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Abstract

We report measurements for in-plane and out-of-plane correlations for p,d,t,^{3}He, and ^{4}He from 40 MeV/nucleon $^{12}C+C$. Silicon-NaI light particle telescopes were placed at $(\theta,\phi)=(45°,90°)$ and $(45°,180°)$ and another telescope was moved from $\theta=25°$ to $120°$ at $\phi=0°$. No peak was observed in the ratio of in- to out-of-plane proton-proton correlations at energies and angles corresponding to quasi-elastic scattering. The Vlasov-Uehling-Uhlenbeck theoretical approach, including Pauli blocking, the mean field, and two body collisions, reproduces the observed angular distribution of the ratio of in- to out-of-plane p-p correlations. The angular distributions of the ratio of in- to out-of-plane for d-d, t-t, ^{3}He-^{3}He, and ^{4}He-^{4}He peak around 40° and the maximum value increases monotonically with mass of the particles reaching a value near 4 for ^{4}He-^{4}He. A calculation incorporating simple kinematic effects cannot reproduce the observed correlations for any of the particle pairs.

The relative importance of direct nucleon-nucleon reactions versus phenomena involving many nucleons simultaneously is central to the understanding of the reaction mechanisms of high energy nucleus-nucleus collisions. At incident energies near the coulomb barrier (below 10 MeV/nucleon) one expects nuclei to interact through their mean fields. As one raises the relative velocity between the two nuclei, one expects direct nucleon-nucleon scattering to become the dominant reaction mechanism at energies high compared with the fermi energy and binding energy of the constituent nucleons (above 200 MeV/nucleon). If enough nucleon-nucleon scatterings occur, the system may approach local thermal kinetic equilibrium. If such a system has a lifetime greater than the formation and decay time of nuclear and baryonic resonances the system may also approach chemical equilibrium.

There is evidence for thermal behavior in nucleus-nucleus collisions where an apparent thermal source of nucleons and complex fragments has been observed with a velocity intermediate between those of the projectile and target for a wide range of incident energies.[1-3] The relative contributions of direct versus thermal phenomena have been studied in $^{12}C+C$, $^{40}Ar+KCl$ and $^{12}C+Pb$ at 800 MeV/nucleon[4] and for 85 MeV/nucleon $^{12}C+C$.[5] When the ratio of in- to out-of-plane correlations was measured for C+C at 85 and 800 MeV/nucleon, a significant enhancement was observed at energies and angles corresponding to quasielestic nucleon-nucleon scattering. For the heavier system Ar+KCl the similar measurements showed less enhancement. Using the reaction C+Pb the ratio was nearly constant as a function of the observed proton energy and angle indicating that when the target nucleus contains a sufficient number of nucleons a thermalized system can be created.

At 40 MeV/nucleon one might expect that the low multiplicity of protons (≈ 2/collision)[6] might lead to a strong apparent direct component. On the other hand the fermi spheres of the two nuclei partially overlap in momemtum space possibly masking any quasi-elastic correlation in proton-proton scattering at these energies by smearing the energy spectra. Our measurements for the ratio of in- to out-of-plane p-p correlations show no peak at quasi-elastic angles and energies. A comparison with a Vlasov-Uehling-Uhlenbeck (VUU) calculation including phase space Pauli blocking, the nuclear mean field, and two body collisions[7] reproduces the observed angular distribution of in- to out-of-plane p-p correlations, but the number of collisions calculated did not allow comparison to the measured correlation of light nuclei. As was observed for 85 MeV/nucleon C+C,[5] correlations between light nuclei (d-d, ^{4}He-^{4}He, t-^{3}He, etc.) exhibit a peak in the angular distribution of the ratio of in- to out-of-plane around 40° that increases in magnitude with increasing mass. This peak cannot be explained in terms of simple kinematic considerations.

The measurements were carried out with the K500 Superconducting Cyclotron at the National Superconducting Cyclotron Laboratory using a beam of 40 MeV/nucleon ^{12}C with an average intensity of 2 particle namps. The target consisted of a 15 mg/cm^2 graphite target. Three particle telescopes were used each consisting of a 100 μm Si surface barrier ΔE detector and a 10 cm NaI E detector. Two of these counters were fixed in place at $(\theta,\phi) = (45°,90°)$ and $(45°,180°)$ comprising an out-of-plane and an in-plane coincidence detector, respectively. A third telescope was moved from $\theta = 25°$ to $120°$ in plane (ϕ=0°). The low energy cut-off of the detectors was 10 MeV for protons which allowed the observation of the quasielastic peak when the counters were placed at 45°.

The inclusive spectra for p,d,t,^{3}He and ^{4}He from 40 MeV/nucleon ^{12}C+C are shown in Fig. 1. These spectra have been corrected for reaction losses in the detectors and the errors are statistical. The energy spectra are featureless and decrease monotonically with increasing angle. These characteristics combined with the exponential fall-off of the energy spectra imply thermal origins for these particles from the inclusive spectra alone.[8] However, there is a small shoulder in the 25° spectra near the incident energy/nucleon indicating contributions from either projectile breakup or quasielastic nucleon-nucleon scattering.

In Fig. 2 the ratio of the in-plane to out-of-plane p-p coincidence spectra for the case of the movable detector at 45° is shown as a function of energy in the movable telescope. The correlations are integrated over all proton energies in the other two telescopes (one in-plane and one out-of-plane) covering the range from 10 to 160 MeV. This ratio is constant as a function of energy up to 60 MeV and then apparently increases although the statistics are poor. The average value for the ratio at this angle is 1.08 ± 0.01. There is clearly no peak at 20 MeV in the ratio of in-plane to out-of-plane coincidence spectra as one would expect from free proton-proton scattering.

In Fig. 3 the ratio of in-plane to out-of-plane coincidence spectra are given for angles from 25 to 120°. The ratio was calculated by integrating the coincident energy spectra over the two in-plane and the two out-of-plane counters. There is a peak in the angular distribution of the ratios at $\theta \approx 40°$. The maximum of the ratio increases with increasing mass of the observed pair. Not shown in Fig. 3 are the correlations between unlike particles (e.g., t-^{3}He) that also increase monotonically with increasing mass of the observed pair of particles.

In order to rule out the possibility that these correlations result from simple kinematic biases we have carried out a calculation based on fireball geometry.[8] In this model[9] one assumes that a system of nucleons emits a particle, re-equilibrates and recoils, and emits a second particle. This result is averaged with the case where the second particle is assumed to be the first emitted. The result is averaged over impact parameter again assuming a fireball geometry. Simple momentum conservation effects are thus treated in the context of this model. In Fig. 4 the results of this calculation are shown as solid lines for p-p and ^{4}He-^{4}He correlations as a function of the angle of the movable telescope. Clearly these calculations do not reproduce the observed correlations implying that the results do not result from trivial momentum conservation effects but could result from other dynamical effects.

To treat these possible dynamical effects we have carried out a VUU calculation[7] for the ratio of in- to out-of-plane p-p correlations and the results are shown in Fig. 4 as circles with a superimposed histogram. There were insufficient statistics to apply the calculation to the ^{4}He-^{4}He correlations. The p-p correlations are very well described by the VUU calculations. This agreement is due to the fact that the VUU approach includes Pauli and mean field effects which are very strong at these incident energies. Even though the VUU approach would allow a direct knockout at higher energies, it does not predict one for the present case. At this energy the main reaction mechanism is a collective bounce-off of the nucleus due to the attractive part of the mean field. Futhermore the small amount of two-body collisions that are allowed after Pauli blocking (≈ 9%) are smeared by the mean field masking any direct knockout component.

One criticism of the VUU calculation[7] as applied to correlation measurements is that momentum is conserved in individual particle-particle interactions and for the set of parallel ensembles but not for each ensemble. These parallel ensembles are used to treat the mean field and Pauli blocking effects. We explicitly calculated the error in momentum conservation in this case to be 38 MeV/c per ensemble which is about 1% of the total momentum of the event. This small error does not affect the results presented here for p-p correlations.

In conclusion we have found that there is no evidence for a peak at energies and angles corresponding to quasielastic nucleon-nucleon scattering for in- to out-of-plane ratios in p-p correlations at 40 MeV/nucleon as opposed to results for 85 and 800 MeV/nucleon C+C. In addition, as was observed at 85 MeV/nucleon, the correlation between light nuclei increases with increasing mass of the observed particles. This effect cannot be described in terms of simple kinematic biases due to momentum conservation constraints. A VUU calculation[7] can reproduce the observed p-p correlations implying, along with the disagreement of the momentum conservation calculations, that the correlations may be due to dynamical effects.

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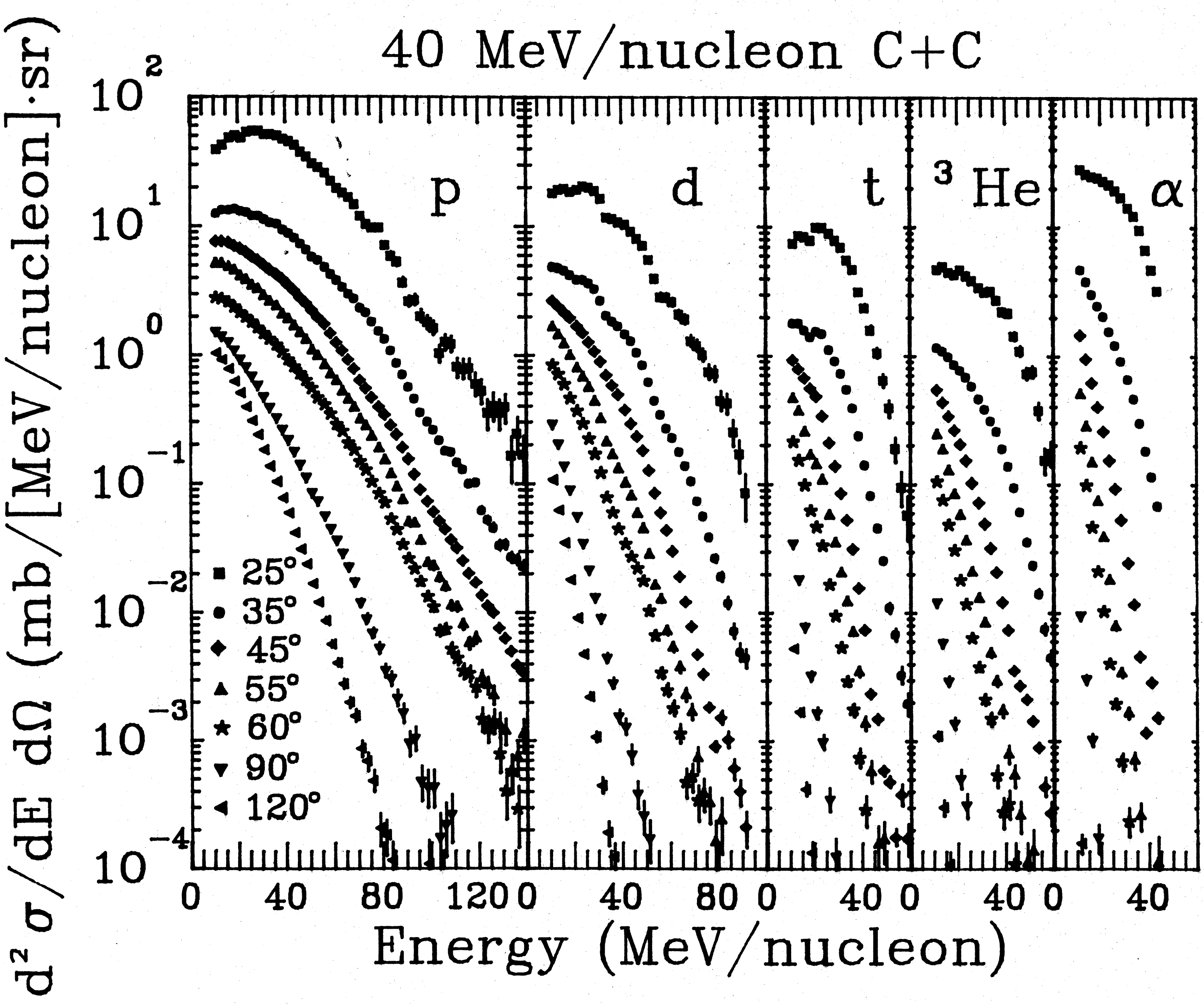
Figure Captions

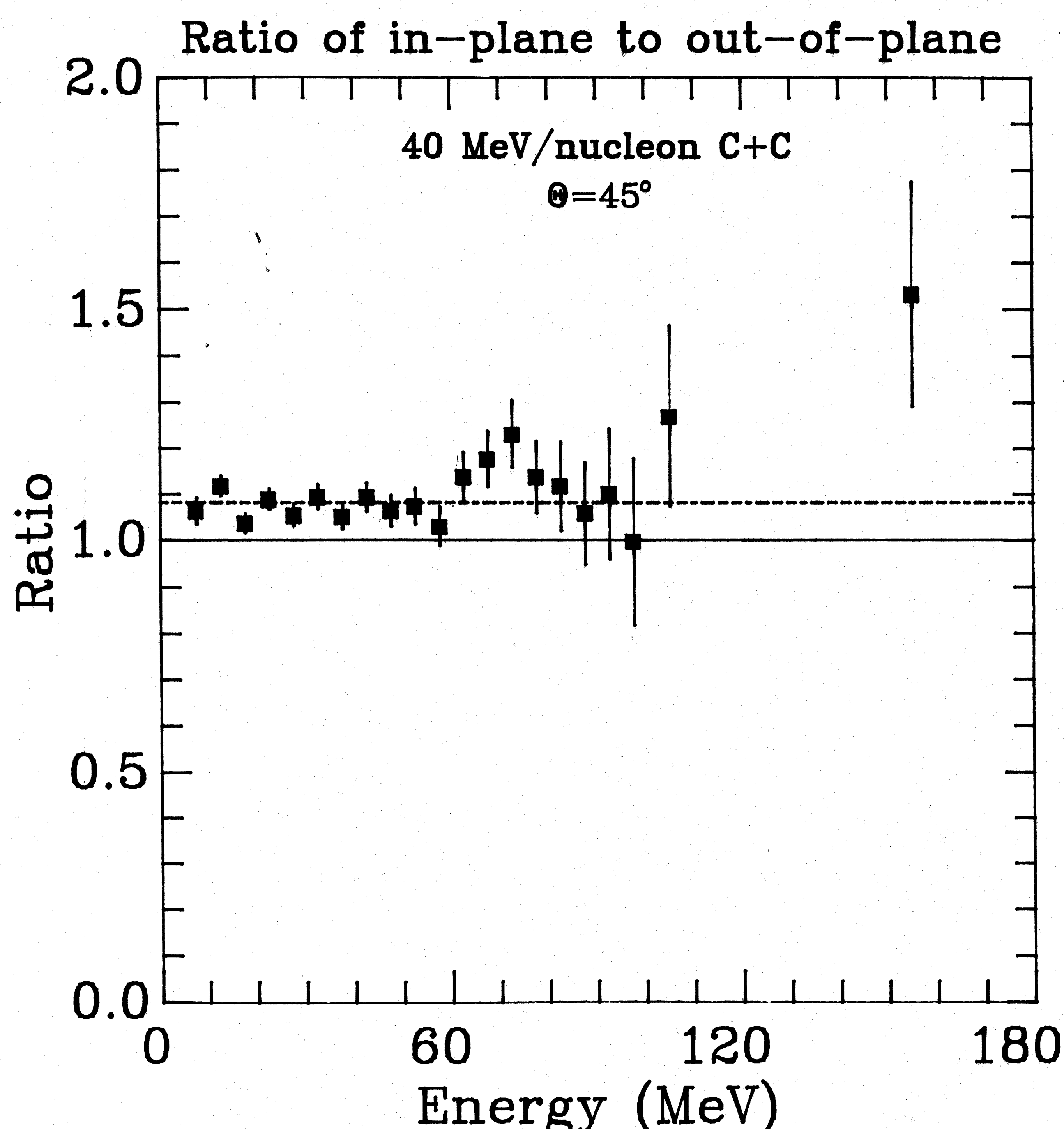
Fig. 1. Inclusive spectra for p,d,t,^{3}He,and ^{4}He from 40 MeV/nucleon C+C.

Fig. 2. Ratio of in- to out-of-plane p-p correlations for $\theta = 45°$ as a function of energy in the movable telescope from 40 MeV/nucleon C+C.

Fig. 3. Angular distribution of the ratio of in-plane to out-of-plane correlations for p-p, d-d, t-t, ^{3}He-^{3}He, and ^{4}He-^{4}He from 40 MeV/nucleon C+C.

Fig. 4. Angular distribution of the ratio of in-plane to out-of-plane correlations for p-p and ^{4}He-^{4}He from 40 MeV/nucleon C+C compared with a momentum conservation calculation (solid lines) and with VUU calculation (circles with histogram).


40 MeV/nucleon C+C
p
d
t
3 He
α
25°
35°
45°
55°
60°
90°
120°
Energy (MeV/nucleon)
d²σ/dE dΩ (mb/[MeV/nucleon]·sr)


Ratio of in−plane to out−of−plane
40 MeV/nucleon C+C
Θ=45°
Ratio
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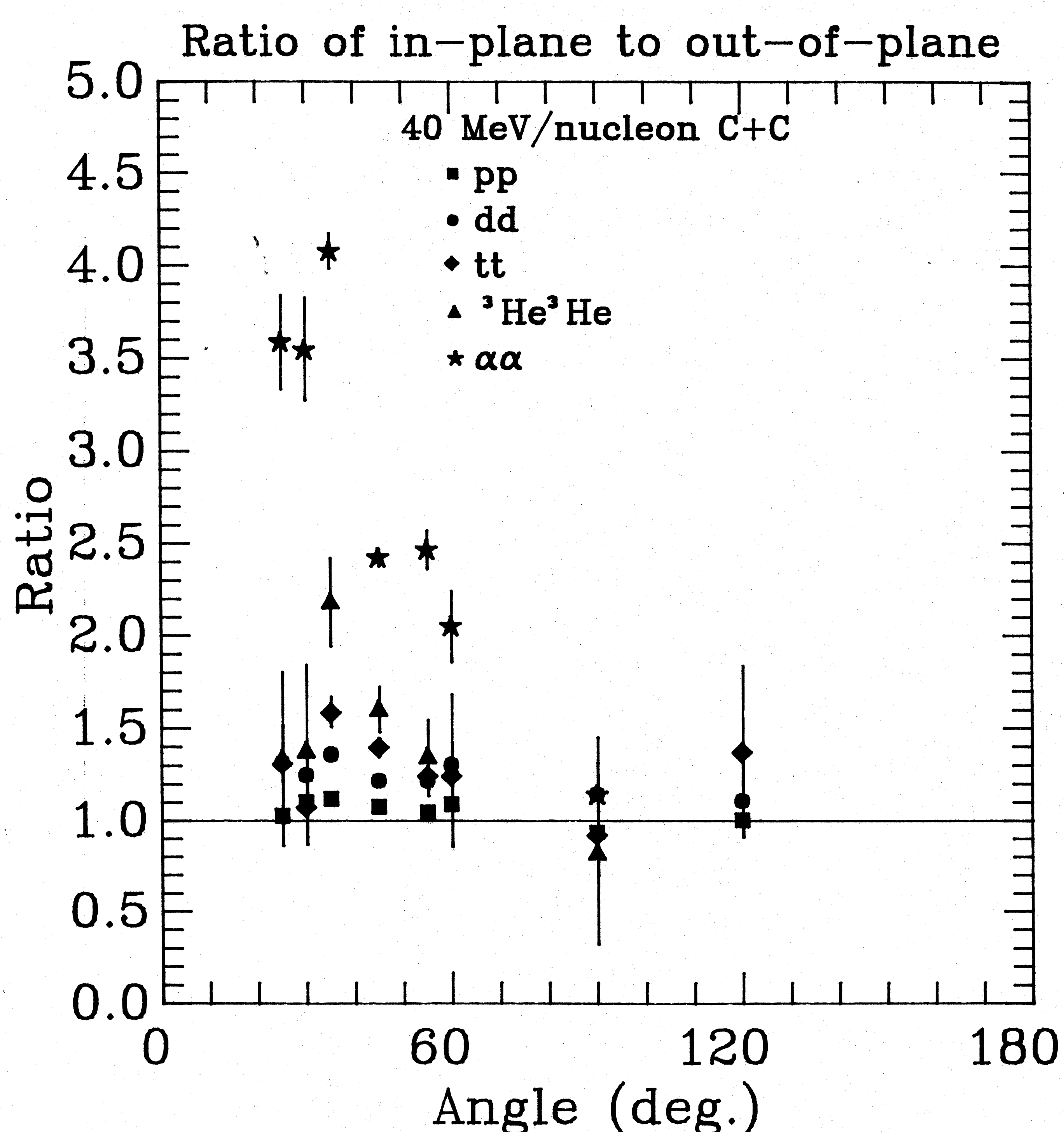
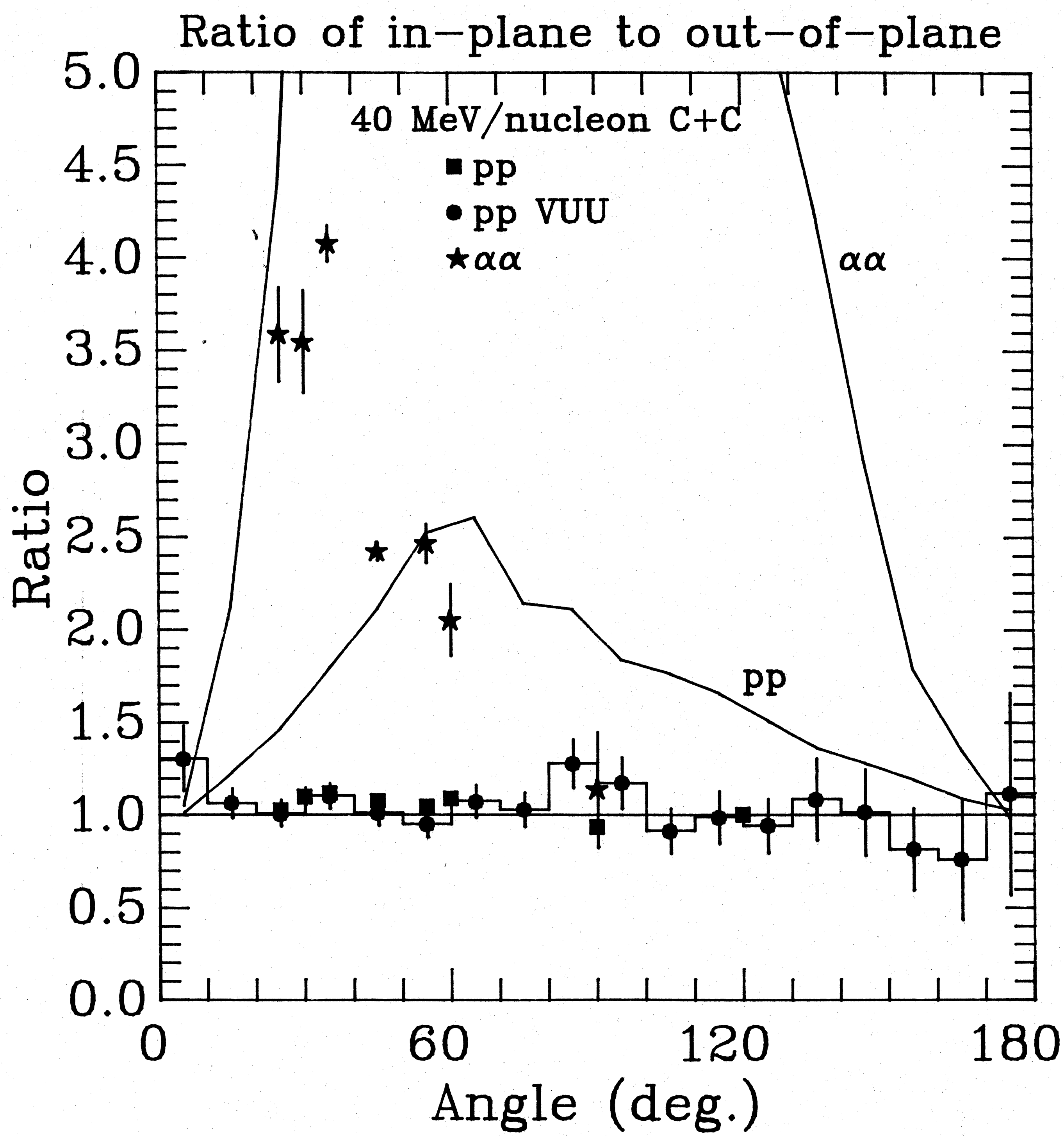
1.5
1.0
0.5
0.0
0
60
120
180
Energy (MeV)



Ratio of in−plane to out−of−plane
40 MeV/nucleon C+C
pp
dd
tt
³He³He
αα
Ratio
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
60
120
180
Angle (deg.)


Ratio of in-plane to out-of-plane
40 MeV/nucleon C+C
pp
pp VUU
αα
αα
pp
Ratio
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
60
120
180
Angle (deg.)