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NEUTRON EMISSION IN Bi + Pb COLLISIONS AT 1 GeV/u

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We report energy spectra of neutrons originating from non-peripheral ^{209}Bi $+^{208}$Pb collisions at 1 GeV/u. A comparison of the spectra measured at three different polar laboratory angles (23.5°, 40° and 60°) shows that the observed emission pattern contradicts a picture where the neutrons are emitted from a single fireball. A unified description of all spectra (scaling) can be achieved under the assumption that the production cross section depends only on the minimum invariant mass necessary to emit the neutron.

I. Introduction

Subtreshold particle production in heavy ion collisions is generally accepted to provide important information about the collision dynamics. For nucleons which are already present in the collision system the equivalent process is the production of these particles with momenta beyond the free nucleon-nucleon kinematical limit. Since identification of minimum ionizing hydrogen isotopes is difficult experimentally, we investigate subtreshold neutron production where a time-of-flight (TOF) measurement is sufficient to determine both the particle type and its energy.

II. Experiment

The experiment was performed at the Heavy Ion Synchrotron SIS at GSI Darmstadt. A 1 GeV/u ^{209}Bi beam with an intensity of 3×10^6 particles per spill (spill duration 4s) was incident on a target tilted at 45° relative to the beam. A 420 mg/cm^2 isotopically enriched ^{208}Pb target was used. Neutrons were detected in a block of seven hexagonal BaF_2 scintillator modules (250 mm long, 59 mm diameter), equipped in front with

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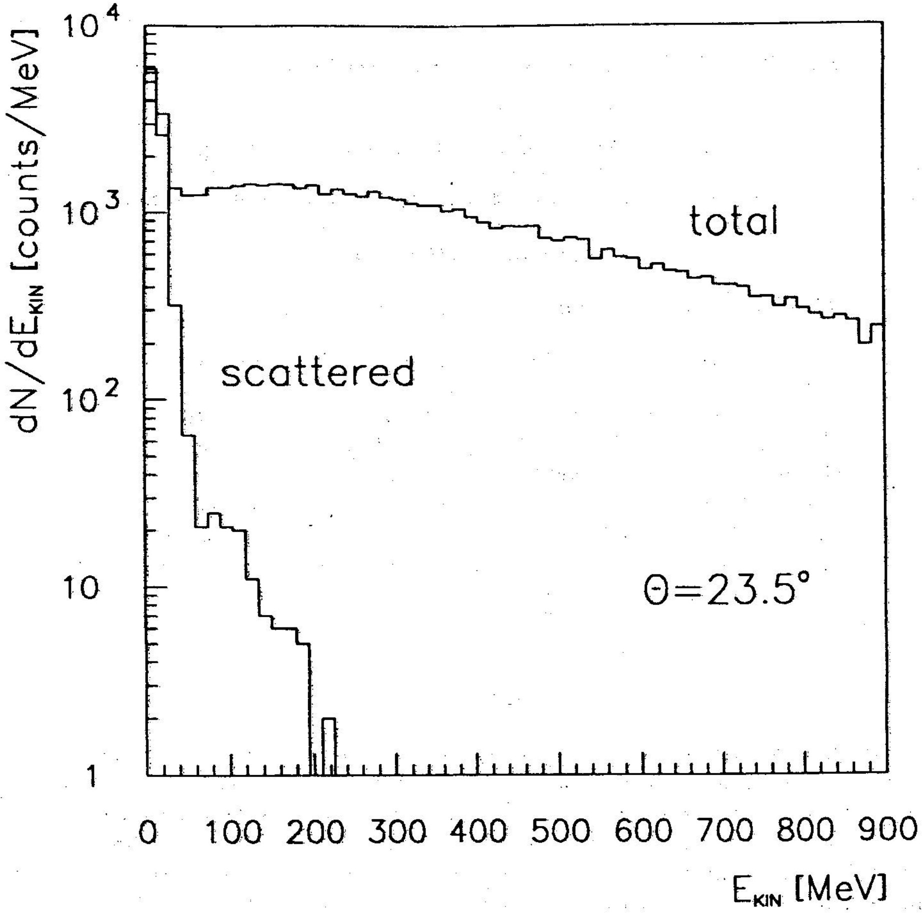

Fig. 1 Simulated kinetic energy spectra for direct and scattered neutrons. Input for the simulation is the neutron distribution of the Fig.2.

a common 10 mm thick plastic charged particle veto detector (CPV). The detector distance from the target was 4.3 m. The detector was placed at polar angles $\Theta = 23.5°$, $\Theta = 40°$ and $\Theta = 60°$, respectively.

The absence of a signal in the CPV allowed us to select neutral particles (neutrons and photons). The kinetic energy of the neutrons observed in the plastic-scintillator BaF_2 telescope was derived from their TOF. The achieved time resolution of photon peak of 360 ps allowed us to discriminate between the prompt photons and neutrons up to very high kinetic energies. For larger polar angles the photon intensity increases relative to the particle intensity. This restricts the maximum observable neutron energy to $E_{kin} < 2$ GeV, $E_{kin} < 1.5$ GeV and $E_{kin} < 1$ GeV for the detector positions at $\Theta = 23.5°$, $\Theta = 40°$ and $\Theta = 60°$, respectively.

Target and detector were positioned two meters above the floor of the experimental hall. At a target-detector distance of 4.3 m, the neutrons scattering off the floor therefore can still be discriminated against direct neutrons over a large range in neutron kinetic energy. Results of Monte Carlo simulations have shown that scattered neutrons have much longer flight paths and hence larger TOF values than direct ones of the same energy. Hence, scattered neutrons can only influence the low energy part of the data, see Fig.1. The shower of secondary particles generated by neutrons in BaF_2 depends on the neutron incident kinetic energy. Because the incident kinetic energy for scattered neutrons does not agree with the energy expected from their TOF, we can exploit the pulse shape information from BaF_2 to further discriminate against scattered neutrons. According to our simulations the background due to scattered neutrons is smaller than 1 % of the accepted events for neutron energies above 100 MeV.

The absolute efficiency of neutron detection in the BaF_2 modules was determined by comparison with that of a liquid NE213 scintillator. The NE213 efficiency is well described by the hadronic shower Monte Carlo program of Cecil et al. [1, 2]. The light-output threshold in BaF_2 was set to be equivalent to a photon energy of 7 MeV.

Events were recorded together with the charged particle multiplicity M_{ch} registered in the outer part of the forward wall (OFW) of the FOPI collaboration [3] which covers polar angles from 7° to 30°. The OFW multiplicity provides information on the centrality of the collision. The events were selected according to the condition that the total multiplicity of the charged fragments detected in the OFW was $M_{ch} \geq 60$. This multiplicity cut corresponds approximately to one half of the maximum measured M_{ch} and excludes peripheral events.

III. Results

Energy spectra of neutrons are shown on Figure 2. For all three angles the neutron spectra extend far beyond the phase space region which is kinematically accessible in free nucleon-nucleon scattering (E^{NN}_{kin} =775 MeV, 481 MeV and 179 MeV for $\Theta =$ 23.5°, 40° and 60°, respectively). Both Fermi motion and multiple scattering of the participants may be responsible for the production of neutrons with such high kinetic energies [4]. Especially the excitation of baryonic resonances and their subsequent decay seems to be an important process to achieve the highest particle momenta [4].

The relevance of these mechanisms could be tested within the framework of microscopic transport model calculations [5, 6]. Instead we perform a more phenomenological analysis of the spectra. First we assume that the observed particle originates from an equilibrated fireball. In a second scenario we weaken the assumption of equilibrium. In this picture the emission of the neutron proceeds in such a way that the number of participating nucleons needed to provide the neutron energy becomes minimal [7, 8].

3.1 Fireball

The data were fitted using the relativistic Boltzmann distribution [9]

$$E\frac{d^3\sigma}{d^3p} \sim m_t \cosh(y - y_{FB}) \exp\left\{-m_t \cosh(y - y_{FB})/T\right\}, \qquad (1)$$

where m_t and y are the neutron transverse mass and its rapidity, respectively, and y_{FB} is the rapidity of the fireball. T is the temperature parameter. The assumption that only one single fireball at mid-rapidity (i.e. $y_{FB} = y_{CMS}$) has been created leads to the following values of the temperature parameter: $T_{23.5°} = 97.5 \pm 0.3$ MeV, $T_{40°} = 80.2 \pm 1.0$ MeV, $T_{60°} = 81.5 \pm 0.5$ MeV. The large difference between the first and last two temperatures makes a unified description of all three data sets impossible. Furthermore, we see a deviation from a purely exponential shape for $\Theta = 40°$ and $60°$, see Fig.2.

The hypothesis that the fireball rapidity may not coincide with y_{CMS} was also tested. The corresponding fits are shown by the dashed lines on Fig.2. The fireball rapidity y_{FB} is lower then y_{CMS} for all angles and decreases with increasing angle.

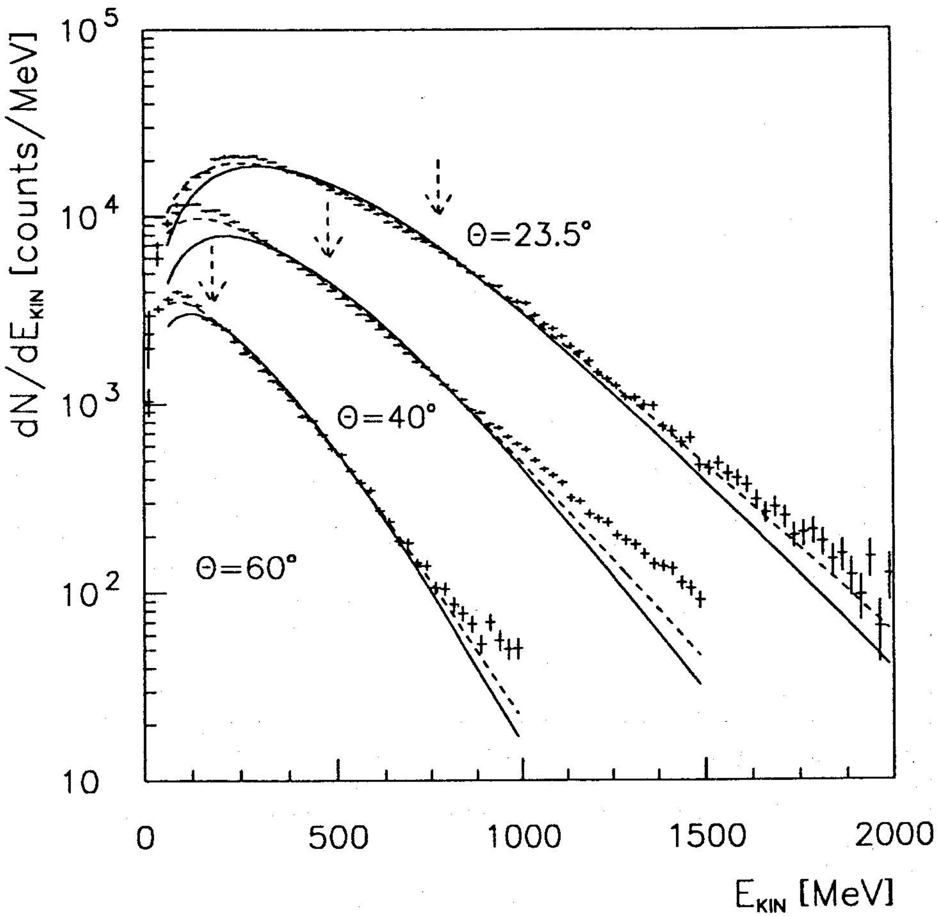

Fig. 2 The experimental energy neutron spectra (symbols) and their thermal fits for the rapidity of the fireball fixed at the value of CMS, $y_{FB} = y_{CMS}$ (full lines) and in the case if y_{FB} is treated as a free parameter (dashed lines).

3.2 Scaling

Consider the inclusive production of particle C in a nuclear reaction

$$A + B \longrightarrow C + X, \tag{2}$$

where X stands for the undetected particles. In this scenario the production of the particle C can be viewed as a process where a fraction of the nucleus A interacts with a fraction of the nucleus B forming a cluster with mass M. Provided the invariant cross section of the inclusive process (2), exhibits scale invariance the threshold for production of particle C with given 4-momentum p_C can be related to the fractions x_A and x_B of the target and the projectile nucleus 4-momenta P_A and P_B. Then the cluster invariant mass M can be written as

$$M = \sqrt{s} = \sqrt{(x_A P_A + x_B P_B)^2}. \tag{3}$$

The minimum value $\sqrt{s_{min}}$ can be determined from the 4-momentum conservation law

$$(x_A P_A + x_B P_B - p_C)^2 = M^2_{min} \tag{4}$$

and the condition

$$\frac{ds}{dx_{A,B}} = 0. \tag{5}$$

The quantity M_{min} is the minimum value of the missing mass M_X of particle system X. Momentum conservation requires that the minimum of M_X is reached only when the relative velocities of all particles forming system X tend to zero. In this limit particle C is a product of a two-body decay. The value of $\sqrt{s_{min}}$ is a complex function of the 4-momentum p_C, see [7, 8].

By use of the dimensionless quantity $\Pi = \sqrt{s_{min}}/2m_N$ the invariant cross section for the inclusive reaction (2) acquires the scale invariant form:

$$E\frac{d^3\sigma}{d^3p} \sim f(\Pi) \tag{6}$$

Our data on $E\ d^3N/d^3p$ for the three polar angles as a function of the variable Π are plotted on Fig. 3. In the region of $0.8 \leq \Pi \leq 2.4$ the invariant cross section clearly exhibits scaling. The flow effect was observed by us in the same experiment [10]. Its magnitude is dependent on the rapidity of the neutron, therefore its influence on the data for the three polar angles is different. This fact can be the reason for the small scalling violation.

IV. Conclusions

We measured the inclusive neutron spectra in non-peripheral ^{209}Bi + ^{208}Pb collisions at 1 GeV/u close and above the free NN kinematical limit where multi-particle phenomena gain in importance. The simple picture of a single mid-rapidity Boltzmann source is not compatible with our data since it leads to an angle-dependent temperature.

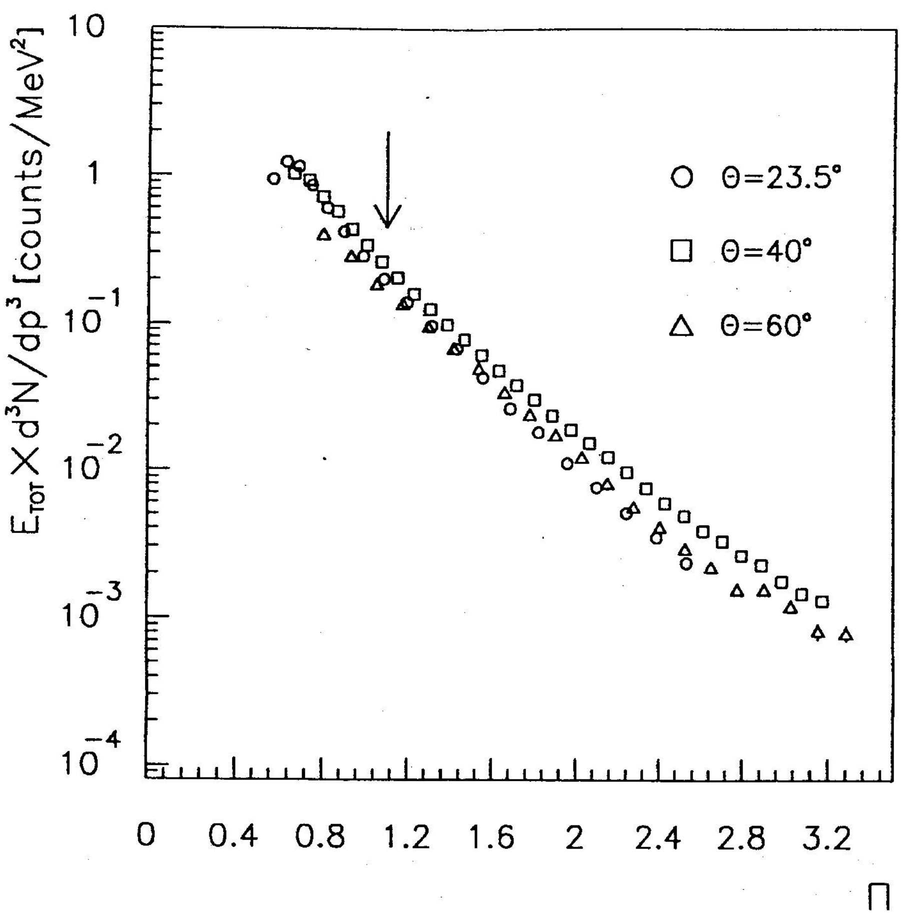

Fig. 3 The invariant cross section for neutron production in ^{209}Bi+^{208}Pb collisions at 1 GeV/u as a function of the scaling variable Π. The kinematical limit is indicated by the vertical arrow.

With the scale-invariant approach of Stavinsky [7] we achieve a good description of our data at all angles. An open question is whether the observed scaling also holds for more peripheral reactions and therefore would be true also for minimum bias data as originally suggested. Another question is how the scaling is related to the observed collective flow of nuclear matter.

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