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Abstract

Using charged-particle-exclusive measurements of Au + Au collisions in the Bevalac's EOS time projection chamber, we investigate phase-space densities of fragments up to ^{4}He as a function of fragment transverse momentum, azimuth relative to the reaction plane, rapidity, multiplicity and beam energy.

Most features of these densities above a transverse momentum threshold are consistent with phase-space coalescence, and in particular, the increase in sideward flow with fragment mass is generally well described by a phase-space power law.

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Measurements of single-particle-inclusive spectra from heavy ion collisions provide evidence for a simple description of light fragment production in terms of a coalescence model [1]: the observed invariant phase-space density ρ_A for fragments with mass number A and momentum $A\mathbf{p}$ closely follows the Ath power of the observed proton density ρ_1^A at momentum $\mathbf{p}$. This power law behavior was found to hold for spectra of fragments up to $A = 14$ with projectiles ranging from protons to Au at a variety of beam energies between $0.1A$ GeV and $15A$ GeV [2]; some deviations occur for spectra at small laboratory polar angles where many of the fragments are emitted from the projectile spectator. We can gain insight into the collision dynamics from a determination of the conditions where the power law holds as well as where it breaks down. In the present work, we test the power law up to ^{4}He in Au + Au collisions, for the first time studying ρ_A as a function of fragment azimuth relative to the event reaction plane.

Power law behavior on the part of participant fragments can be compatible with many possible descriptions of the collision process. These range from the simple fireball model [3] where the participants are assumed to resemble a thermally-equilibrated gas, to elaborate microscopic approaches [4] where the time-evolution of the system is followed at the nucleon level. In central heavy ion collisions at a few hundred MeV/nucleon, each nucleon undergoes many interactions in which the available energy is large in comparison to the binding energy of nuclei, and it is doubtful that the correlations which govern the formation of composite fragments can exist [4,5] until the system has expanded to where the rate of interactions drops towards zero and chemical freezeout takes place. In a coalescence description, nucleons that are close in position and velocity at freezeout emerge from the interaction zone as composite fragments. Because participant fragments generally obey the power law in momentum space alone, we conclude that spatial density variations are independent of momentum. On the other hand, phase-space coalescence is inappropriate for describing fragments resulting from spectator breakup, since the process in this case is totally different from the freezeout of a hot nucleon gas [4,6].

The simplest phase-space coalescence model [1], which neglects differences between proton and neutron spectra and ignores spatial density effects, predicts that coalescence coefficients $C_A = \rho_A/\rho_1^A$ depend only on fragment type. An explicit treatment of spatial density through six-dimensional coalescence [7] can be useful if the number of participants varies. Assuming that the average spatial density at freezeout varies little with the size of the system, we expect C to decrease if the number of participants increases, as occurs with an increase in the mass of the colliding ions or with an increase in the centrality of the collisions. This trend is indeed observed among the inclusive data [2], and the multiplicity dependence of abundance ratios measured by the Plastic Ball is also consistent with six-dimensional coalescence [8].

This Letter is based on Au + Au data from the EOS time projection chamber (TPC) at Lawrence Berkeley Laboratory. This TPC is the principal subsystem of the EOS detector; it has rectangular geometry and operates in a 1.3 T magnetic field. Details about the detector and its performance can be found elsewhere [9,10,6]. We report results for fragments emitted forward of mid-rapidity, where acceptance is optimum; our samples after multiplicity selection contain about 35,000 events at a beam energy of $1.15A$ GeV, and typically, 6,000 events each at $1.0A$, $0.8A$, $0.6A$ and $0.25A$ GeV. Following the convention introduced by the Plastic Ball group, we characterize the centrality of collisions in terms of baryonic fragment multiplicity M as a fraction of $M_{\max}$, where $M_{\max}$ is a value near the upper limit of the M spectrum where the height of the distribution has fallen to half its plateau value [11]. Mult 1 through Mult 4 denote the four intervals of M with upper boundaries at 0.25, 0.5, 0.75 and 1.0 times $M_{\max}$, respectively, and Mult 5 denotes $M > M_{\max}$.

To assess the extent to which a coalescence prescription describes light composite fragment production in the EOS TPC, we first use our largest sample ($1.15A$ GeV Au + Au) to test the agreement between the shapes of $\rho_A(x)$ and $\rho_1^A(x)$, where x is any observable such that ρ varies significantly over its range. The solid circles in the upper panels of Fig. 1 show the dependence on $p^\perp/A$ of the deuteron density $\rho_2 = kA^2 dN/p^\perp dp^\perp$ for Mult 4 events in five intervals of center-of-mass rapidity y', where y' denotes rapidity divided by the projectile rapidity. The constant k is a normalization factor, and the ordinate has arbitrary units. We show the relative proton density as solid curves normalized to the same area, and the normalized proton density squared is given by the dashed curves. This normalization is equivalent to optimizing coalescence coefficients C separately in each y' interval; the variation of C with y' is considered later. Statistical uncertainties approach the symbol size near the upper end of the $p^\perp/A$ scale, but are far smaller at the lower end. Accordingly, the insets in the upper right corners show the same data with better resolution at lower $p^\perp/A$, using a linear scale on the ordinate. These results for high multiplicity Au + Au collisions show a level of adherence to power law behavior that is comparable to what was reported previously for single-particle-inclusive measurements, and demonstrate the persistence of phase-space coalescence behavior for a larger mean number of participant nucleons.

We do not expect C to be constant across regions where the assumptions underlying the simple phase-space coalescence model do not hold, for example, where proton and neutron spectra differ due to Coulomb effects. Inclusive neutron [12] and proton [2] spectra have been published for the same system in the case of $0.8A$ GeV Ne + NaF; no differences within uncertainties are observed at large $p^\perp$, whereas at $p^\perp_{\rm neut} \sim 0.3$ GeV/c, proton spectra are shifted about 0.1 GeV/c. For all results that follow (other than the determination of $\mathbf{Q}$, described below), a cut requiring $p^\perp/A \geq 0.2$ GeV/c is imposed. Adherence to the power law deteriorates marginally using the cut $p^\perp/A \geq 0.15$ GeV/c, and with no cut, discrepancies can be large compared with statistical errors.

The center panels of Fig. 1 show the dependence of phase-space density on $\Phi = |\phi - \phi_R|$, the azimuthal angle of fragment i relative to the event reaction plane as defined by the vector $\mathbf{Q}_i = \sum_{j\neq i}^{M} w(y'_j)\mathbf{p}^\perp_j$ [13]. The weighting factor $w(y'_j)$ is designed to optimize the correlation of $\mathbf{Q}$ with the reaction plane; we follow the prescription $w(y'_j) = \min(1,\ y'_j/0.8)$, where $y' > 0$. Here, the normalization factor k is chosen so that the mean ordinate is 1. The solid circles, the solid curves and the dashed curves have the same meaning as in the upper panels, while the open circles denote the relative density of fragments with $A = 3$ and the dotted curves denote the three-halves power of the deuteron density. We choose to plot $\rho_2^{3/2}$ in place of ρ_1^3; these two quantities are close to each other, but ρ_1^3 can have a larger uncertainty because of the larger exponent. There is a considerable body of experimental literature [14–19] describing an increase with A of observables related to the mean in-plane transverse momentum per nucleon $\langle p^x(y)/A \rangle$ [13]. This phenomenon was first suggested by hydrodynamic models [20], in which collective effects were seen more clearly for heavier fragments. Quantum Molecular Dynamics, a model which follows the time evolution of the full multi-nucleon phase space distribution, also exhibits a mass dependence, attributed to early formation and sideward deflection of light and intermediate-mass composites [21]. The mass dependence of $\langle p^x(y)/A \rangle$ persists when the standard $p^{\perp}$ cut is applied to our data. The lower panels of Fig. 1 show relative p^x/A densities for protons and deuterons using the same symbols as before. The combination of power law behavior and the asymmetry in the p^x distribution can suffice to explain the A dependence of $\langle p^x(y)/A \rangle$ for $p^{\perp}/A \geq 0.2$ GeV/c.

The applicability of the phase-space power law to $\rho(\Phi)$ or $\rho(p^x)$ has not been explored previously. However, using a Boltzmann-Uehling-Uhlenbeck (BUU) model combined with a six-dimensional coalescence prescription for separating masses 1 and 2 from 3 and 4, Koch *et al.* [22] reported reasonable agreement with Plastic Ball $\langle p^x(y)/A \rangle$ data for charges 1 and 2 in 200A MeV Au + Au collisions [15]. BUU uses a test-particle method for treating the nuclear mean field that smears-out local density fluctuations and casts doubt on the suitability of this model for treating composite fragment formation unless final state coalescence is the only important mechanism. Koch *et al.* did not impose a $p^{\perp}$ cut, but their satisfactory agreement can be reconciled with our findings by noting that Plastic Ball is inefficient for fragments with low $p^{\perp}/A$ and uncertainties arise from the need to simulate its acceptance; furthermore, the BUU calculation introduced possible model dependence and involved coalescence radii in both position and momentum.

Our results offer the first quantitative illustration that the A dependence of sideward flow above a $p^{\perp}$ threshold can be understood, using only experimental data, as a phase-space coalescence effect. Our data do not exclude the possibility that a general coalescence prescription determines composite formation at low $p^{\perp}/A$, because Coulomb effects or spatial correlations or both may be responsible for departures from the power law in this region.

Because of the high density of fragments close to the reaction plane in high multiplicity Au + Au collisions, there is a large difference between the density of free protons and the density of all protons be they bound in fragments or not; good agreement with the power law is obtained only if the free protons are used. This finding is consistent with chemical equilibrium being established at the time of freezeout [7].

Figure 2 displays the variation of C as a function of multiplicity and rapidity for Au + Au at 1.15A GeV. We define coalescence coefficient as $C_{AA'} = \rho_A / \rho_{A'}^{A/A'}$ where ρ here denotes dN/dy'. Choosing $A' > 1$ can help avoid magnification of uncertainties, as explained in the discussion of Fig. 1. The observed C is consistent with being independent of rapidity except where spectator fragmentation becomes important, in agreement with the inclusive data from the Bevalac [2]. The decrease in C with increasing multiplicity is a trend that is expected if spatial effects are considered, as explained previously.

In this Letter, we focus on the extent to which the power law describes the A-dependence of $\rho_A(\Phi)$ for light fragments. The $dN/d\Phi$ spectra, as illustrated in the center panels of Fig. 1, have been fitted to functions of the form $1+\lambda\cos\Phi+\alpha\cos 2\Phi$. The second term allows better fits to be obtained for the strongest azimuthal asymmetries, where there are deviations from a cosine shape. The notation λ_A signifies fit values for fragments with mass A, while $\lambda_{AA'}$ signifies fits to the spectrum for mass A' raised to the power of A/A'. In Fig. 3, we present tests of power law behavior through λ comparisons for the full Au + Au sample spanning beam energies between 0.25A GeV and 1.15A GeV. Overall, we conclude that the power law is remarkably consistent in describing fragment flow for $p^{\perp}/A \geq 0.2$ GeV/c, as parametrized by λ. The most prominent deviation is a tendency for the Ath power of the proton spectra (the open triangles) to overpredict the observed λ values at forward rapidities. The same tendency is not repeated in the deuteron spectra to the power of $A/2$. This deviation has a pattern of dependence on rapidity and multiplicity that is qualitatively consistent with the excess protons having evaporated from the projectile spectator, which is known to experience a sideward deflection in the reaction plane [11].

An important advantage of the EOS TPC is its good particle identification [10] and its seamless acceptance, which are simple enough to be simulated accurately. Using various event generators, we have compared the observables under investigation before and after filtering through a detailed GEANT-based simulation of the TPC. We find that detector distortions are comparable to or smaller than the symbol sizes or error bars in Figs. 1 and 3. In Fig. 2, the uncertainties in cases where error bars are larger than the symbol size are predominantly systematic, and are due to uncertainties in particle identification.

Because fragment distributions at $p^{\perp}/A \geq 0.2$ GeV/c are described within the uncertainties of this experiment by the phase-space power law, an experimental flow analysis subjected to this cut and using observables that are invariant under coalescence may not incur a loss of information about the compressional effects which are believed to cause the flow [4] if the observables are averaged over all abundant fragment species. However, the widely used $\langle p^{x}/A \rangle$ analysis is not coalescence invariant. Likewise, our findings support the use of one-body transport models such as BUU for drawing inferences about the nuclear equation of state from comparisons with coalescence-invariant flow observables averaged over all abundant fragment species, as long as fragments with low $p^{\perp}/A$ are excluded. A caveat is that a significant amount of the observed flow signal is carried by particles with lower $p^{\perp}/A$, and it is important to complement what is learned from comparisons of the type just described by carrying out more demanding comparisons in which models that include a more general treatment of composite formation [4,5] are tested against the flow data for a variety of fragments species without $p^{\perp}$ cuts [23]. Overall, we conclude that the simple phase-space power law consistently describes light fragment production in the participant zone over a remarkably wide range of conditions in intermediate-energy heavy-ion collisions.

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REFERENCES

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[1] S.F. Butler and C.A. Pearson, Phys. Rev. **129**, 836 (1963).

[2] H.H. Gutbrod *et al.*, Phys. Rev. Lett. **37**, 667 (1976); M.-C. Lemaire *et al.*, Phys. Lett. **85B**, 38 (1979); B.V. Jacak, D. Fox, and G.D. Westfall, Phys. Rev. C **31**, 704 (1985); S. Hayashi *et al.*, Phys. Rev. C **38**, 1229 (1988); N. Saito *et al.*, Phys. Rev. C **49**, 3211 (1994).

[3] G.D. Westfall *et al.*, Phys. Rev. Lett. **37**, 1202 (1976).

[4] For reviews, see H. Stöcker and W. Greiner, Phys. Rep. **137**, 277 (1986); G.F. Bertsch and S. Das Gupta, Phys. Rep. **160**, 189 (1988); J. Aichelin, Phys. Rep. **202**, 233 (1991).

[5] P.-B. Gossiaux *et al.*, submitted to Phys. Rev. C.

[6] M.L. Gilkes *et al.*, submitted to Phys. Rev. Lett.

[7] A.Z. Mekjian, Nucl. Phys. **A312**, 491 (1978); H. Sato and K. Yazaki, Phys. Lett. **98B**, 153 (1981).

[8] K.G.R. Doss *et al.*, Phys. Rev. C **32**, 116 (1985).

[9] G. Rai *et al.*, IEEE Trans. Nucl. Sci. **37**, 56 (1990).

[10] E. Hjort *et al.*, in *"Advances in Nuclear Dynamics"*, ed. B. Back, W. Bauer and J. Harris, (World Scientific, Singapore, 1993), p. 63.

[11] H.-Å. Gustafsson *et al.*, Phys. Rev. Lett. **52**, 1590 (1984).

[12] R. Madey *et al.*, Phys. Rev. Lett. **55**, 1453 (1985).

[13] P. Danielewicz and G. Odyniec, Phys. Lett. **157B**, 146 (1985).

[14] M.B. Tsang *et al.*, Phys. Rev. Lett. **57**, 559 (1986).

[15] K.G.R. Doss *et al.*, Phys. Rev. Lett. **59**, 2720 (1987).

[16] C.A. Ogilvie *et al.*, Phys. Rev. C **40**, 2592 (1989).

[17] J.P. Sullivan *et al.*, Phys. Lett. B **249**, 8 (1990).

[18] G.D. Westfall *et al.*, Phys. Rev. Lett. **71**, 1986 (1993).

[19] A. Kugler *et al.*, Proc. of *International Workshop XXII on Gross Properties of Nuclei and Nuclear Excitations*, ed. H. Feldmeier and W. Nörenberg, (GSI, Darmstadt, 1994), and Phys. Lett. B (in press).

[20] H. Stöcker, A.A. Ogloblin, and W. Greiner, Z. Phys. **A303**, 259 (1981); H.G. Baumgardt *et al.*, Z. Phys. **A273**, 359 (1975).

[21] G. Peilert *et al.*, Phys. Rev. C **39**, 1402 (1989).

[22] V. Koch *et al.*, Phys. Lett. B **241**, 174 (1990).

[23] M.D. Partlan *et al.*, to be published.

FIGURES

FIG. 1. Relative phase-space density for deuterons (solid circles), protons (solid curves) and relative proton density squared (dashed curves) in Mult 4 collisions of $1.15A$ GeV Au + Au as a function of transverse momentum per nucleon (top), azimuth relative to the event reaction plane (center), and transverse momentum per nucleon projected on the reaction plane (bottom). In the center panels, the open circles indicate the density for fragments with $A = 3$ and the dotted curves the density for deuterons to the power of 3/2.

FIG. 2. Coalescence coefficients $C_{AA'}$ as a function of multiplicity and rapidity for light fragments from $1.15A$ GeV Au + Au collisions. The coefficients were calculated in units of tracks/event/y' unit, and were multiplied by 100 times the indicated scale factors before plotting.

FIG. 3. Sideward flow parameters λ as a function of rapidity. The open triangles indicate λ_{A1}, the parameter based on the Ath power of the proton spectrum. The solid circles indicate both λ_2, the parameter for deuterons, and λ_{A2}, the parameter for the deuteron spectrum to the power of $A/2$. Likewise, the open circles indicate λ_3 and λ_{A3}, and the solid triangles indicate λ_4.

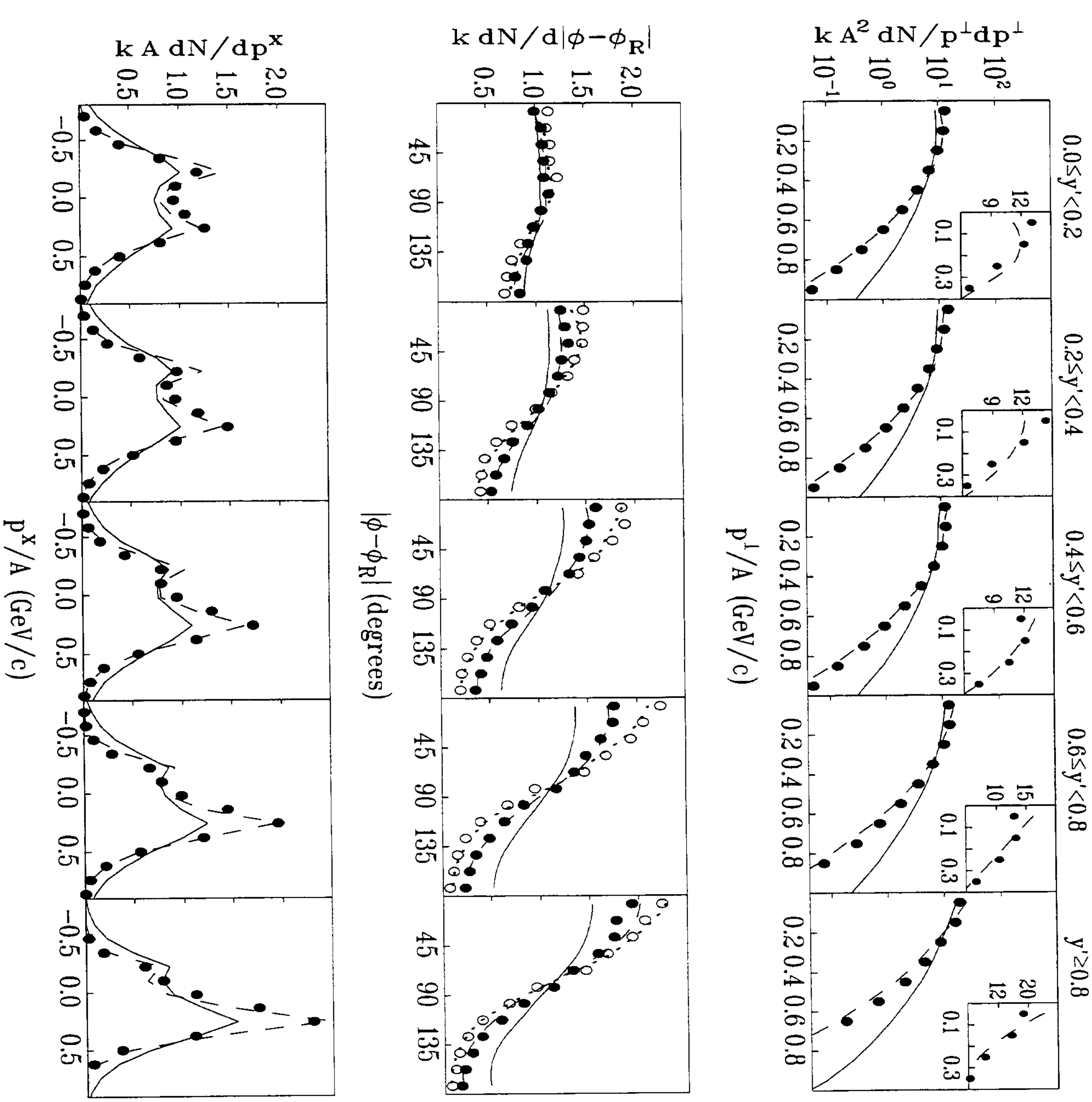

Figure 1: S. Wang and the EOS Collaboration

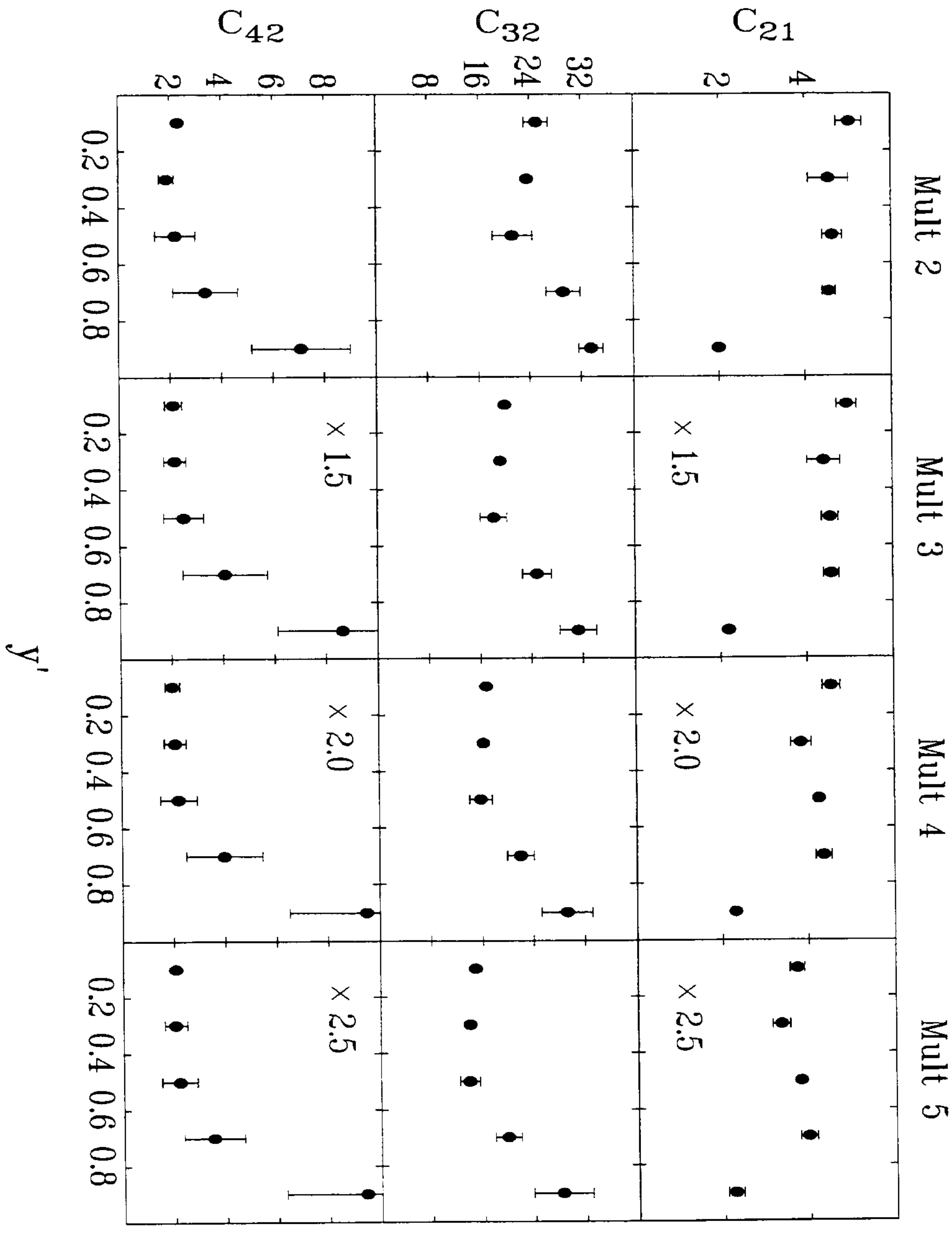

Figure 2: S. Wang and the EOS Collaboration

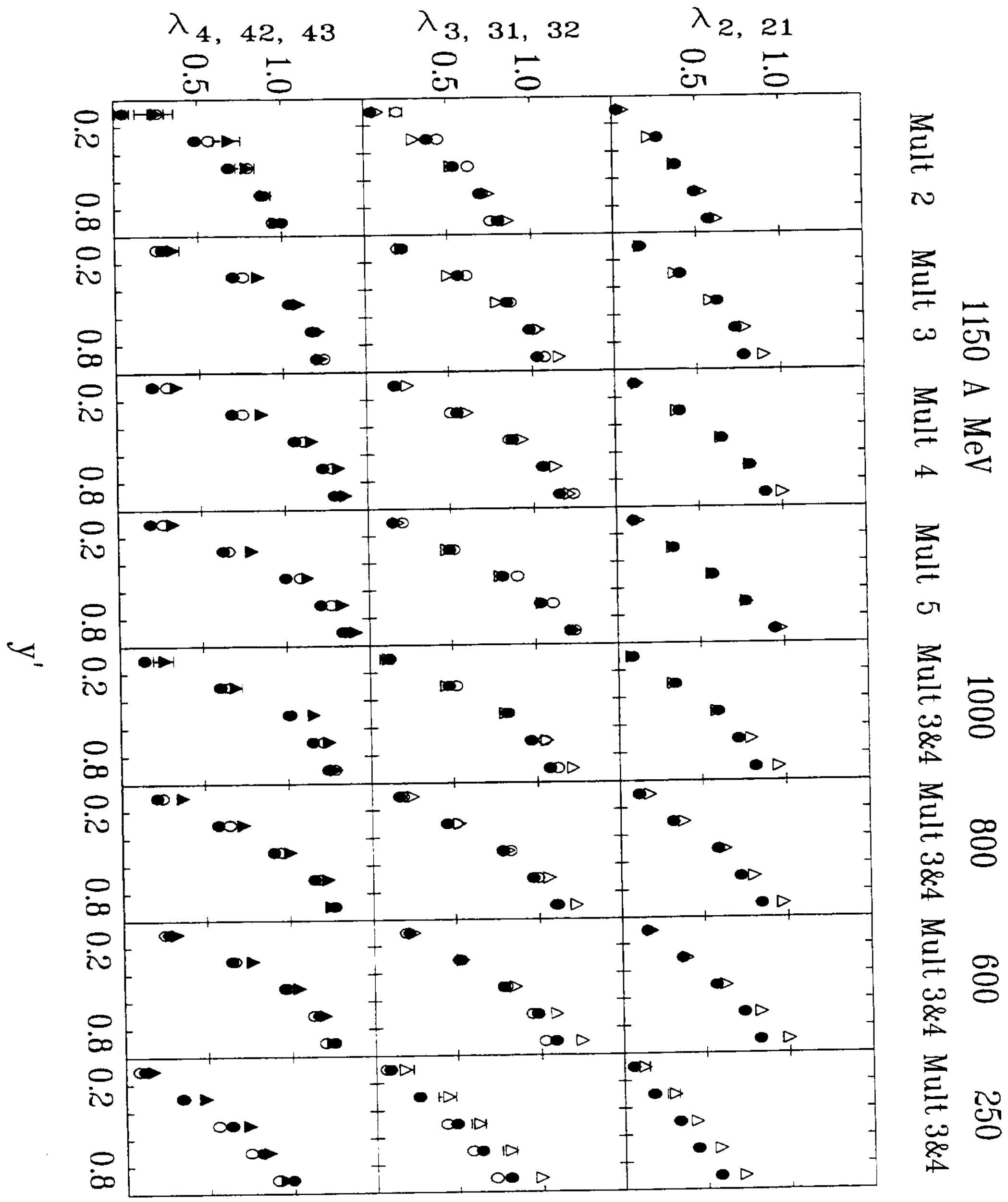

Figure 3: S. Wang and the EOS Collaboration