Radial Flow in Au + Au Collisions at $E = (0.25\text{–}1.15)A$ GeV

M. A. Lisa,[1] S. Albergo,[6] F. Bieser,[1] F. P. Brady,[4] Z. Caccia,[6] D. A. Cebra,[4] A. D. Chacon,[5] J. L. Chance,[4] Y. Choi,[3] S. Costa,[6] J. B. Elliott,[3] M. L. Gilkes,[3] J. A. Hauger,[3] A. S. Hirsch,[3] E. L. Hjort,[3] A. Insolia,[6] M. Justice,[2] D. Keane,[2] J. Kintner,[4] H. S. Matis,[1] M. McMahan,[1] C. McParland,[1] D. L. Olson,[1] M. D. Partlan,[4] N. T. Porile,[3] R. Potenza,[6] G. Rai,[1] J. Rasmussen,[1] H. G. Ritter,[1] J. Romanski,[6] J. L. Romero,[4] G. V. Russo,[6] R. Scharenberg,[3] A. Scott,[2] Y. Shao,[2] B. K. Srivastava,[3] T. J. M. Symons,[1] M. Tincknell,[3] C. Tuvé,[6] S. Wang,[2] P. Warren,[3] G. D. Westfall,[1,7] H. H. Wieman,[1] and K. Wolf[5]

(EOS Collaboration)

[1]*Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley, California 94720*
[2]*Kent State University, Kent, Ohio 44242*
[3]*Purdue University, West Lafayette, Indiana 47907-1396*
[4]*University of California, Davis, California 95616*
[5]*Texas A&M University, College Station, Texas 77843*
[6]*Università di Catania & INFN-Sezione di Catania, Catania, Italy 95129*
[7]*NSCL, Michigan State University, East Lansing, Michigan 48824*

(Received 15 August 1994)

A systematic study of energy spectra for light particles emitted at midrapidity from Au + Au collisions at $E = (0.25\text{–}1.15)A$ GeV reveals a significant nonthermal component consistent with a collective radial flow. This component is evaluated as a function of bombarding energy and event centrality. Comparisons to quantum molecular dynamics and Boltzmann-Uehling-Uhlenbeck models are made for different equations of state.

PACS numbers: 25.75.+r, 25.70.Gh

Collective motion plays an important role in the expansion and decay of compressed and excited nuclear matter created in nucleus-nucleus collisions over a wide range of incident energies [1–15]. Initial interest in collective motion centered on the possibility that one might learn about nuclear matter compressibility and the nuclear equation of state from its measurement [1,3,4]. Two different major forms of collective matter flow can be distinguished. First, there is a nonisotropic streaming pattern of hadrons leading to the well-established "side splash" and "bounce-off" phenomena [5–8]. The focus of the present Letter is on the second form of collective matter flow: isotropic radial flow. Originally suggested [9] as a signal of an isentropic expansion mechanism that converts part of the primordial isotropic thermal energy density to a radially ordered expansion flow pattern, this collective mode may actually account for a higher fraction of the final hadronic kinetic energy than the subtle directed flow modes. Its most direct signature should be a modification of the hadronic transverse momentum spectra. In the simple thermodynamic "fireball" model [16], a nonisentropic expansion results in transverse momentum spectra that are, in the classical limit, of Maxwell-Boltzmann type, determined by the source temperature T. In an isentropic hydrodynamic expansion model a "shoulder arm" spectral shape arises, controlled by the radial velocity β and by the temperature T.

While pion spectra turn out to be rather insensitive to the radial flow phenomenon [9], for heavier particles, the shoulder arm clearly manifests itself. We shall show in this Letter that the radial velocity grows up to $\beta \approx 0.33$ with increasing bombarding energy in Au + Au collisions, and we find the "true" hadronic decoupling temperature to be below 85 MeV, whereas the Maxwell-Boltzmann interpretation would suggest an (implausible) freeze-out temperature of about 160 MeV, and a temperature that changes with emitted particle type. Furthermore, by comparing our data to mean field dynamical model calculations, we arrive at the (unexpected) conclusion that radial flow exhibits little sensitivity to the nuclear compressibility, in contrast to the behavior of the directed flow.

The data were taken at Lawrence Berkeley Laboratory using Au beams from the Bevalac with bombarding energies in the range $E = (0.25\text{–}1.15)A$ GeV incident on a gold target. Reaction products were measured in the EOS experimental setup, which included a time projection chamber (TPC) [17], a multisampling ion chamber [18], a time-of-flight wall, a neutron spectrometer [19], and beam diagnostic detectors. This Letter is concerned only with data measured in the TPC.

The TPC is well suited to search for radial flow. Its good particle identification [20] allows simultaneous study of particle species with different masses, important since a particle's energy due to flow is proportional to the mass, while its thermal energy is not [2,9,10,12]. The absence of a low-p_T detection threshold and good acceptance at midrapidity allow the study of spectral shapes for particles emitted primarily from the midrapidity source ($\theta_{\text{c.m.}} \approx 90°$), eliminating the need for very stringent centrality cuts that attempt to select spherically symmetric events

0031-9007/95/75(14)/2662(4)$06.00

[10], and allowing us to explore the impact parameter dependence of the radial flow. We determine the event centrality by multiplicity cuts similar to those used by the Plastic Ball group [6]. The multiplicity distribution assumes a value of half its plateau value at $M_{\max}$. The region $M = 0 - M_{\max}$ is divided into eight equal-width bins. The most central events have $M > M_{\max}$ and fall into bin 9.

The energy spectrum in the center of mass for a particle emitted from a thermally equilibrated, radially expanding source, characterized by a temperature T and a radial flow velocity β, is given by [9]

$$\frac{d^3N}{dEd^2\Omega} \sim pe^{-\gamma E/T}\left\{\frac{\sinh\alpha}{\alpha}(\gamma E + T) - T\cosh\alpha\right\}, \tag{1}$$

where E and p are the total energy and momentum of the particle in the center of mass, $\gamma = (1 - \beta^2)^{-1/2}$, and $\alpha = \gamma\beta p/T$. Although somewhat schematic, the concept of a source provides a useful way to parametrize the data and identify important components in the decay of the excited system.

We have extracted source temperature and radial flow velocity parameters by fitting the form (1) to the energy spectra measured at $\theta_{\mathrm{c.m.}} = 90° \pm 15°$, using a χ^2 minimization technique. In Fig. 1, we show kinetic energy spectra for H and He isotopes for the reaction Au + Au at $E = 1.0A$ GeV. The data are from the most central (highest multiplicity) events, corresponding to less than 5% of the total cross section ($b \approx 0$–3 fm in a geometrical picture). Also shown are fits to the spectrum with the form (1). Solid lines indicate a simultaneous fit to all spectra, excluding the proton spectrum (see below), by varying β and T, and fixing the relative normalization of the fits for different particle types to match measured relative yields. A good overall fit is obtained ($\chi^2/\nu \sim 1$). Dashed lines show fits with a purely thermal scenario ($\beta = 0$). The spectral shapes are not as well reproduced, especially for the heavier fragments. At all bombarding energies, fits with nonzero flow consistently yield a χ^2/ν value 2–4 times smaller than thermal fits. Fits to event-generated spectra before and after filtering through the simulated detector response indicate that temperature and flow velocity change by less than 10% and 4%, respectively, well within the statistical uncertainties.

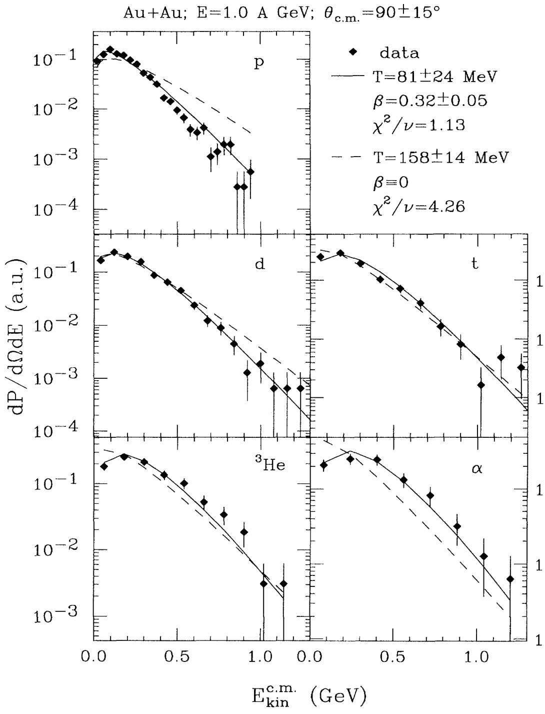

FIG. 1. Center-of-mass kinetic energy spectra for light fragments emitted into $\theta_{\mathrm{c.m.}} = 90° \pm 15°$ from the reaction Au + Au at $E = 1.0A$ GeV are shown with statistical uncertainties. Fits of the spectra assuming a radially expanding thermal source (solid lines) and a purely thermal source (dashed lines) are also shown.

Fits to d, t, ^{3}He, and α spectra individually yield T and β values consistent with those obtained with the simultaneous fit of all particle types. However, fit parameters for proton spectra consistently indicate a lower temperature (by ~20%) and greater flow (by about 0.06c). Calculations with a fireball model [16] indicate that these deviations can be qualitatively understood in terms of distortions of the proton spectrum due to baryonic (e.g., Δ) and nuclear (e.g., ^{5}Li) resonance decay. At $E_{\mathrm{beam}} = 600A$ MeV, for example, fitting the calculated spectrum for "thermal" (primordial) protons with Eq. (1) gives $(T, \beta) = (74\ \mathrm{MeV}, 0)$, while the spectra for protons coming from baryonic and nuclear resonances give $(T, \beta) = (58\ \mathrm{MeV}, 0.22)$ and $(35\ \mathrm{MeV}, 0.07)$, respectively. Fitting the overall calculated spectrum gives $(T, \beta) = (66\ \mathrm{MeV}, 0.13)$. A further complication is that the TPC detector acceptance for midrapidity protons begins to differ slightly from 100%.

To explore the possibility that directed flow effects are affecting the fits of the spectra, which are integrated over azimuthal angle, we also constructed and fit energy spectra at $\theta_{\mathrm{c.m.}} = 90° \pm 15°$ for particles emitted in and out of the reaction plane [5] ($|\phi_{\mathrm{rp}}| < 45°$ and $|\phi_{\mathrm{rp}}| > 45°$, respectively). Differences between in- and out-of-plane fits were 1–2 MeV in T and 0.01c in β (compared to uncertainties of about 20 MeV and 0.05c). To increase sensitivity to possible squeeze-out effects [21,22], the spectra were measured at 90° with respect to the flow axis (as opposed to the beam axis) and cut on $|\phi_{\mathrm{rp}}|$; again, the changes (about 15 MeV in T and 0.04 in β) were smaller than the uncertainties (about 30 MeV in T and 0.1 in β).

In Fig. 2, we plot extracted flow and temperature parameters as a function of bombarding energy for central collisions. Both are seen to increase with bombarding energy. However, if we estimate the average thermal and collective components of the energy of a particle as $E_T = 3T/2$ and $E_F = (\gamma - 1)m$ [where $\gamma = (1 - \beta^2)^{-1/2}$], respectively, then our results for central collisions indicate

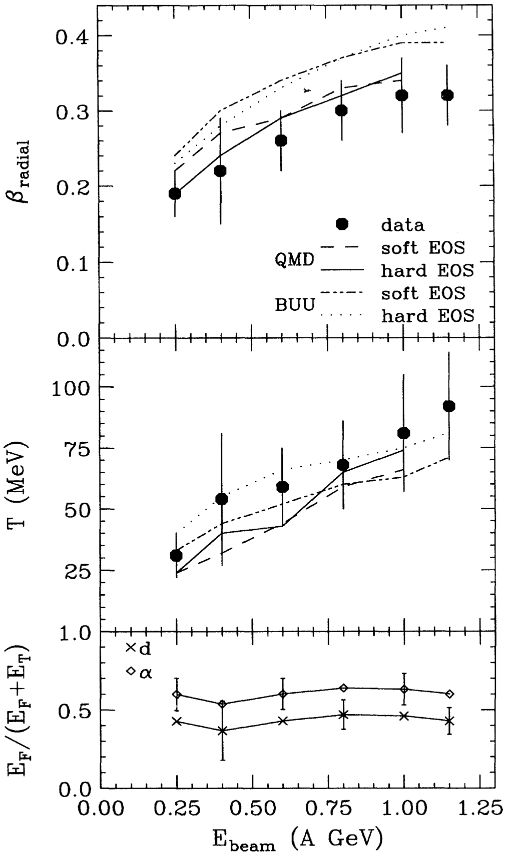

FIG. 2. Bombarding energy dependence of the temperature and radial flow parameters extracted from the spectra for central Au + Au collisions. Fits to spectra generated by QMD model with soft (dashed lines) and hard (solid lines) equations of state (EOS), and by a BUU model with a soft (dot-dashed lines) and hard (dotted lines) EOS, are also shown; uncertainties for these parameters are on the same order as those for the data. The bottom panel shows the average fractional contribution of the collective flow to the energy of emitted deuterons and alphas; every second error bar is omitted for clarity.

that about 45% of the kinetic energy of deuterons goes into collective radial flow (60% for alphas), independent of bombarding energy, as is shown in the bottom panel of Fig. 2. Also shown are the results of fits to energy spectra generated by a quantum molecular dynamics (QMD) model with momentum-dependent interactions [23], and with a Boltzmann-Uehling-Uhlenbeck (BUU) transport model that incorporates the emission light mass fragments [2], using a geometric impact parameter distribution in the range $b = 0-3$ fm. These fits are based solely on the shape of the energy spectra, and not on the relative yield, since the BUU model only produces fragments up to mass $A = 3$, and the QMD model has been shown to produce too few complex fragments [24]. The calculated spectra follow the form of Eq. (1), and uncertainties in the model fits are of the same order as those for the data [e.g., for a hard equation of state at $E_{\text{beam}} = 600A$ MeV, $(T, \beta) = (43 \pm 16$ MeV, $0.29 \pm 0.04)$ for QMD, and $(66 \pm 9$ MeV, $0.33 \pm 0.02)$ for BUU].

Good agreement in T and β values is observed between the data and QMD with a soft or hard equation of state ($\kappa = 200$ and 380 MeV, respectively). The temperature parameters extracted from the BUU spectra ($\kappa = 200$ and 375 MeV) agree well with the data, while the radial flow values are systematically somewhat high. The uncertainties in the fit parameters for both the experimental and calculated spectra are larger than the difference between model predictions for different equations of state.

For noncentral collisions and at angles away from 90°, directed flow effects may dominate the energy spectra. An examination of the average energy of emitted particles is illustrative. Neglecting small relativistic effects, the average energy of a particle emitted from a thermal source depends only on the temperature. Superposition of radial flow adds an additional energy component proportional to the particle mass [2,9,10,12]. As shown in Fig. 3, a roughly linear relationship between $\langle E_{\text{kin}} \rangle$ and A is observed [25] for particles emitted at $\theta_{\text{c.m.}} \approx 90°$ from central Au + Au collisions. This linear scaling of $\langle E_{\text{kin}} \rangle$ with A, and not with Z, is a strong indication that Coulomb effects are not the dominant source of the radial flow signal. Also indicated is the relationship between $\langle E_{\text{kin}} \rangle$ and A expected from the β and T values extracted from the spectral shapes.

Similar linear relationships are observed for particles emitted at forward angles and for all multiplicities above the third multiplicity bin. The slopes of these relationships for Au + Au reactions at $E = 1.0A$ GeV are plotted as a function of multiplicity bin in Fig. 4 for $\theta_{\text{c.m.}} = 30°, 60°, 90° \pm 15°$. The absolute value and multiplicity dependence of the slopes of the relationships at 30°,

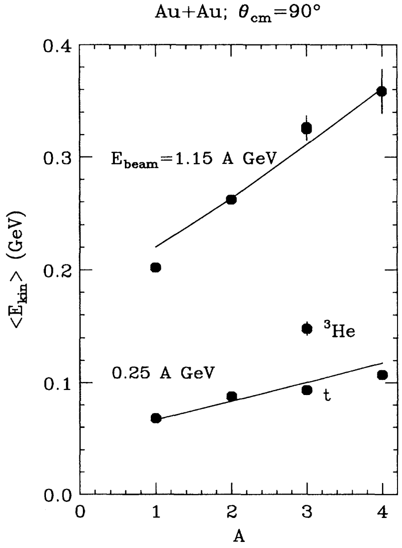

FIG. 3. Average kinetic energy for particle emitted at 90° in the center of mass as a function of the mass number A. Solid lines indicate $\langle E_{\text{kin}} \rangle$ vs A relationships corresponding to β and T parameters shown in Fig. 2.

where directed flow effects should play a more dominant role, differ markedly from those at 60° and 90°. In particular, at 90° the energy per nucleon induced by collective effects is seen to increase with increasing event centrality, while the A dependence of $\langle E_{\mathrm{kin}} \rangle$ for particles emitted at 30° decreases for the most central collisions, where directed flow is observed to decrease [6]. Indeed, when an additional cut is made such that the particle emitted at 30° is also emitted in the direction opposite of the flow ($p_x < 0$, where the positive $p_x - p_z$ quadrant contains the major axis of the momentum ellipse), the slope decreases with increasing event centrality, until it is seen to coincide with the slope values at 60° and 90°. Similar cuts have little effect on the slope values at 60° and 90°. Thus, the most central events, which are expected to be the most spherical in nature, show the clearest signal of "radial" flow. For reference, an impact parameter scale based on particle multiplicity [28] is indicated in Fig. 4.

In summary, energy spectra for light particle emitted from Au + Au reactions are well described in terms of a radially expanding, thermal source. At $\theta_{\mathrm{c.m.}} \approx 90°$, the collective contribution to the energy is seen to increase with decreasing impact parameter. At forward angles in the flow direction, directed flow is superimposed on the radial flow, while away from the flow direction, the collective energy values converge with those measured at $\theta_{\mathrm{c.m.}} \approx 90°$ for the most central collisions. The radial flow is seen to increase as a function of bombarding energy, while the relative contribution of collective and thermal motion to the energy of an emitted particel remains constant at ~50°. It will be interesting to follow this trend to higher energies (the Brookhaven AGS and CERN). QMD and BUU model calculations reproduce the temperature and flow parameters satisfactorily, with the BUU exhibiting somewhat too much flow. Surprisingly, the radial flow shows no dependence on the nuclear equation of state, within the sensitivity of our measurement. More theoretical work is needed to understand the origin of this collective mode of decay.

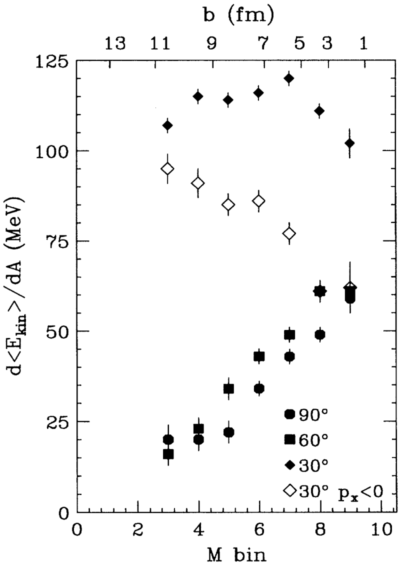

FIG. 4. Fitted slopes of the $\langle E_{\mathrm{kin}} \rangle$ vs A relationship as a function of multiplicity bin are shown for $\theta_{\mathrm{c.m.}} = 30°, 60°, 90° \pm 15°$ (filled diamond, squares, and circles, respectively) for the reaction Au + Au at $E = 1.0A$ GeV. Open diamonds indicate slopes for particles emitted into $\theta_{\mathrm{c.m.}} = 30°$ on the negative side of the reaction plane.

The authors thank Dr. Georg Peilert and Dr. Pawel Danielewicz for discussions and the use of their codes, and Dr. Reinhard Stock for helpful suggestions. This work was supported by the U.S. Department of Energy under Contracts No. DE-AC03-76SF00098, No. DE-FG02-89ER40531, No. DE-FG02-88ER40408, No. DE-FG02-88ER40412, and No. DE-FG05-88ER40437, and by the National Science Foundation under Grant No. PHY-9123301.

[1] H. Stöcker and W. Greiner, Phys. Rep. **137**, 277 (1986).
[2] P. Danielewicz and Q. Pan, Phys. Rev. C **46**, 2002 (1992).
[3] G. Peilert *et al.*, Phys. Rev. C **39**, 1402 (1989).
[4] Q. Pan and P. Danielewicz, Phys. Rev. Lett. **70**, 2062 (1993).
[5] P. Danielewicz and G. Odyniec, Phys. Lett. **157B**, 146 (1985).
[6] K. G. R. Doss *et al.*, Phys. Rev. C **32**, 116 (1985); H. H. Gutbrod, A. M. Poskanzer, and H. G. Ritter, Rep. Prog. Phys. **52**, 1267 (1989).
[7] J. Gossett *et al.*, Phys. Rev. Lett. **62**, 1251 (1989).
[8] J. Barrette *et al.*, Phys. Rev. Lett. **73**, 2532 (1994).
[9] P. J. Siemens and J. O. Rasmussen, Phys. Rev. Lett. **42**, 880 (1979).
[10] S. C. Jeong *et al.*, Phys. Rev. Lett. **72**, 3468 (1994).
[11] W. C. Hsi *et al.*, Phys. Rev. Lett. **73**, 3367 (1994).
[12] H. W. Barz *et al.*, Nucl. Phys. **531A**, 453 (1991).
[13] W. Bauer *et al.*, Phys. Rev. C **47**, R1838 (1993).
[14] K. S. Lee, U. Heinz, and E. Schnedermann, Z. Phys. C **48**, 525 (1990).
[15] R. T. de Souza *et al.*, Phys. Lett. **B300**, 29 (1993).
[16] G. D. Westfall *et al.*, Phys. Rev. Lett. **37**, 1202 (1976).
[17] G. Rai *et al.*, IEEE Trans. Nucl. Sci. **37**, 56 (1990).
[18] W. F. J. Müller *et al.*, Report No. LBL-24580 389, 1988.
[19] S. Albergo *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **311**, 280 (1992).
[20] A. Scott *et al.*, LBL Nuclear Science Division Annual Report 95 (1992).
[21] M. Demoulins *et al.*, Phys. Lett. B **241**, 476 (1990).
[22] H. H. Gutbrod *et al.*, Phys. Lett. B **216**, 267 (1989).
[23] G. Peilert *et al.*, Phys. Rev. C **39**, 1402 (1989).
[24] M. B. Tsang *et al.*, Phys. Rev. Lett. **71**, 1502 (1993).
[25] For the lower bombarding energies ($E \leq 0.80A$ GeV), an enhancement in the ^{3}He average energy, too large to be explained by Coulomb effects, is observed. This enhancement is at present not understood. It may be an experimental artifact due to difficult particle identification of ^{3}He at low bombarding energies in the TPC, or it may be a real physics effect [26,27].
[26] K. G. R. Doss *et al.*, Mod. Phys. Lett. A **3**, 849 (1988).
[27] G. Poggi *et al.*, Nucl. Phys. **A586**, 755 (1995).
[28] L. Phair *et al.*, Nucl. Phys. **A548**, 489 (1992).