Strong enhancement of extremely energetic proton production in central heavy ion collisions at intermediate energy

P. Sapienza,1 R. Coniglione,1 M. Colonna,1 E. Migneco,1,2 C. Agodi,1 R. Alba,1 G. Bellia,1,2 A. Del Zoppo,1 P. Finocchiaro,1 V. Greco,1,2 K. Loukachine,1 C. Maiolino,1 P. Piattelli,1 D. Santonocito,1 P.G. Ventura,1 Y. Blumenfeld,3 M. Bruno,4 N. Colonna,9 M. D’Agostino,6 L. Fabbietti,4 L. M. Fiandrì,4 F. Graemeeta,7 I. Iori,5,8 G.V. Margagliotti,9 P.F. Mastinu,7 P.M. Milazzo,9 A. Moroni,8 R. Ruì,9 J.A. Scarpacci,3 and G. Vannini1

(1) INFN - Laboratorio Nazionale del Sud, Via S. Sofia 44, I-95123 Catania (ITALY)
(2) Dipartimento di Fisica dell’Università di Catania (ITALY)
(3) Institut de Physique Nucléaire, IN2P3-CNRS-F-91406 Orsay, France
(4) INFN and Dipartimento di Fisica dell’Università di Bologna (ITALY)
(5) INFN - Sezione di Bari, Bari (ITALY)
(6) Dipartimento di Fisica dell’Università di Milano (ITALY)
(7) INFN - Laboratori Nazionali di Legnaro, Legnaro (ITALY)
(8) INFN - Sezione di Milano, Milano (ITALY)
(9) INFN - Sezione di Trieste, Trieste (ITALY)

(March 30, 2022)

The energetic proton emission has been investigated as a function of the reaction centrality for the system $^{58}\text{Ni} + ^{58}\text{Ni}$ at 30A MeV. Extremely energetic protons ($E_p^{NN} \geq 130$ MeV) were measured and their multiplicity is found to increase almost quadratically with the number of participant nucleons thus indicating the onset of a mechanism beyond one and two-body dynamics.

PACS numbers: 25.70.-z, 25.75.Dw

Heavy ion collisions at intermediate energy allow to investigate the properties of nuclear matter far from stability. Dynamical calculations show that, in the early non equilibrated stage of the reaction, high temperatures and densities are reached. Since heavy ion reactions at intermediate energy are described in terms of mean field and two body collisions, experimental observables sensitive to basic ingredients of the models such as the nucleon-nucleon (NN) cross section in matter and the mean field potential are needed to probe the nuclear dynamics and the equation of state of nuclear matter (EOS). In particular, particles such as subthreshold mesons or energetic photons and nucleons are expected to provide information on the nuclear dynamics at the pre-equilibrium stage and reference therein. Experimentally the presence of a pre-equilibrium component in the light particle emission has been observed in the energy spectra. The impact parameter dependence of the pre-equilibrium protons, investigated for several systems, shows that the average energetic proton multiplicity increases almost linearly with the number of participant nucleons. These features support the hypothesis of pre-equilibrium proton emission due to incoherent quasi-free NN collisions. Moreover, experimental evidences, such as the observed $\gamma$-proton anti-correlation and the energetic proton angular distributions reported in reference, provide information on the space-time origin of the energetic protons indicating that a relevant fraction is emitted from first chance NN collisions in the interaction zone. These evidences show that the energetic protons are emitted in the first stage of the reaction according to expectations and therefore are good candidates to probe the pre-equilibrium phase. On the other hand, the observation of extremely energetic nucleons or deep subthreshold particles over a broad range of incident energy addresses the question of which mechanisms could enable to concentrate a relevant fraction of the available energy in the production of a single energetic or massive particle. In fact, the emission of particles with energy or mass much larger than that provided by the coupling of the nucleon Fermi motion with the relative motion of the colliding nuclei is a challenging aspect of heavy ion collisions both experimentally and theoretically, due to the very low production rates and the lack of information on the production mechanism.

In this letter we present results concerning the emission of protons with energy extending up to almost 20% of the total available energy in the reaction $^{58}\text{Ni} + ^{58}\text{Ni}$ at 30A MeV. Since these energies largely exceed the maximum energy expected in first chance NN collisions due to the coupling of the relative motion with a sharp nucleon Fermi momentum distribution (kinematical limit), this investigation can also provide a clue for the comprehension of the deep subthreshold particle emission in this energy domain. In particular, for the first time, the proton multiplicity as a function of the impact parameter was measured for extremely energetic protons ($E_p^{NN} \geq 130$ MeV). A strong non linear dependence on the number of participant nucleons is observed thus providing important information on the production mechanism. A detailed comparison with a microscopic transport model was also performed aiming to extract information on the dynamics at pre-equilibrium and the nature of energetic proton emission.
The experiment was performed at Laboratori Nazionali del Sud with the MEDEA and MULTICS apparatus. A $^{58}\text{Ni}$ beam at 30A MeV delivered by the Tandem and Superconducting Cyclotron (CS) acceleration system bombarded a $^{58}\text{Ni}$ target 2 mg/cm$^2$ thick. MEDEA consists of a ball made of 180 BaF$_2$ detectors placed at 22 cm from the target which covers the polar angles from 30$^\circ$ to 170$^\circ$. The BaF$_2$ permits to detect and identify LCP ($E_\gamma \leq 300$ MeV) and photons up to $E_\gamma \approx 200$ MeV. The time of flight and pulse shape discrimination analysis allows to clearly identify photons, protons, deuterons and tritons, alpha particles. The response of BaF$_2$ crystals to LCP has been investigated using monoenergetic particle beams and a calibration procedure based on the $\gamma$ calibration with $\gamma$ sources and cosmic rays has been established as described in ref.\cite{[11]}. The MULTICS array is made of 55 telescopes covering the angular range $3^\circ \leq \theta_{\text{lab}} \leq 28^\circ$. Each telescope consists of an Ionization Chamber, a Silicon detector and a CsI crystal, and allows the identification of charged particles up to $Z = 83$. The threshold for charge identification was about 1.5A MeV $\gamma$. The total geometric acceptance was greater than 90% of 4$\pi$.

Energetic protons were detected in coincidence with photons, light charged particles ($Z = 1, 2$) (LCP) and intermediate and heavy fragments on an event by event basis, thus allowing a rather complete description of the reaction dynamics as well as an estimate of impact parameter which represents a crucial problem in this energy domain. Due to the very low cross section expected for extremely energetic protons, high statistics spectra are needed. To increase the fraction of events containing energetic protons, the main trigger required the presence of at least one BaF$_2$ signal above a threshold level corresponding to proton energy of about 30 MeV. Moreover the coincidence with MULTICS reduced the cosmic ray contamination to a negligible level. All the MEDEA detector with $\theta \geq 75^\circ$ and a few detectors of the forward rings took part in this trigger. Events corresponding to a minimum bias trigger, defined by the OR between MEDEA and MULTICS, were also scaled down and registered. Altogether approximately $4 \times 10^8$ events have been collected and analysed.

According to the standard three moving source analysis, the high energy proton emission at large polar angles can be described by a source emitting with velocity close to the half beam velocity and a high inverse slope parameter. A selection of the energetic protons emitted from this intermediate velocity source is possible by applying kinematical constraints ($E_{p_{\text{lab}}} \geq 40$ MeV, $\theta_{\text{lab}} \geq 42^\circ$)\cite{[12]}. The experimental proton spectra, transformed in the NN frame ($v/c = 0.127$) are reported in fig. 1a (full symbols) together with the intermediate source component of the fit (solid lines) for inclusive data. The inverse slope parameter deduced from the maxwellian fit with a volume emission is in good agreement with the systematics ($T \approx 11$ MeV)\cite{[3]}. Very energetic protons are observed in the spectra, with energy well above the kinematical limit expected in the hypothesis of first chance NN collisions and sharp Fermi momentum distribution ($v_{\text{max}} = v_F + 0.5v_{\text{beam}}$) (arrows of fig. 1).

![FIG. 1. (a) Experimental inclusive proton multiplicity spectra in the NN reference frame at different polar angles ($8^\circ, 110^\circ, 113^\circ, 126^\circ, 140^\circ$). (b) Experimental and BNV proton energy multiplicity spectrum in the NN reference frame for central collisions ($< b > \approx 2.5$ fm, $98^\circ \leq \theta_{NN} \leq 124^\circ$). Experimental data (full squares), local Skyrme interaction (open squares) and momentum dependent interaction (open circles) are reported. The arrows indicate the expected kinematical limit for first chance NN collisions.](image)
the BNV code: one using a local Skyrme interaction for
the mean field (open squares of fig. 1b) and another using
a Gale–Bertsch–Das Gupta momentum dependent inter-
action (GBD) (open circles of fig. 1b) [14]. Concerning
the reaction dynamics, both calculations exhibit similar
features leading to the formation of a heavy residue in
central collisions, whereas binary collisions dominate at
larger impact parameters. However, although momentum
dependent effects are expected to be more impor-
tant at higher bombarding energy, it is interesting to un-
derstand how far their inclusion can affect the energetic
proton production which is ruled by a delicate balance
between the mean field and the nucleon-nucleon cross
section. The experimental and calculated spectra in the
NN frame are shown in fig. 1b for central collisions. To
achieve a satisfactory statistics for energetic proton pro-
duction, about 250 events have been simulated per im-
pact parameter (using 200 test particles per nucleon).
The criteria for impact parameter selection and assign-
ment will be discussed in detail in the following. Our
results point out remarkable differences: the spectrum
calculated with the local Skyrme interaction strongly un-
dershoots the data and exhibits a lower inverse slope pa-
rameter than the experimental one, while the spectrum
calculated with the momentum dependence is in better
agreement with the data concerning both the yield and
the slope (at least up to \( \approx 110 \text{ MeV} \)). Due to the less at-
tractive mean field, we observe in the GBD calculations a
larger fraction of escaping particles. For the same reason,
these particles can also be more energetic. Moreover, the
calculated yields should be slightly reduced since in this
kind of calculation only free nucleons are emitted while
in the reaction also complex particles are emitted and
observed experimentally [1].

From the comparison with the experimental data one
can get a deeper insight into the behaviour of nuclear
matter at large density and temperature. Therefore, with
the aim of improving the overall understanding of the
energetic proton emission and disentangling between the
various hypotheses for the production of the most ener-
getic protons, we have investigated the impact parameter
dependence. Indeed, the dependence of multiplicity on
the number of nucleons participating in the reaction can
provide information about a change in the production
mechanism. A stronger than linear increase of the multi-
plicity as a function of the number of participant nucleons
has been observed, at much higher incident energy, in the
depth subthreshold production of \( \eta \) [12] and high
transverse-mass \( \pi^0 \) [8].

At energy as low as 30A \( \text{MeV} \), the fluctuations on
global variables such as the charge particle multiplicity
and transverse energy affect the determination of the im-
pact parameter especially for the most central collisions
[17]. To solve the problem of the event selection over a
wide range of impact parameters, we exploit the reaction
mechanism and hard photon multiplicity information to
determine the size of the interaction zone [18,19]. In-
deed, the detection of heavy fragments from projectile-
like fragments to evaporation residues and their relative
velocities allows to select classes of events with different
centrality. In particular, the most central collisions
were selected requiring the presence of an evaporation
residue with velocity close to the centre of mass velocity
and charge higher than the projectile charge. On the
other hand, the detection of fragments originating from
projectile fragmentation and deep inelastic collisions was
exploited to reach classes of events spanning the range of
impact parameters from peripheral to mid-central. The
same procedure was also applied to some classes of events
selected in terms of total charged particle multiplicity.
Finally, to obtain a quantitative estimate of the impact
parameter, the hard photon multiplicity has been cal-
culated for the various classes of events. The number of
participant nucleons \( A_{\text{part}}(b) \) has been extracted from
the hard photon (\( E_\gamma \geq 30 \text{ MeV} \)) multiplicity, according
to the relation \( M_\gamma(b) = P_\gamma \cdot N_{\text{np}}(b) \approx 0.5 \cdot A_{\text{part}}(b) \)
where \( P_\gamma \) is the probability of emitting a hard photon
in a np collision deduced from inclusive data \( P_\gamma(E_\gamma \geq
30 \text{ MeV}) \approx 2.7 \cdot 10^{-3} \) and \( N_{\text{np}}(b) \) is the number of first
chance np collisions occurring in the overlap region. This
relation has been satisfied by several experiments which
show that the hard photon multiplicity provides a snap-
shot of the participant region [2, 22].

In fig. 2 the average proton multiplicity is reported as a
function of the number of nucleons participating \( A_{\text{part}}(b) \)
in the collision for different energy bins in the NN ref-
ence frame (60 \( \div \) 80 MeV (\( M_p(60) \)), 100 \( \div \) 120 MeV
(\( M_p(100) \)), 130 \( \div \) 150 MeV (\( M_p(130) \)). The experimental
proton multiplicity (full squares) displays the expected
linear dependence on \( A_{\text{part}}(b) \) [4] for energy close to the
kinematical limit (60 \( \leq \ E_p \leq \ 80 \text{ MeV} \) fig. 2a), while a
stronger dependence is observed with increasing proton
energy, in particular the multiplicity of extremely ener-
getic protons \( (M_p(130)) \) exhibits an almost quadratic in-
crease with \( A_{\text{part}} \) (fig. 2c).

The BNV calculations, filtered with the experimental
apparatus, are also reported in fig. 2 (open circles). The
\( A_{\text{part}}(b) \) assignment relies on the hypothesis of a geo-
metrical correlation between \( b \) and \( A_{\text{part}}(b) \) [13].
The calculations have been scaled by a factor 0.6 to allow a
better comparison with the data. This scaling is con-
sistent with the yield reduction needed to account for
complex particle emission. Within this assumption, a
good agreement with the data is observed in fig. 2a and
fig. 2b, confirming that the energetic proton production is
described with good accuracy up to \( \approx 110 \text{ MeV} \). On
the other hand, BNV calculations fail in the most ener-
getic bin \( (M_p(130)) \) where the almost quadratic
dependence on \( A_{\text{part}} \) observed experimentally is not re-
produced thus showing the onset of effects beyond the
mean field and two body collisions. It is interesting to
notice that a non linear dependence is observed, both
experimentally and theoretically, also for $M_p(100)$. The calculation can account for this behaviour due to the increasing importance of multistep two-body collisions in the production mechanism of protons with energy higher than the kinematical limit $\theta_{\mathrm{lab}} = 138^\circ$. However, this mechanism seems not to be able to explain the almost quadratic behaviour observed for $M_p(130)$. Indeed, for extremely energetic protons, this multistep process is associated with larger time scale. Therefore the system can emit nucleons and rapidly evolves far from the initial geometrical overlap configuration. This can explain the weaker dependence on the impact parameter observed in the calculations (fig. 2c).

![Graph](image)

**FIG. 2.** Proton multiplicities as a function of the number of participant nucleons (see text) for different energy bins. Experimental values (solid squares) and momentum dependent BNV calculations (open circles) scaled by a factor 0.6 are reported. Only protons emitted in the angular range $75^\circ \leq \theta_{\mathrm{lab}} \leq 138^\circ$ are considered. To compare the trends a linear and a quadratic dependence are reported (solid lines) in panels a) and c), respectively.

The observed behaviour of the multiplicity of very energetic protons on the number of participant nucleons (fig. 2c) puts constraints on the mechanism responsible for the production of extremely energetic protons. Dynamical fluctuations [23] are not expected to lead to the $A_{\text{part}}$ quadratic behaviour observed experimentally. Other effects, such as high momentum tails, are weakly dependent on density and, at the energy considered, density variation from central to peripheral impact parameters are small [24]. Cooperative effects, where more nucleons or clusters of nucleons participate in the collision, seem very promising and should be investigated.

In summary, the energetic proton production has been investigated up to proton energy corresponding to about 20% of the total energy available in the system. The energetic protons up to $\approx 110$ MeV are emitted as a consequence of NN collisions in the first stage of the reaction and their characteristics are well reproduced by BNV calculations which include the momentum dependence in the effective potential. On the other hand, the BNV approach fails to explain the almost quadratic dependence on the number of participant nucleons of the yield of very energetic protons ($E_{NN}^{p} \geq 130 MeV$). This behaviour calls for the introduction of mechanisms beyond the mean field and two body nucleon-nucleon collisions such as cooperative effects. These results shed some light on the emission of extremely energetic protons and can improve the understanding of the mechanism responsible for deep subthreshold particle production.

We thank Prof. M. Di Toro for the critical reading of the manuscript and the LNS staff for the high-quality beam and the support during the experiment.

[1] W. Cassing et al., Phys. Rep. 188, 365 (1990).
[2] C. Gelbke, Prog. in Part. and Nucl. Phys. 42, 91 (1999).
[3] H. Fucks and K. Mohring, Rep. Prog. Phys. 57, 231 (1994).
[4] R. Wada et al., Phys. Rev. C 39, 497 (1989).
[5] R. Alba et al., Phys. Lett. B 322, 38 (1994).
[6] P. Sapienza et al., Phys. Rev. Lett. 73, 1769 (1994).
[7] R. Coniglione et al., Phys. Lett. B 471, 339 (2000).
[8] G. Martinez et al., Phys. Rev. Lett. 83, 1538 (1999) and reference therein.
[9] E. Migneco et al., Nucl. Instr. and Meth., A 314, 31 (1992).
[10] I. Iori et al., Nucl. Inst. and Meth., A 325, 458 (1993).
[11] A. Del Zoppo et al., Nucl. Inst. and Meth., A 327, 363 (1993).
[12] P. Sapienza et al., Il Nuovo Cimento, Vol. 111 A, 999 (1998).
[13] A. Bonasera et al., Phys. Rep. 243, 1 (1994).
[14] V. Greco et al., Phys. Rev. C 59, 810 (1999).
[15] D. Miskowiec et al., Phys. Rev. Lett. 72, 3650 (1994).
[16] A.R. Wolf et al., Phys. Rev. Lett. 80, 5281 (1998).
[17] A. Del Zoppo et al., Phys. Rev. C 50, 497 (1994).
[18] H. Nifenecker and J.A. Pinston, Annu. Rev. Nucl. Part. Sci. 40, 113 (1990).
[19] W. Bauer et al., Phys. Rev. C 34, 2127 (1986).
[20] E. Migneco et al., Phys. Lett. B 298, 46 (1993).
[21] P. Piattelli et al., Phys. Lett. B 442, 48 (1998).
[22] J.H.G. van Pol et al., Phys. Rev. Lett. 76, 1425 (1996).
[23] M. Germain et al., Phys. Lett. B 437, 19 (1998).
[24] M. Baldo and U. Lombardo, private communications.