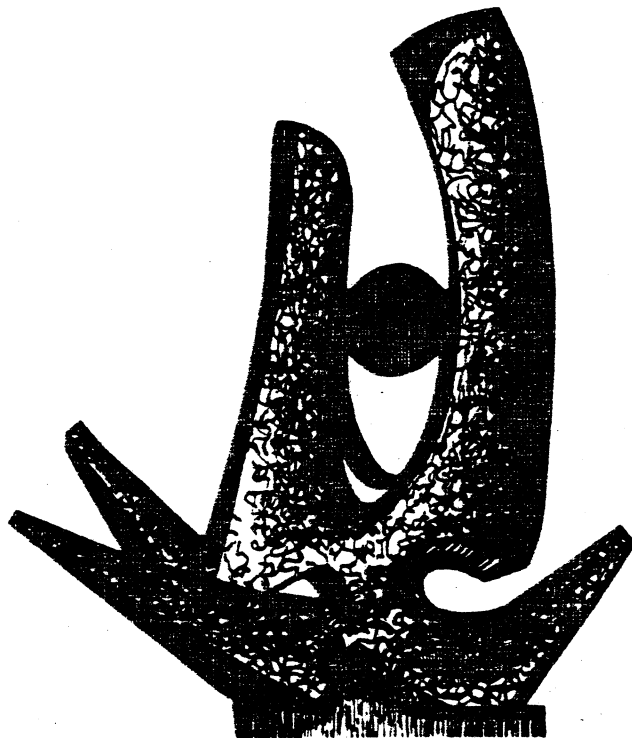


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DEFLECTION OF NON-EQUILIBRIUM LIGHT PARTICLES
BY THE NUCLEAR MEAN FIELD

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Abstract:

The sign of the average emission angle of non-equilibrium light particles was determined from the circular polarization of coincident γ -rays emitted from residual nuclei for ^{14}N -induced reactions on ^{154}Sm at $E/A=20$ and 35 MeV. Light particles (p,d,t, α) are preferentially emitted to negative angles. This effect is consistent with deflection of the particles by the attractive nuclear mean field. Numerical solutions of the Boltzmann-Uehling-Uhlenbeck equation demonstrate that the experimental result is sensitive to the interplay between nuclear mean field and nucleon-nucleon collisions.

The dynamics of intermediate energy nucleus-nucleus reactions are governed by the nuclear mean field and by collisions between individual nucleons. Each effect evolves dramatically as the bombarding energy is increased. At low energies ($E/A \leq 10$ MeV), the mean field is predominantly attractive and individual nucleon-nucleon collisions are hindered by the Pauli exclusion principle. At much higher energies ($E/A \geq 400$ MeV), nucleon-nucleon collisions are frequent and densities may be achieved where the nuclear mean field becomes repulsive.¹⁾ The transition from mean field dominated dynamics of low energy reactions to nucleon-nucleon collision dominated dynamics of high energy reactions is expected to occur at incident velocities comparable to the Fermi velocity where Pauli-blocking becomes less effective.

In intermediate energy nucleus-nucleus collisions, non-equilibrium light particles are observed to be emitted preferentially in the entrance channel scattering plane,²⁾ indicating a collective motion in this plane and transverse to the beam axis.^{2,3)} Microscopic calculations with the Boltzmann-Uehling-Uhlenbeck equation interpret this effect in terms of the deflection to negative emission angles by the attractive nuclear mean field.^{1,4)} Since the collective motion in the nuclear mean field is damped by individual nucleon-nucleon collisions, the relative importance of positive and negative emission angles is sensitive to the interplay between mean field dynamics and two-body dissipation.

We have addressed these issues experimentally by determining the sign of the average emission angle of non-equilibrium light particles from the circular polarization of associated γ -rays emitted by the residual nucleus for ^{14}N

induced reactions on ^{154}Sm at $E/A = 20$ MeV and $E/A = 35$ MeV. For these mass-asymmetric systems, the light particle spectra are dominated by non-equilibrium processes.^{3,5-7)}

The experiment was performed at the National Superconducting Cyclotron Laboratory at Michigan State University. A metallic self-supporting ^{154}Sm target of 11 mg/cm^2 areal density was bombarded with ^{14}N ions of 280 and 490 MeV energy. Light particles were detected with four ΔE -E telescopes arranged in a doubly symmetric geometry⁸⁾ at polar angles of $\theta=30^\circ$ and 60° and azimuthal angles of $\phi=0^\circ$ and 180° with respect to the beam axis. The telescopes consisted of $400 \text{ }\mu\text{m}$ thick surface barrier detectors and 10 cm thick NaI detectors and subtended solid angles of $\Delta\Omega(30^\circ)=44 \text{ msr}$ and $\Delta\Omega(60^\circ)=53 \text{ msr}$. The circular polarization of coincident γ -rays was measured with two forward scattering polarimeters⁸⁾ positioned at $\theta=90^\circ$, $\phi=90^\circ$ and $\theta=90^\circ$, $\phi=270^\circ$. The polarimeters had in-beam analysing powers of $1.30\pm 0.25\%$ and $1.20\pm 0.25\%$, at the bombarding energies of $E/A=20$ and 35 MeV, respectively. Only statistical errors are displayed in the figures.

The measured light particle energy spectra and γ -ray polarizations are shown in Figures 1 and 2. The cross sections are forward peaked and the energy spectra exhibit nearly exponential slopes in agreement with the trends established previously for non-equilibrium light particle emission.^{6,7)} Positive polarizations are observed at both energies and emission angles. The magnitude of the measured polarization increases with increasing energy and mass of the coincident light particles. No significant dependence on beam energy is observed. For a given particle and energy, the polarization is slightly larger at $\theta=60^\circ$ than at $\theta=30^\circ$. In our sign convention,⁸⁾ the

quantization axis \vec{n} is defined by: $\vec{n} = \vec{k}_i \times \vec{k}_f / |\vec{k}_i \times \vec{k}_f|$ where \vec{k}_i and \vec{k}_f are the momentum vectors of the beam and the detected particle respectively; positive circular γ -ray polarizations correspond to negative deflection angles and vice versa. Our experiment clearly establishes the preferential emission of non-equilibrium light particles to negative emission angles, consistent with an attractive nuclear mean field and with measurements at lower energies.^{9,10)} The sign is opposite to what is expected if only shadowing by the residual nucleus would affect the particle emission.³⁾ For light particle energies of $E/A = 35$ MeV, P_γ increases approximately linearly with A as would be expected in a coalescence model of light particle production.

Both the polarization and spin alignment²⁾ tend to increase with mass and energy of the light particles. In order to estimate whether the magnitude of the measured polarizations is limited by the statistical spin de-orientation, we have calculated the spin alignment, $P_{zz} \approx \langle 3M^2/2J^2 \rangle - .5$, of the residual nucleus with respect to the reaction normal \vec{n} . We have estimated P_{zz} using the two schematic parameterizations employed in ref. 2 which were used to describe the out-of-plane to in-plane ratios of light particles in coincidence with fission-fragments for the comparable reaction of $^{14}\text{N} + ^{197}\text{Au}$ at $E/A = 30$ MeV.²⁾ Both parameterizations give similar estimates of P_{zz} . The estimated values of $P_{zz} = 0.44$ and 0.77 are consistent with polarizations, P_γ^{max} , as large as 0.6 and 0.7 ,¹¹⁾ for the emission of protons ($E_p = 30-50$ MeV) and alpha particles ($E_\alpha = 120-200$ MeV) at $\theta_{\text{lab}} = 60^\circ$. (In these estimates, it is assumed that the presence of non-stretched γ -ray transitions¹²⁾ reduces P_γ^{max} by about 20% below the values expected for purely stretched transitions.) These upper bounds are

significantly larger than the measured polarizations, indicating that light particles are scattered to both positive and negative emission angles.

Considerable progress has been made recently in treating the dynamics of the nucleon-nucleon collisions in the presence of the mean field generated by the participating nuclei.^{1,4,13)} We have performed numerical calculations with the Boltzmann-Uehling-Uhlenbeck (BUU) equation^{4,13)} for $^{14}\text{N}+^{154}\text{Sm}$ collisions at $E/A=35$ MeV with impact parameters between $b=1$ to 10 fm. A Skyrme-type interaction with a compressibility coefficient of $K=200$ MeV and an isotropic nucleon-nucleon cross section of $\sigma_{NN}=41$ mb were used. The impact parameter averaged azimuthal distributions of nucleons with energies larger than 30 MeV, emitted at $\theta=30^\circ$ and 60° , are shown in Figure 3. In the figure, positive and negative scattering angles correspond to $\phi=0^\circ-90^\circ$ and $\phi=90^\circ-180^\circ$, respectively. The calculations predict the preferential emission of nucleons to negative angles, in qualitative agreement with the experimental observations.

To allow a more quantitative comparison with the data, we have calculated the circular polarization predicted by the BUU model. The angular momentum, $\vec{J}(b)$, of the residual nucleus (assumed to correspond to nucleons within a radius of 7.5 fm at the collision time of 200 fm/c) was determined for each impact parameter. For simplicity, the residual nucleus was assumed to decay via stretched E2 transitions, corresponding to a γ -ray multiplicity of $M_\gamma=J(b)/2$. Integrating over the geometry of the polarimeters⁸⁾ Ω_γ , and averaging over impact parameters b , gives for the predicted polarization:

$$\langle P_Y(\theta) \rangle = \frac{2\pi \sum_b b M_J(b) \int dE \int d\phi \sigma_N(\theta, \phi, E) \int d\Omega_Y P(\beta) Y(\beta)}{2\pi \sum_b b M_J(b) \int dE \int d\phi \sigma_N(\theta, \phi, E) \int d\Omega_Y Y(\beta)} . \quad (1)$$

Here $Y(\beta) = 1 - \cos^4 \beta$ and $P(\beta) = 2 \cos \beta / (1 + \cos^2 \beta)$ are the angular distribution of the γ -ray yield and circular γ -ray polarization, respectively, and $\cos(\beta) = \vec{k}_\gamma \cdot \vec{J} / (k_\gamma J)$; k_γ is the momentum vector of the emitted photon and $\sigma_N(\theta, \phi, E)$ is the nucleon differential cross section. The polarization is integrated over the azimuthal angles of the emitted nucleons and over energies greater than 30 MeV. At the angles of 30° and 60° , the predicted polarizations are 0.18 ± 0.03 and 0.25 ± 0.03 , respectively. The values should be reduced by about 20% if one accounts for non-stretched transitions.^{11,12)} In comparison, the calculated polarizations, 0.14 and 0.2 at $\theta = 30^\circ$ and $\theta = 60^\circ$ respectively are larger than the experimentally observed proton polarizations of .07 both at $\theta = 30^\circ$ and $\theta = 60^\circ$. However, the present calculations do not include emission of composite particles which have larger measured polarizations. In accordance with the coalescence picture, one may assess the effects of complex particle emission by evaluating an "effective nucleon polarization" according to the definition:

$$P_{\text{eff}}(\theta) = \frac{\sum_i \sum_j A_i \sigma_i(\theta, E_j) P_i(\theta, E_j)}{\sum_i \sum_j A_i \sigma_i(\theta, E_j)} , \quad (2)$$

where A_i , $P_i(\theta, E_j)$ and $\sigma_i(\theta, E_j)$ denote mass, experimentally measured polarization and cross section for particle i and $i = p, d, t, \alpha$. For particle energies $E/A \geq 30$ MeV, the effective polarizations are $P_{\text{eff}}(30^\circ) = 0.17 \pm 0.03$ and $P_{\text{eff}}(60^\circ) = 0.12 \pm 0.03$. Considering the experimental uncertainties of the absolute calibrations of the analysing power and the theoretical

uncertainties in the relative weights for the composite particles, $P_{\text{eff}}(\theta)$ and the calculated polarizations $\langle P_{\gamma}(\theta) \rangle$ are in good agreement.

In order to illustrate the dependence of the predicted polarizations on the nucleon-nucleon collision dynamics, we have varied the strength of the residual interaction. For simplicity, calculations were only performed for one impact parameter, $b=6.5$ fm. This impact parameter contributes the largest weight to the polarization integral of equation 1. Table 1 shows the dependence of the predicted polarization on the strength of the nucleon-nucleon scattering cross section. The predicted polarization decreases monotonically for larger values of σ_{NN} . For $\sigma_{\text{NN}} = 41$ mb, the polarization is reduced by over a factor of three below the value calculated with the mean field alone. Thus the magnitude of the impact parameter averaged polarizations calculated with equation 1 reflect the balance between deflection by the mean field and randomization of the particle velocities by nucleon-nucleon collisions.

In summary, measurements of the circular polarizations of γ -rays in coincidence with light particles indicate that non-equilibrium light particles are predominantly emitted to negative emission angles. Negative emission angles are consistent with the deflection of non-equilibrium light particles by an attractive nuclear mean field. Calculations with the Boltzmann-Uehling-Uhlenbeck equation predict preferential emission to negative angles and suggest that collisions between individual nucleons reduce the polarizations significantly below what might be expected from mean field dynamics alone.

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Table 1:

Polarizations predicted by the Boltzmann-Uehling-Uhlenbeck equation using different nucleon-nucleon scattering cross-section σ_{NN} . The calculations were performed for a fixed impact parameter of $b=6.5$ fm.

σ_{NN} (mb)	$P_Y(30^\circ)$
0	0.82 ± 0.08
10.3	0.56 ± 0.04
20.5	0.24 ± 0.08
41.0	0.25 ± 0.07
82.0	0.04 ± 0.10

Figures Captions:

Fig. 1. Circular γ -ray polarizations plotted as a function of particle energies for p, d, t, and α (upper part) for $E/A = 35$ MeV. Closed and open circles correspond to measurements in coincidence with light particles detected at 30° and 60° , respectively. The lower part shows the inclusive energy spectra for the corresponding light particles.

Fig. 2. Circular γ -ray polarizations plotted as a function of particle energies for p, d, t, and α (upper part) for $E/A = 20$ MeV. Closed and open circles correspond to measurements in coincidence with light particles detected at 30° and 60° , respectively. The lower part shows the inclusive energy spectra for the corresponding light particles.

Fig. 3. Azimuthal distribution of nucleons scattered to $30 \pm 10^\circ$ (closed points) and $60 \pm 10^\circ$ (open) points from BUU calculations. $\phi > 90^\circ$ corresponds to negative scattering angles and $\phi < 90^\circ$ corresponds to positive scattering angles.

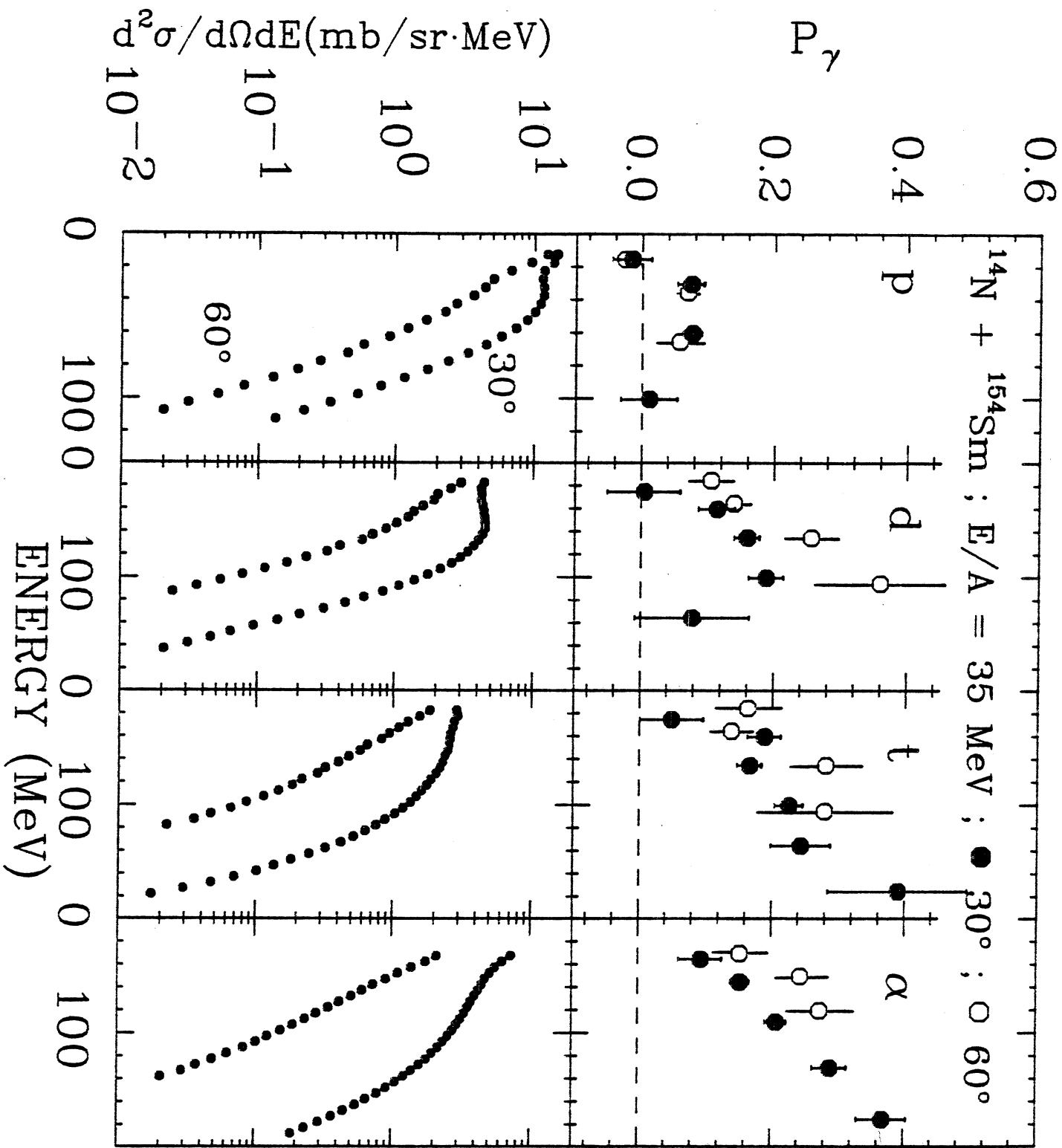


Fig 1

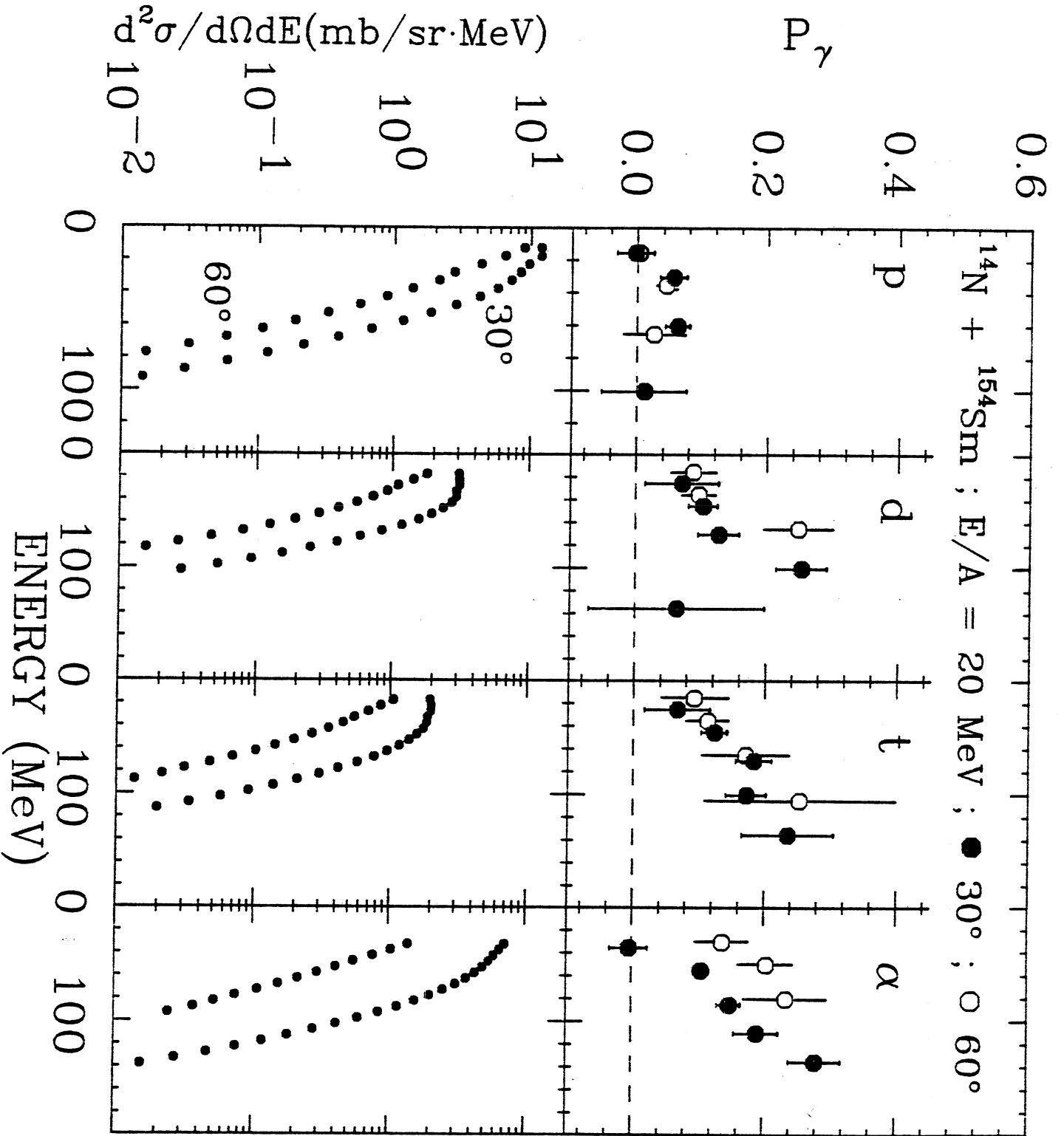


Fig 2

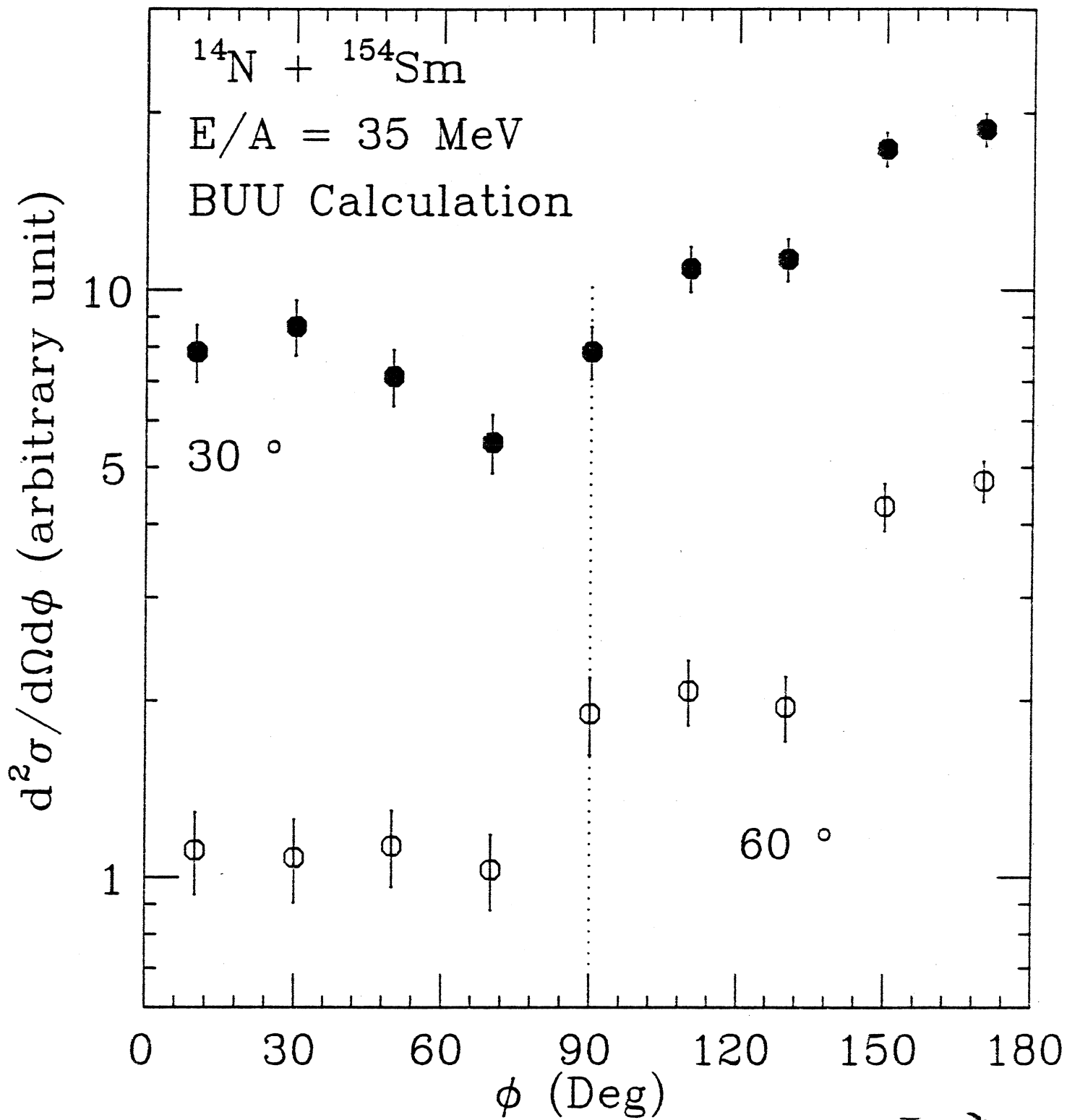


Fig. 3