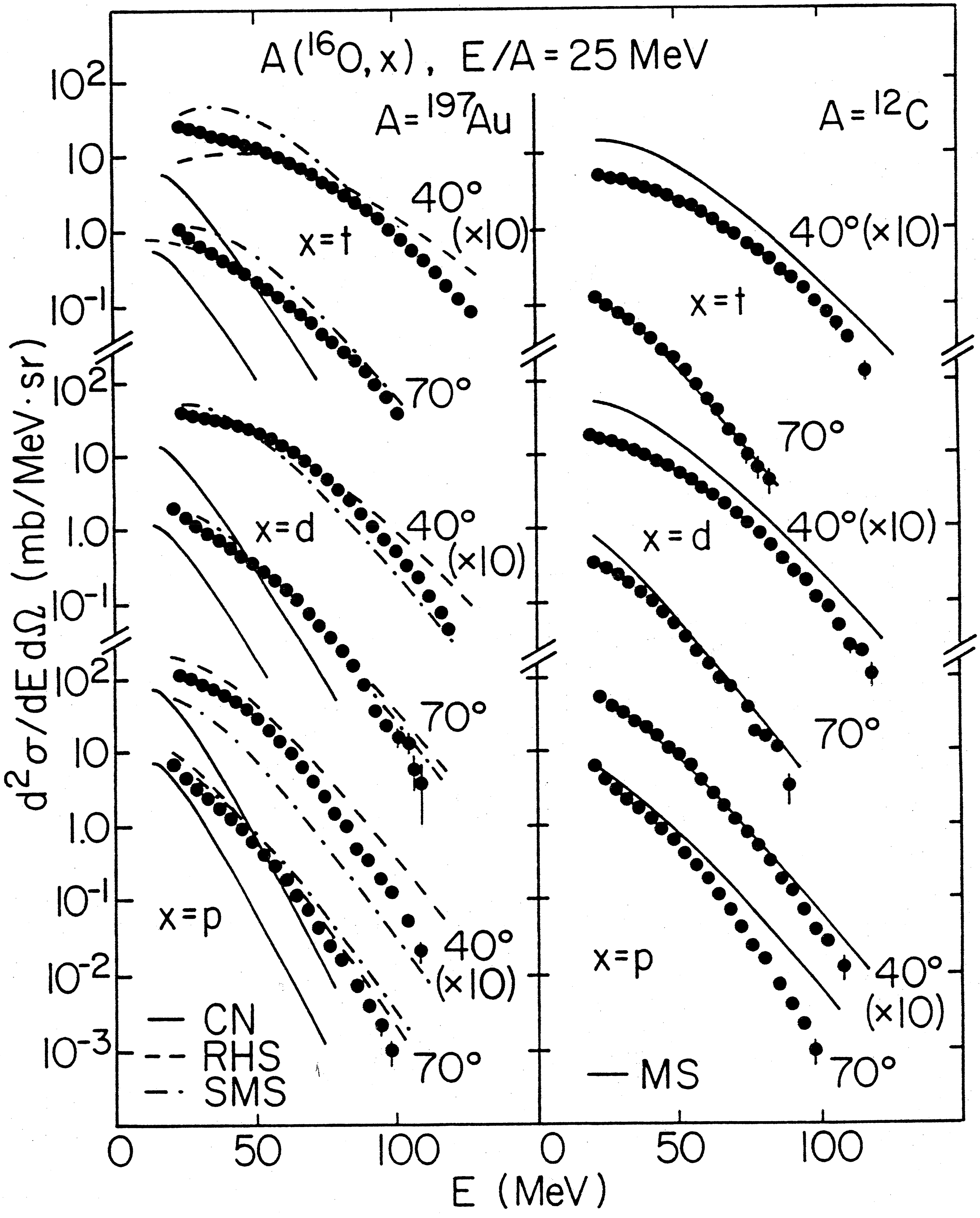
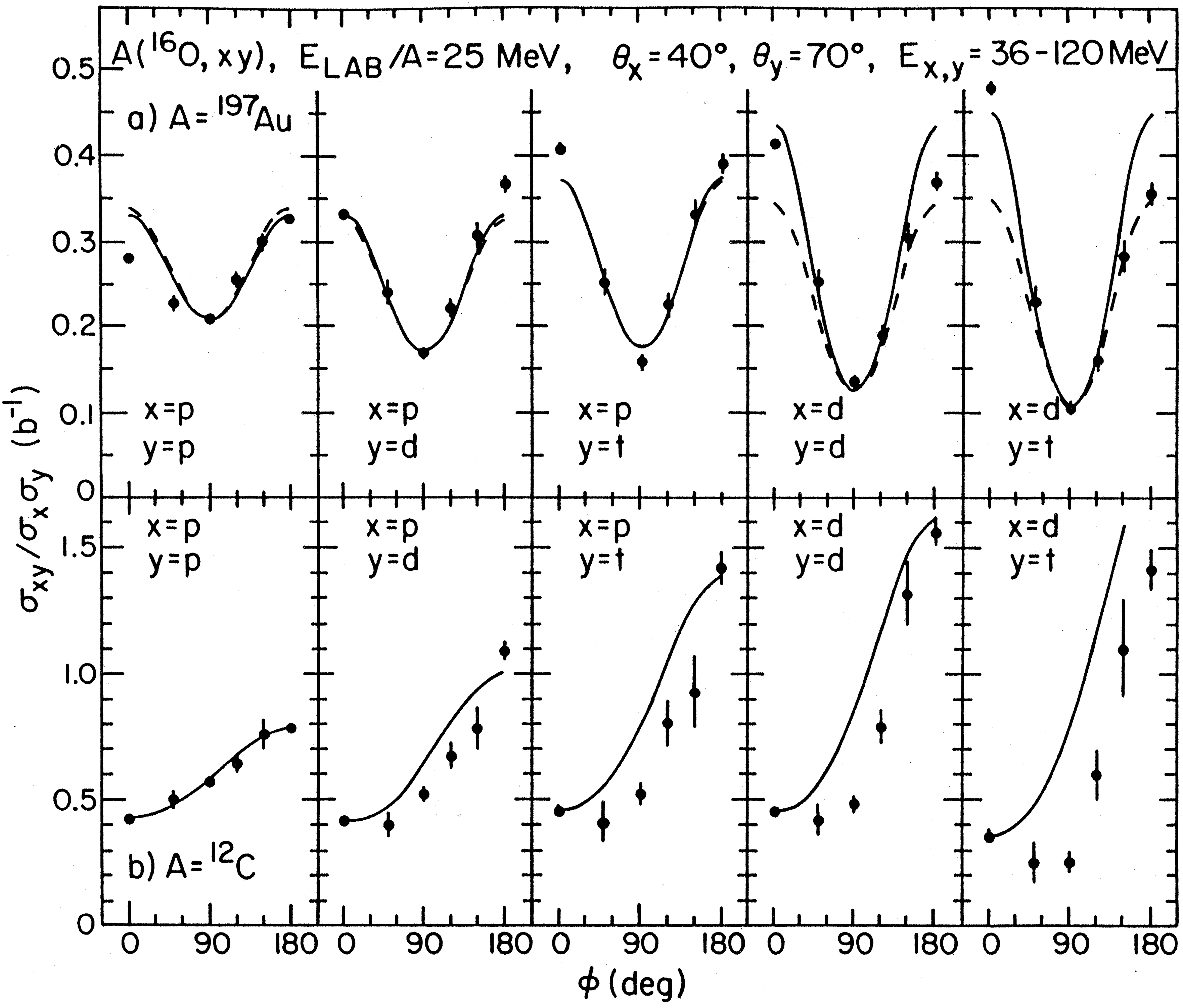
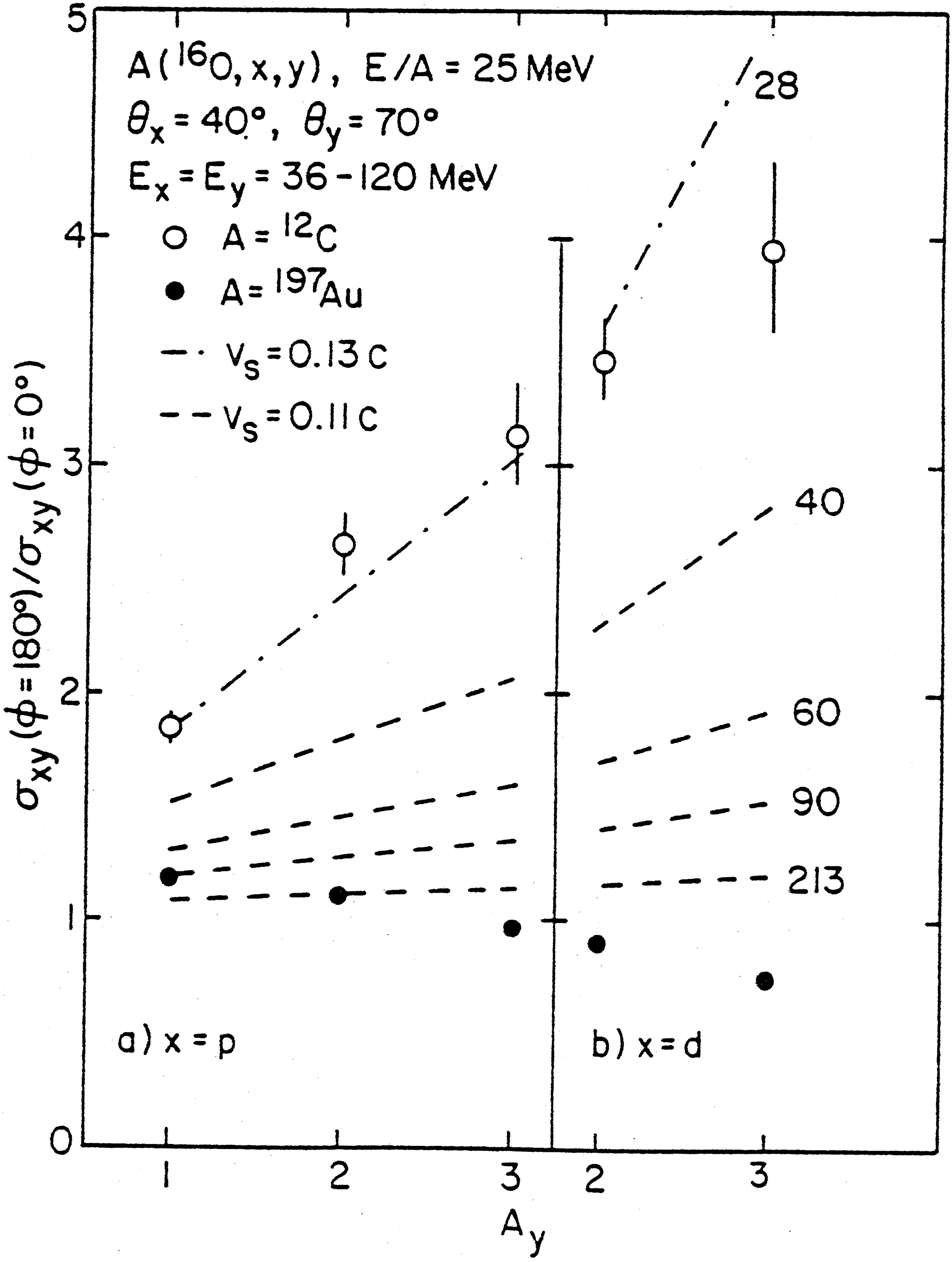

A(^{16}O, x), E/A = 25 MeV
A = ^{197}Au
A = ^{12}C
$d^2\sigma/dE\,d\Omega$ (mb/MeV·sr)
10^2
10
1.0
10^{-1}
10^{-2}
10^{-3}
x = t
x = d
x = p
40°
(×10)
40°(×10)
70°
CN
RHS
SMS
MS
0
50
100
E (MeV)


A(^{16}O, xy), E_{LAB}/A=25 MeV, θ_x=40°, θ_y=70°, $E_{x,y}$=36-120 MeV
a) A=^{197}Au
b) A=^{12}C
x=p y=p
x=p y=d
x=p y=t
x=d y=d
x=d y=t
$\sigma_{xy}/\sigma_x\sigma_y$ (b^{-1})
0
0.1
0.2
0.3
0.4
0.5
1.0
1.5
0
90
180
ϕ (deg)

MSU-84-137



A(^{16}O, x, y), E/A = 25 MeV
θ_x = 40°, θ_y = 70°
$E_x = E_y$ = 36-120 MeV
○ A = ^{12}C
● A = ^{197}Au
— · v_s = 0.13 c
- - v_s = 0.11 c
28
40
60
90
213
a) x = p
b) x = d
$\sigma_{xy}(\phi = 180°)/\sigma_{xy}(\phi = 0°)$
A_y
0
1
2
3
4
5
1
2
3
2
3