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SQUEEZE-OUT IN RELATIVISTIC HEAVY ION
COLLISIONS**

S.A. BASS, C. HARTNACK, H. STÖCKER, W. GREINER

Gesellschaft für Schwerionenforschung mbH
Postfach 110552 · D-64220 Darmstadt · Germany

Transverse energy dependence of neutron squeeze-out in relativistic heavy ion collisions*

S. A. Bass^{a,b}, C. Hartnack^{b,c}, H. Stöcker^a and W. Greiner^a

^aInstitut für Theoretische Physik der J. W. Goethe Universität
Postfach 11 19 32, 60054 Frankfurt am Main, Germany

^bGSI Darmstadt, Postfach 11 05 52, 64220 Darmstadt, Germany

^cLaboratoire de Physique Nucléaire, Nantes, France

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Abstract

We present a microscopic calculation of neutron *squeeze-out* in relativistic heavy ion collisions at beam energies between 400 and 1000 MeV/nucleon. The *squeeze-out ratio* increases monotonously with the transverse momentum of the neutrons. This ratio is independent of the incident beam energy if plotted versus $p_t/p_{proj.}$. We observe a strong dependence on the nuclear equation of state and momentum dependent interaction. An energy dependence manifests itself when plotting the *squeeze-out ratio* versus the impact parameter.

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The study of relativistic heavy ion collisions is one of the major tools to investigate the properties of hot and dense nuclear matter [1, 2, 3, 4, 5, 6, 7, 8]. Among the goals of this research is the determination of the nuclear equation of state and the in-medium properties of nuclear matter. Apart from particle production the study of nuclear *collective flow* is one of the most promising approaches for investigating those questions. *Collective flow* effects for nucleons are well established: They have been predicted by nuclear fluid dynamics [9, 10, 11, 12, 13] and have experimentally been confirmed at the BEVALAC [14, 15, 16] for charged particles by the Plastic-Ball collaboration. Microscopic models such as MDM (Molecular Dynamics Model), VUU (Vlasov Uehling Uhlenbeck), and QMD (Quantum Molecular Dynamics) have reproduced the NFD (Nuclear Fluid Dynamics) predictions and show good agreement with the experimental findings [17, 18, 19, 20, 21, 22, 23, 24]. One has to distinguish between two different types of *collective flow*: The *bounce-off* [11] of cold spectator matter from hot and compressed participant matter *in the reaction plane* and the *squeeze-out* [12] of this hot and compressed participant matter *out of the reaction plane*. The most strongly stopped, compressed matter at midrapidity is responsible for the *squeeze-out* [25]. A strong dependence on the nuclear equation of state for this collective effect is seen [23, 24].

The recent measurements of the pion *squeeze-out* [26] by the KaoS [27] and TAPS [28] collaborations as well as the neutron *squeeze-out* by the TAPS [28] and LAND [29] collaborations have triggered new interest into this collective effect. In this letter we present the first microscopic calculation of neutron *squeeze-out* and its energy dependence. We explicitly take the isospin degree of freedom into account.

For our investigation we have calculated samples of 10000 Au+Au collisions for each of the incident beam energies of 400, 600, 800 and 1000 MeV/nucleon, respectively, with the IQMD model which is an extension of the **Q**uantum **M**olecular **D**ynamics model (QMD) [30, 31, 32, 33]. The IQMD model explicitly incorporates isospin and pion production via the delta resonance [20, 21, 34]. In the QMD model the nucleons are represented by Gaussian shaped density distributions. They are initialized in a sphere of a radius $R = 1.12A^{1/3}$ fm, according to the liquid drop model. Each nucleon is supposed to occupy a volume of h^3 , so that the phasespace is uniformly filled. The initial momenta are randomly chosen

between 0 and the local Thomas-Fermi-momentum. The A_P and A_T nucleons interact via two- and three-body skyrme forces, a Yukawa potential, momentum dependent interactions, a symmetry potential (to achieve a correct distribution of protons and neutrons in the nucleus) and explicit Coulomb forces between the Z_P and Z_T protons. Two different equations of state using this ansatz have been implemented: A *hard* equation of state with a compressibility of 380 MeV and a *soft* equation of state with a compressibility of 200 MeV [35, 36]. For the momentum dependent interaction we use a phenomenological ansatz [5, 31, 37] which fits experimental measurements [38, 39] of the real part of the nucleon optical potential. The nucleons are propagated according to Hamiltons equations of motion. A clear distinction is made between protons and neutrons with coulomb forces acting only on the protons and an *asymmetry potential* containing the asymmetry term from the Bethe-Weizsäcker formula acting between protons and neutrons. Furthermore parameterized free pn and pp cross sections are used instead of an averaged nucleon-nucleon cross section. They differ by 50% at 150 MeV. Hard N-N-collisions are included by employing the collision term of the well known VUU/BUU equation [3, 36, 40, 41, 42, 43]. The collisions are done stochastically, in a similar way as in the CASCADE models [44, 45]. In addition, the Pauli blocking (for the final state) is taken into account by regarding the phase space densities in the final states of a two body collision. Only free unbound protons and neutrons were used for the analysis, all fragments were subtracted using a minimum spanning tree technique.

Figure 1 shows the azimuthal angular distribution of high p_t ($p_t \geq 400$ MeV) free protons and neutrons at midrapidity. φ is the angle between the transverse momentum vector $\vec{p}_t$ and the x -axis (which lies in the reaction plane and is perpendicular to the beam axis). The *squeeze-out* is clearly seen by the pronounced maximum at $\varphi = 90^\circ$. The full and dashed lines are least square fits with the function $f(\varphi) = a(1 + s_1 \cos(\varphi) + s_2 \cos(2\varphi))$ which has been used to fit the *squeeze-out* phenomenon. We use an absolute parameter-free normalization per event. The larger yield for neutrons compared to protons is due to the isospin composition of the gold nuclei. It should be noted, however, that the correct treatment of isospin in inelastic collisions causes a change in the neutron to proton ratio which can be seen in the figure.

Let us now show the dependence of the observed *squeeze-out* on increasing beam energy, transverse momentum and impact parameter. We define a *squeeze-out ratio* [25]

$$R_{out/in} = \frac{\frac{dN}{d\varphi}(\varphi = 90^\circ) + \frac{dN}{d\varphi}(\varphi = 270^\circ)}{\frac{dN}{d\varphi}(\varphi = 0^\circ) + \frac{dN}{d\varphi}(\varphi = 180^\circ)} \Big|_{y=y_{CM}}$$

For values $R_{out/in} > 1$ neutrons are emitted preferentially perpendicular to the reaction plane.

Figure 2 shows $R_{out/in}$ versus scaled transverse momentum p_t/p_{proj} for the four studied beam energies with cuts on rapidity ($-0.15 \leq y_{CM} \leq 0.15$) and impact parameter ($3 \leq b [fm] \leq 9$). The ratio increases monotonously with the transverse momentum.

This ratio is independent of the beam energy if the transverse momenta are scaled with the projectile momenta. Therefore, higher transverse momenta must be probed with increasing beam energy if a clean *squeeze-out* signal is to be isolated. Such a scaling behaviour has already been extracted for the *in-plane bounce-off* in the hydrodynamic model [46]. It has been experimentally observed in the case of the neutron *squeeze-out* [47]. Further insight into the reaction mechanism of heavy ion collisions can be gained by this effect, which may serve to predict the magnitude and p_t dependence of the neutron *squeeze-out* for other beam energies than those analyzed in this Letter.

The dependence of the neutron *squeeze-out* on the momentum dependent interaction and the equation of state for 1 GeV/nuc. is shown in Figure 3: The upper frame shows the hard equation of state with and without momentum dependent interaction (mdi). With mdi, $R_{out/in}$ increases by 50% for large transverse momenta! A difference of 50% can also be observed by comparing the hard and soft equations of state (both including mdi) in the lower frame of Figure 3: At high transverse momenta the hard equation of state with mdi exhibits a 50% higher *squeeze-out ratio* than the soft equation of state with mdi. The hard equation of state without mdi shows a $R_{out/in}$ vs. p_t dependence similar to the soft equation of state with mdi. It is important to note, however, that these differences are only seen for high transverse momenta $p_t/p_{proj} \geq 1$. Analyzing p_t -integrated data will therefore severely diminish the sensitivity towards the nuclear equation of state and the momentum dependent interaction.

A cut of $p_t/p_{proj} \geq 0.4$ is employed for the impact parameter dependence of $R_{out/in}$ seen Figure 4: The *squeeze-out ratio* reaches a maximum (within statistical errorbars) for medium impact parameters around 6 fm for Au+Au independently of the beam energy in the interval between 400 and 1000 MeV/nucleon. Without this cut, the high energies show an increase in $R_{out/in}$ for large impact parameters. However, the *squeeze-out ratio* exhibits an energy dependence: For 1000 MeV/nucleon and impact parameters up to 8 fm the calculated points consistently lie below those for the lower energies. Figure 4 shows the respective calculations for 400 and 1000 MeV/nucleon. The points for 600 and 800 MeV/nucleon are between the depicted points.

New experimental findings by the TAPS collaboration [28, 48] show a neutron *squeeze-out* also at 1 GeV/nucleon. They also exhibit a neutron *bounce-off* in the reaction plane and present for the first time experimental evidence for the predicted [49] anticorrelation between pions and nucleons in their azimuthal angular distribution for a symmetric system at 1 GeV/nucleon.

A direct comparison with experimental results [14, 15, 16, 28, 29] must employ the full detector acceptance cuts on the calculation. This can be done for the mature Plastic Ball data (a filter routine is generally accessible [7, 24]). For the fresh data from GSI, such a detailed acceptance routine is not yet publically available. First preliminary comparisons with experimental data [47] at 400 MeV/nucleon look promising.

We have presented a microscopic model dubbed IQMD which incorporates all necessary isospin degrees of freedom. The IQMD model predicts a clear neutron *squeeze-out* signal. The model exhibits a monotonous p_t dependence of the *squeeze-out ratio* and a broad maximum in the impact parameter dependence around $b = 6$ fm. The *squeeze-out ratio* versus p_t is invariant under the increase in beam energy if scaled with p_t/p_{proj} . However, if the *squeeze-out ratio* is plotted versus the impact parameter a decrease of the *squeeze-out ratio* with increasing beam energy can be observed. Most importantly, the *squeeze-out ratio* exhibits a strong sensitivity towards momentum dependent interactions and the nuclear equation of state for high transverse momenta $p_t/p_{proj} \geq 1$.

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Figure 1: Azimuthal angular distribution for high p_t neutrons and protons in Au+Au collisions with 400 MeV/nucleon at midrapidity. Only collisions with impact parameters in the range of $3 \leq b \leq 9$ fm selected from a minimum bias calculation were used. Protons as well as neutrons exhibit a pronounced peak at $\varphi = 90^\circ$ perpendicular to the event plane. The higher yield for neutrons is due to the isospin decomposition of the system.

Figure 2: *Squeeze-out ratio* $R_{out/in}$ versus scaled transverse momentum p_t/p_{proj} for neutrons in Au+Au collisions at 400, 600, 800 and 1000 MeV/nucleon. The ratio increases monotonously with the transverse momentum. By scaling p_t with p_{proj} , the ratio becomes indepent of the incident beam energy. The binning is identical for all 4 energies, the symbols were shifted to increase the readability of the figure.

Figure 3: *Squeeze-out ratio* $R_{out/in}$ versus scaled transverse momentum p_t/p_{proj} for neutrons in Au+Au collisions at 1 GeV/nucleon. The upper frame shows a comparison between calculations with a hard equation of state with and without momentum dependent interaction (mdi). For large transverse momenta $p_t/p_{proj} \geq 1$ the calculation with mdi exhibits a 50% larger *squeeze-out ratio*. The lower frame shows a comparison between calculations with hard equation of state with mdi and soft equation of state with mdi: Again, for large transverse momenta $p_t/p_{proj} \geq 1$ the hard equation of state shows a 50% higher *squeeze-out ratio* than the soft equation of state.

Figure 4: *Squeeze-out ratio* $R_{out/in}$ versus impact parameter for high p_t neutrons at midrapidity for 400 and 1000 MeV/nucleon. The *squeeze-out* can best be observed at impact parameters between 3 fm and 9 fm. Analogously to figure 2 we employed a cut of $p_t/p_{proj.}$. However, for impact parameters up to 8 fm a diminishing of the *squeeze-out* with increasing beam energy is visible. The respective curves for 600 and 800 MeV/nucleon lie between those shown but were omitted to increase the readability of the figure.