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Multidimensional Analysis of Collective Sidewards Flow in Au on Au Reactions between 100 and 1050 A MeV

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Abstract: An excitation function of the Au on Au reaction from 100 to 1050 A MeV was measured using the FOPI-facility at GSI Darmstadt. Nuclear charge ($Z \leq 15$) and velocity of the products were detected with full azimuthal acceptance at laboratory angles $1^\circ \leq \Theta_{lab} \leq 30^\circ$. For the first time an analysis is presented which combines the azimuthally asymmetric part of the transverse flow (sidewards flow), stopping and the associated collision geometry. In comparison to microscopic transport model calculations we demonstrate the relevance of this method for the extraction of the nuclear equation of state.

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The collective motion produced in relativistic heavy ion collisions is a heavily debated topic since its magnitude gives information about the effective pressure which was generated due to compression and heat during the high density phase. The potential energy stored in the system depends on the nuclear equation of state (**EOS**). The question about the stiffness of the **EOS** i.e. the incompressibility modulus of nuclear matter might therefore be answered by studying collective motion in heavy ion collisions [1]. However, the interpretation of the available data is currently not unique. One of the problems is the ambiguity introduced by the momentum dependent forces; simulations using a soft **EOS** plus momentum dependent forces yield similar flow values as a hard **EOS** without momentum dependent forces [2].

Here we present new experimental data on collective motion (sidewards flow) of Au on Au from 100 to 1050 A MeV. We investigate the correlations of collective motion with the stopping and impact parameter (extracted from integrated cross sections) at all measured beam energies. By a comparison of a microscopic transport model (IQMD) [25] to our data we demonstrate that the mentioned ambiguity can be removed in principle when such correlations are taken into account. This gives new hope that the **EOS** might indeed be determined although none of the present model parametrizations can reproduce all of the experimental results.

Several signals of collective motion have been observed in heavy ion collisions such as the flow angle [3], the sidewards flow [4, 5], and the out of plane 'squeeze - out' [6, 7]. Very recently the flow component associated with the collective expansion in very central collisions was quantified [8]. In contrast to the sidewards flow which represents only a minor fraction (a few percent) of the transverse kinetic energy, the latter was reported to account for a large fraction (up to 50%) of the available energy [9]. Whereas the flow angle is expected to be a maximum in central collisions [10] the sidewards flow and out of plane 'squeeze - out' [11] vanish for symmetry reasons.

Indeed, a maximum of the sidewards flow and the azimuthal alignment was observed at intermediate impact parameters [5, 12, 13].

In this paper we use the quantity $E_{RAT} = \sum_i E_{\perp,i} / \sum_i E_{\|,i}$ as a measure of centrality [14], where $E_{\perp,i}$ and $E_{\|,i}$ denote the perpendicular and longitudinal energy components of particle i, respectively. It quantifies conversion of initial longitudinal motion into transverse motion which increases with the centrality of the collision. The following quantities are investigated: i) the maximum of the global sidewards flow (integrated over all charged particles in the forward hemisphere) extracted from its dependence on E_{RAT}: this observable F_S^{MAX} is defined below. ii) The degree of stopping, namely the value of E_{RAT} at which this maximum flow is observed, E_{RAT}^{MAX}. iii) The impact parameter b_{MAX}, where F_S^{MAX} is reached, connected to the integrated cross section, called σ_{int}^{MAX}.

The excitation function of F_S^{MAX} yields information about e.g. the scaling of the sidewards flow with the projectile momentum. E_{RAT}^{MAX} describes the global stopping at the maximum sidewards flow. As we will show this allows to distinguish the hard **EOS** from the soft **EOS** with momentum dependent forces. b_{MAX} is calculated under the assumption that the impact parameter correlates resonably well with E_{RAT} so that the relation $\sigma_{int}^{MAX} = \int \frac{d\sigma}{dE_{RAT}} dE_{RAT} = \pi * b_{MAX}^2$ is valid. This information is sensitive to the inclusion of momentum dependence in addition.

The experimental setup allowed the measurement of nuclear charge and velocity of reaction products at laboratory angles between 1° and 30° [15]. Charge identification was achieved up to about $Z \approx 15$ by an energy loss ($\triangle E$) versus time-of-flight (TOF) method. TOF and $\triangle E$ were measured with a highly granular and azimuthally symmetric Plastic Scintillator Wall. The energy loss of slow and heavy particles which were stopped in the Scintillator Wall was detected in an array of ionization chambers and thin plastic scintillators placed in front of the Wall. At each incident energy about 10^6 events have been recorded with a multiplicity trigger corresponding to an impact parameter range less than 9 fm in a sharp cut-off model. The results presented here have been analysed under this trigger condition. To extract a global information about the sidewards flow we calculate the strength of the many - particle azimuthal correlation using a quantity F_s (compare to [4, 16, 17]):

$$F_s = \frac{N_c}{N_c - 1} * \frac{\sum_i \sum_{j \neq i} \mid \vec{p}_{t(i)} \mid\mid \vec{p}_{t(j)} \mid cos\varphi_{ij}}{(\sum_i A_i)^2}$$

The indices i and j are running over all N_c charged particles measured in the forward center-of-mass hemisphere. The transverse momenta are denoted by $\vec{p}_t$ and the relative azimuthal angle in each pair by φ_{ij}. In order to determine the momenta we assume that the fragments masses are given by $A = 2 * Z$. With this definition of F_s a determination of the reaction plane is not necessary.

A typical correlation of the event-averaged F_s to E_{RAT} as observed in the reaction at 150 A MeV is presented in Fig. 1. It shows a well pronounced maximum at intermediate values of E_{RAT} and vanishes in events with a very low or very high degree of stopping. This agrees with the expectation that the sidewards flow has to be zero for very peripheral and for head on collisions although the selection of the latter ones is certainly limited by fluctuations in the observable E_{RAT}. $< F_s >$ might also become slightly negative in truly central events due to anticorrelations induced by momentum conservation. Filtered events generated by the Quantum Molecular Dynamics model [20, 22] produce a good correlation of E_{RAT} to the impact parameter in the regime of semi - central to central collisions [8, 9]. For the discussion of the beam energy dependence we focus on the three observables which have been defined before (see also Fig. 1): F_S^{MAX}, E_{RAT}^{MAX}, and the integrated cross section σ_{int}^{MAX}.

F_S^{MAX} and E_{RAT}^{MAX} were extracted using a gaussian fit of the correlation $< F_S >$ with $log_{10}(E_{RAT} + 0.1)$ on the abscissa[1] (a typical fit result is represented by the solid

[1] the logarithmic scale yields a more gaussian like shape of the curve and the average impact

line in Fig. 1). The excitation function of $\sqrt{F_S^{MAX}}$ is displayed in Fig. 2 (upper part). We observe a roughly logarithmic rise with the incident energy. The normalization to the projectile momentum per nucleon in the center of mass indicates deviations from a perfect scaling on a 20% level [21]. This finding is similar to the behaviour of the flow signal extracted earlier by the Plastic Ball Group [5], although a more detailed comparison of both signals reveals important differences. The slope of $< p_x/A >$ at midrapidity as defined in [5] is higher than the quantity $P_x^{dir} =< \Sigma(p_x)_i/\Sigma A_i >$, which is averaged over all particles of the forward hemisphere, because of the normally S - shaped dependence of $< p_x/A >$ on the rapidity y and because the intensity information (dN/dy) is neglected. In QMD simulations $\sqrt{F_S^{MAX}}$ was found to be close to the maximum of P_x^{dir} (within 5% at 400 A MeV and 10% at 150 A MeV) calculated with the exact reaction plane determined by the theory.

For the extraction of the EOS, comparisons of filtered microscopic transport model calculations to data are necessary. Here we have chosen the IQMD - model [25] (for comparison of QMD calculations using the G - Matrix formalism and BUU calculations to data see [19, 23]). It uses the free nucleon - nucleon cross sections taking into account the isospin degree of freedom and static Skyrme potentials adjusted to a stiff EOS (Version H, K = 380 MeV) or a soft EOS (Version S, K = 200 MeV). The momentum dependence is optionally introduced by an additional potential depending on the relative momenta (Version M). The simulations have been performed for the full impact parameter range from 0 to 14 fm calculating a few thousand events per energy and version. These events were filtered applying geometrical cuts, experimental thresholds and a global cut to approximate the multiplicity trigger used in the experiment. For the extraction of the simulated observables we have applied the same procedure as used for the data. The influence of multiple hits was studied via

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parameter turned out to be approximately a linear function of $log_{10}(E_{RAT} + 0.1)$.

GEANT - simulations using events generated with the version HM of IQMD which yields, as demonstrated in the following, on the average the best description of our experimental data. Due to the high granularity of our setup a multiple hit correction of only −9% to $\sqrt{F_S^{MAX}}$ at 600 A MeV had to be applied (included in the IQMD - result in Fig. 2). The geometrical cut $\theta_{lab} < 30^0$ has negligible influence ($< 5\%$) to $\sqrt{F_S^{MAX}}$ and to σ_{int} when compared to the unfiltered calculations. According to this model $\sqrt{F_S^{MAX}}$, derived under our assumption $A = 2 * Z$, agrees reasonably well with $\sqrt{F_S^{MAX}}$ calculated from the exact momenta (including charged pions). Within the remaining uncertainties, our experimental observable $\sqrt{F_S^{MAX}}$ is best reproduced with a stiff EOS plus momentum dependent interaction, below 400 A MeV all versions underestimate the data. Version 'SM' yields practically the same result as version 'H'. The softening of the EOS seems to be compensated by the additional potential from the momentum dependence. This ambiguity can obviously not be solved with the maximum sidewards flow alone.

Our second observable, the associated degree of stopping at maximum sidewards flow, E_{RAT}^{MAX}, slightly rises with the incident energy (Fig. 2, lower part). In contrast to $\sqrt{F_S^{MAX}}$ and σ_{int}^{MAX} this observable is strongly biased by our limited polar angle acceptance. Nevertheless it provides a stringent test to the theory predictions if the experimental filter is applied as illustrated in the figure. Adding the information of this observable, a significant separation of the two versions 'SM' and 'H' is possible at all incident energies. Even if the theory produces the same amount of sidewards flow, E_{RAT}^{MAX} is larger for the version without the momentum dependence. Again the experimental data are in better agreement with the prediction of the version 'HM'.

The motivation behind our third observable, σ_{int}^{MAX}, is the extraction of the collision geometry, i.e. the impact parameter at F_S^{MAX} via the integrated cross section (Fig. 3). According to the experimental result, the maximum sidewards flow is reached at $\sigma_{int} \approx 500\,\mathrm{mb}$ which corresponds to a maximum impact parameter of roughly 4 fm in the sharp cut-off model. The incident energy dependence is weak. However, the theoretical predictions are again very sensitive to the inclusion of the momemtum dependence with respect to this observable. Both versions, 'HM' and 'SM', using momentum dependent potentials predict significant larger integrated cross sections as compared to the mean field potential alone. Similar conclusions can be drawn from the impact parameter dependence of the average $< P_x/A >$ in the QMD - calculations with the G - matrix formalism [24]. The interpretation of the experimental cross sections in terms of impact parameters might be problematic if the relation between the impact parameter and the stopping (E_{RAT}) is dominated by fluctuations. We have tested the result by correlating $< F_S >$ directly with the impact parameter instead of E_{RAT} for the IQMD - events. The impact parameter where the sidewards flow is maximal agrees surprisingly well with the one calculated via the integrated cross sections (Fig. 3, right panel).

In summary we have presented new experimental data on sidewards flow, nuclear stopping and the associated cross sections at maximum sidewards flow in the reaction Au on Au between 100 and 1050 A MeV. A first comparison of microscopic transport model calculations (IQMD) to the data has demonstrated the sensitivity of the 'multidimensional' analysis for the extraction of the nuclear equation of state. In the current study a better agreement is found for the stiff EOS plus momentum dependent interaction although a consistent description of all the presented experimental observables is not achieved. Similar systematic comparisons to other advanced dynamical theories [24, 26, 27] may help to solve the complicated interplay between the EOS, the momentum dependent interaction and possibly in medium nucleon - nucleon cross sections using experimental observables.

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References

[1] H. Stöcker et al., Phys. Rep. **137**, 277-392 (1986);
J. Aichelin, Phys. Rep. **202**, 233 (1991).

[2] J. Aichelin et al., Phys. Rev. Lett. **58**, 1926 (1987);
C. Gale et al., Phys. Lett. **B 209**, 135 (1988).

[3] H.A. Gustafsson et al., Z. Phys. **A 321**, 389 (1985).

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

[5] K.G.R. Doss et al., Phys. Rev. Lett. **57**, 302 (1986).

[6] D. L'Hôte, Nucl. Phys. A488, 457c (1988).

[7] H.H. Gutbrod et al., Phys. Lett. **B 216**, 267 (1989).

[8] S.C. Jeong et al., Phys. Rev. Lett. **72**, 3468 (1994).

[9] W. Reisdorf, Proc. XXII. Workshop on Prop. of Nuclei and Nuclear Excitation, Hirschegg, Austria 1994 (published by GSI, Darmstadt, 1994)

[10] H. Stöcker et al., Phys. Rev. Lett. **44**, 725 (1980).

[11] Y. Leifels et al., Phys. Rev. Lett. **71**, 963 (1993).

[12] P. Beckmann et al., Mod. Phys. Lett. **A 2**, 163 (1987).

[13] R. Bock et al., Mod. Phys. Lett. **A 2**, 721 (1987).

[14] W. Reisdorf, Proc. XX. Workshop on Prop. of Nuclei and Nuclear Excitation, Hirschegg, Austria 1992 (published by GSI, Darmstadt, 1992)

[15] A. Gobbi et al., Nucl. Instr. Meth. **A 324**, 156 (1993).

[16] P. Danielewicz et al., Phys. Rev. **C 38**, 120 (1988).

[17] W.M. Zhang et al., Phys. Rev. **C 42**, R491 (1990).

[18] G.F. Bertsch et al., Phys. Rev. **C 29**, R673 (1984).

[19] N. Herrmann, Nucl. Phys. **A 553**, 739c (1993).

[20] G. Peilert et al., Phys. Rev. **C 39**, 1402 (1990).

[21] A. Gobbi, Proc. V Int. Conf. on Nucleus - Nucleus Collisions, Taormina 1994

[22] C. Hartnack, PhD - thesis University Frankfurt (1993), GSI Report 93-05

[23] V. Ramillien et al., to be published in Nucl. Phys. **A**

[24] J. Jaenicke et al., Nucl. Phys. **A 536**, 221 (1992).

[25] C. Hartnack et al., Phys. Lett. **B 336**, 131 (1994) and references therein

[26] W. Cassing et al., Nucl. Phys. **A 545**, 123 (1992).

[27] D. Klakow et al., Phys. Rev. **C 48**, 1982 (1993);
G. D. Westfall et al., Phys. Rev. Lett. **71**, 1986 (1993).

Figure 1: Average of the flow quantity F_S (see text for definition) as a function of E_{RAT} (upper frame) and differential cross section versus E_{RAT} (lower frame). The experimental data for Au on Au at 250 are shown by the solid points; the curve represents a fit to determine the maximum F_S^{MAX} and its corresponding E_{RAT}^{MAX}. The open points denote the distribution derived under the very same data analysis, after the azimuthal angles of the fragments have been randomized in each event. The hatched area in the lower part represents the integrated cross section σ_{int}^{MAX} up to the value E_{RAT}^{MAX}.

Figure 2: Excitation function of the maximum sidewards flow $\sqrt{F_S^{MAX}}$ (upper frame) and the corresponding value E_{RAT}^{MAX} (lower frame). Results of filtered IQMD calculations are represented by the solid (HM), dashed (H) and dotted (SM) lines; see text for details.

Figure 3: Excitation function of the integrated cross sections σ_{int}^{MAX} (left). The corresponding model predictions after filtering are given by the solid (HM), dashed (H) and dotted (SM) lines. The right hand scale denotes the impact parameter calculated from the cross section in a sharp cut-off scenario. For comparison the true impact parameter, where the maximum sidewards flow is found in the model caluclations, is shown in the right panel; see text for details.

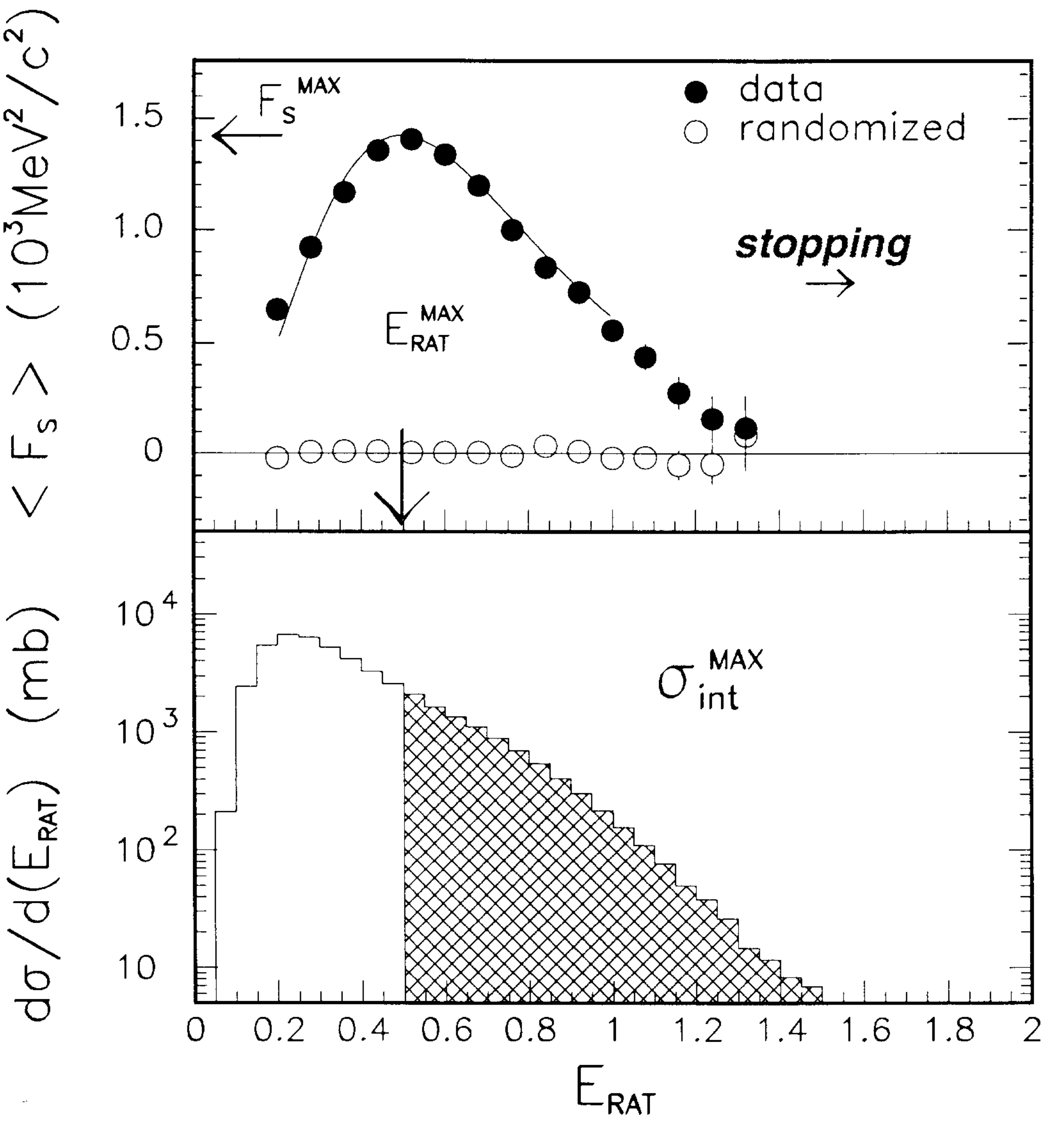
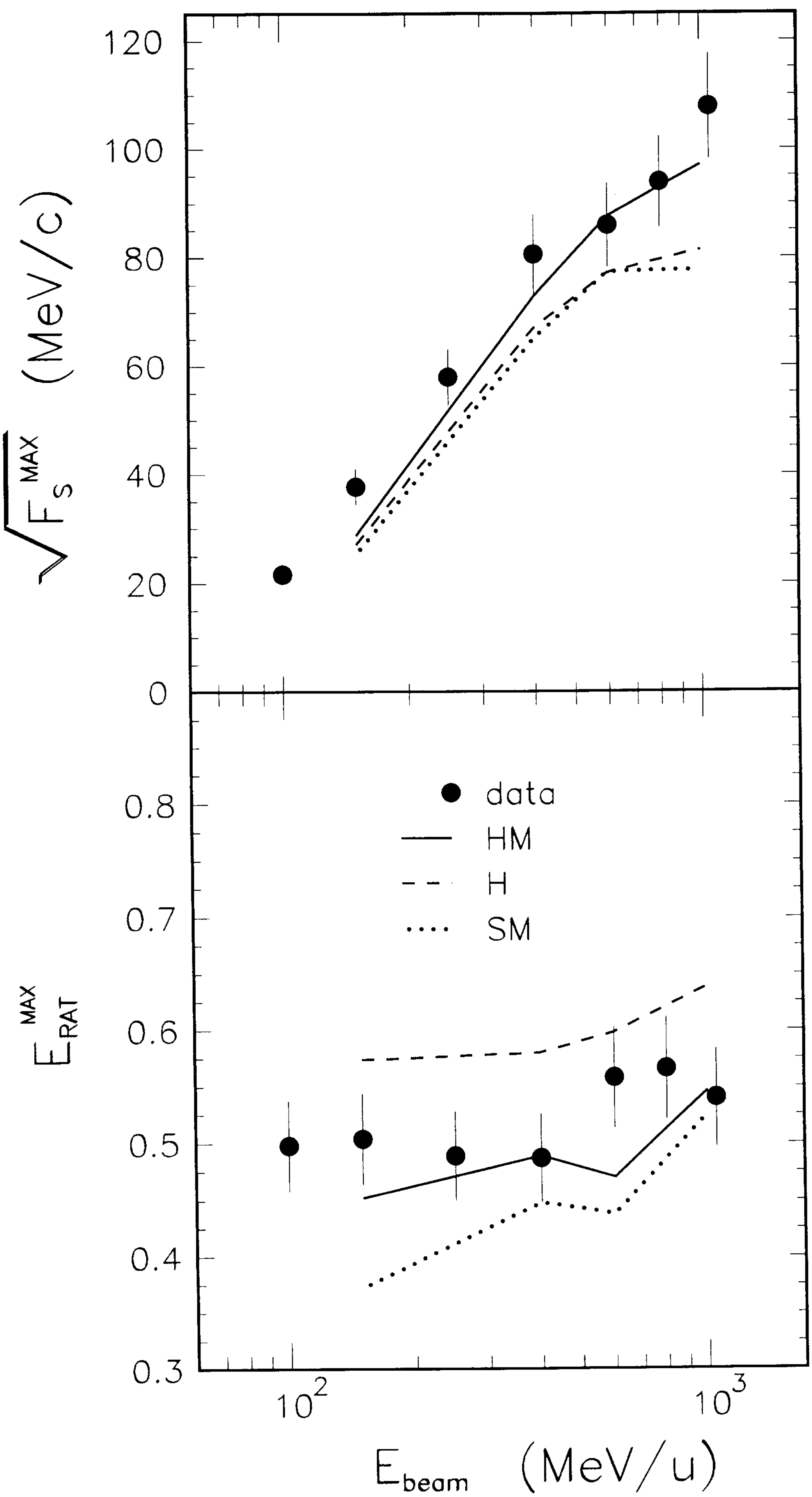

F_s^{MAX}
data
randomized
stopping
E_{RAT}^{MAX}
σ_{int}^{MAX}
$< F_s >$ $(10^3 MeV^2/c^2)$
$d\sigma/d(E_{RAT})$ (mb)
E_{RAT}
1.5
1.0
0.5
0
10^4
10^3
10^2
10
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

Figure 1



120
100
80
60
40
20
0
$\sqrt{F_s^{MAX}}$ (MeV/c)
0.8
0.7
0.6
0.5
0.4
0.3
E_{RAT}^{MAX}
data
HM
H
SM
10^2
10^3
E_{beam} (MeV/u)

Figure 2

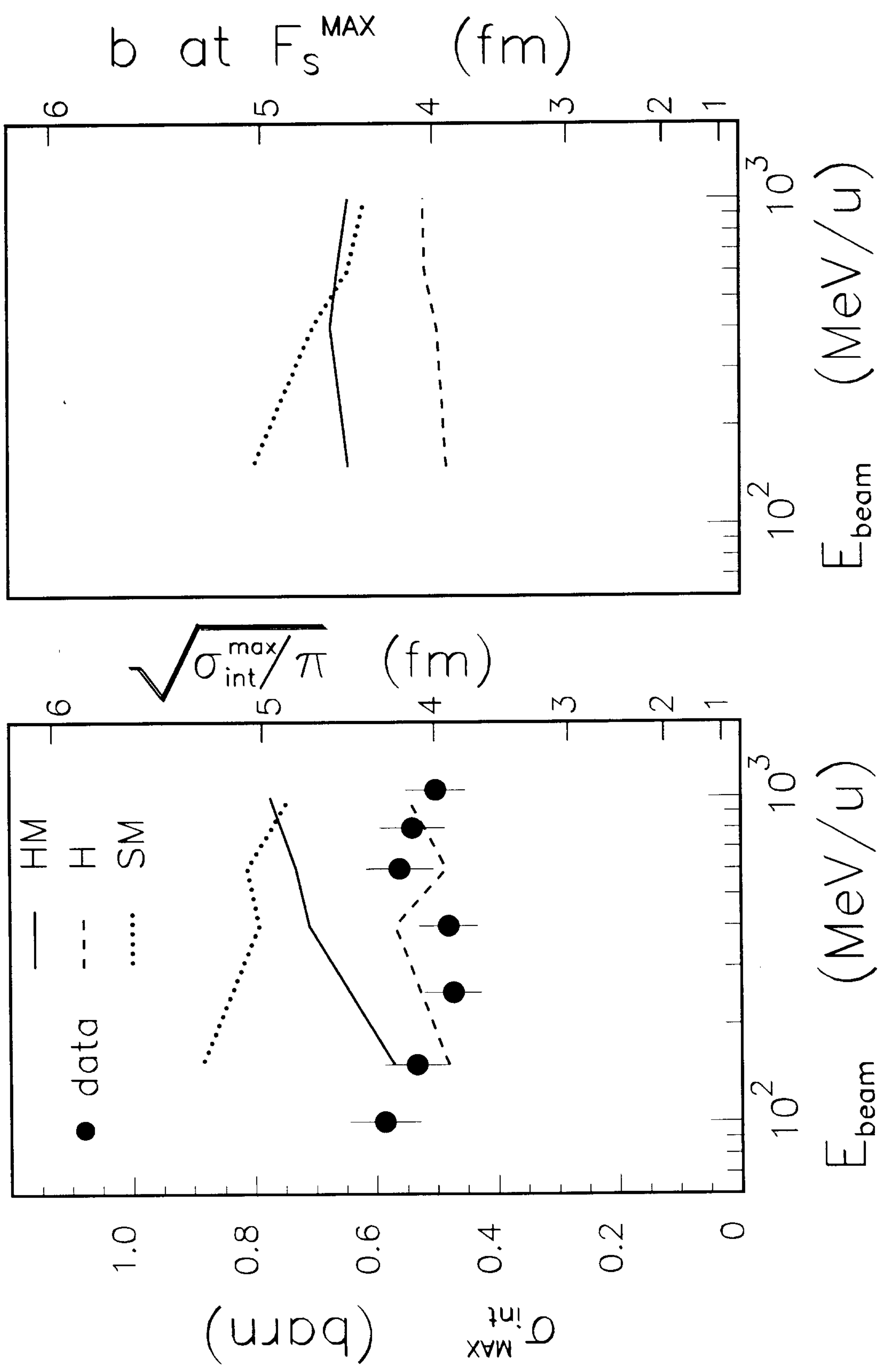

b at Fs MAX (fm)
6
5
4
3
2
1
10^2
10^3
E beam (MeV/u)
√(σ int max/π) (fm)
data
HM
H
SM
σ int MAX (barn)
1.0
0.8
0.6
0.4
0.2
0

Figure 3