Strong Enhancement of Extremely Energetic Proton Production in Central Heavy Ion Collisions at Intermediate Energy

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The energetic proton emission has been investigated as a function of the reaction centrality for the system ^{58}Ni + ^{58}Ni at 30*A* 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.

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Heavy ion collisions at intermediate energy allow one to investigate the properties of nuclear matter far from stability. Dynamical calculations show that, in the early nonequilibrated 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. In particular, particles such as subthreshold mesons or energetic photons and nucleons are expected to provide information on the nuclear dynamics at the preequilibrium stage (see [1,2] and references therein). Experimentally the presence of a preequilibrium component in the light particle emission has been observed in the energy spectra [3,4]. The impact parameter dependence of the preequilibrium protons, investigated for several systems, shows that the average energetic proton multiplicity increases almost linearly with the number of participant nucleons [5] as expected for incoherent quasifree *NN* collisions [3]. Moreover, experimental evidences, such as the observed γ-proton anticorrelation [6] and the energetic proton angular distributions [7], 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 [1] and therefore are good candidates to probe the preequilibrium 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 one to concentrate a relevant fraction of the available energy in the production of a single energetic or massive particle [8]. 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}Ni + ^{58}Ni at 30*A* 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 nonlinear 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 preequilibrium and the nature of energetic proton emission.

The experiment was performed at Laboratori Nazionali del Sud with the MEDEA [9] and the MULTICS [10] apparatus. A ^{58}Ni beam at 30*A* MeV delivered by the superconductive cyclotron system bombarded a ^{58}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° to 170°. The BaF_2 permits one to detect and identify light charged particles (LCP) ($E_p \leq 300$ MeV) and photons up to $E_\gamma \approx 200$ MeV. The time of flight and pulse shape discrimination analysis allows one to clearly identify photons, protons, deuterons, and tritons, alpha particles [9]. The response of BaF_2 crystals to LCP has been investigated using monoenergetic particle beams and a calibration procedure based on the γ calibration with γ sources and cosmic rays has been established [11]. The MULTICS array is made of 55 telescopes covering the angular range $3° \leq \theta_{\text{lab}} \leq 28°$. 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 1.5*A* MeV [10]. The total geometric acceptance was larger than 90% of 4π.

Energetic protons were detected in coincidence with photons, LCP ($Z = 1, 2$), 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. Because of the very low cross section expected, high statistics proton 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 detectors with $\theta \geq 75°$ 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 4×10^8 events were collected and analyzed.

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, $\theta_{\text{lab}} \geq 42°$) [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) [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 ($v_{\text{max}} = v_F + 0.5 v_{\text{beam}}$) (arrows of Fig. 1).

Extremely energetic protons were already observed in heavy ion collisions (see [7] and references therein), but those experiments did not allow a conclusive answer on the production mechanism to be drawn. In order to explain the production of particles with energy or mass larger than the energy available in *NN* collisions including the Fermi motion, several hypotheses, such as the presence of high momentum tails in the nucleon momentum distribution, the onset of multistep processes, cooperative effects, and the presence of dynamical fluctuations, have been proposed.

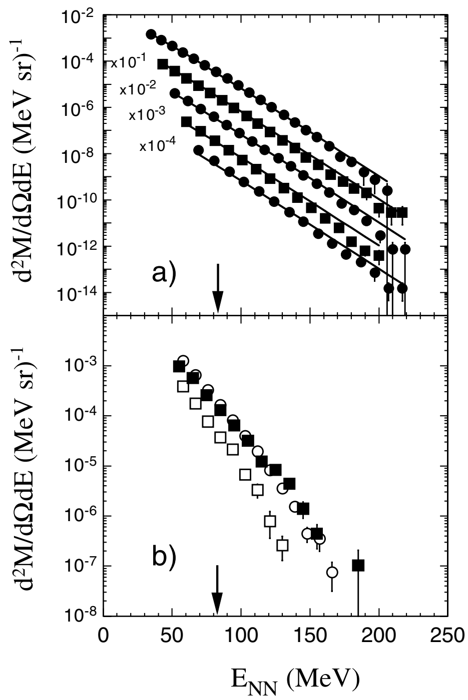

FIG. 1. (a) Experimental inclusive proton multiplicity spectra in the *NN* reference frame at different polar angles (87°, 100°, 113°, 126°, 140°). (b) Proton energy multiplicity spectrum in the *NN* reference frame for central collisions ($\langle b \rangle \approx 2.5$ fm; $98° \leq \theta_{NN} \leq 124°$). Data (full squares), BNV with local Skyrme interaction (open squares) and with momentum dependent interaction (open circles) are reported. The arrows indicate the expected kinematical limit for first chance *NN* collisions.

To gather more information on the energetic proton emission, we have performed simulations with a Boltzmann-Nordheim-Vlasov (BNV) code which is based on mean field and two-body dynamics [13]. To explore the sensitivity to basic ingredients of the calculations two different potentials were implemented in the BNV code: one using a local Skyrme interaction for the mean field (open squares in Fig. 1b) and another using a Gale–Bertsh–Das Gupta (GBD) momentum dependent interaction (open circles in 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 important at higher bombarding energy, it is interesting to understand 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. About 400 events have been simulated per impact parameter (using 200 test particles per nucleon). Our results point out remarkable differences: the spectrum calculated with the local Skyrme interaction strongly undershoots the data and exhibits a lower inverse slope parameter 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 MeV). Because of the less attractive 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 [4].

From the comparison with the experimental data one can get a deeper insight into the behavior 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 energetic protons, we have investigated the impact parameter dependence. Indeed, the dependence of multiplicity on the number of nucleons participating in the reaction $A_{\rm part}$ can provide information about a change in the production mechanism. A stronger than linear increase of the multiplicity as a function of the number of participant nucleons has been observed, at much higher incident energy, in the deep subthreshold production of K^+ [15], η [16], and energetic π^0 [8]. In particular, the trend of the multiplicity of high transverse mass π^0, which scales as $A_{\rm part}^{4/3}$, has been interpreted in terms of rescattering of the pion (two step process) [8].

At energy as low as 30*A* MeV, the fluctuations on global variables such as the charged particle multiplicity and transverse energy affect the determination of the impact parameter especially for the most central collisions [17]. To cover 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]. Indeed, the detection of heavy fragments from projectilelike fragments to evaporation residues allows one 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 center 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 midcentral. A few classes of events were also selected in terms of total charged particle multiplicity. Finally, to obtain a quantitative estimate of the impact parameter, the hard photon multiplicity, which provides a snapshot of the participant region [20–22], has been calculated for the various classes of events. The number of participant nucleons $A_{\rm part}(b)$ has been extracted from the hard photon ($E_\gamma \geq 30$ MeV) multiplicity, according to the relation $M_\gamma(b) = P_\gamma \times N_{np}(b) \simeq P_\gamma \times 0.5 \times A_{\rm part}(b)$, where P_γ is the probability of emitting a hard photon in a np collision deduced from inclusive data [$P_\gamma(E_\gamma \geq 30 \text{ MeV}) \approx 2.7 \times 10^{-5}$] and $N_{np}(b)$ is the number of first chance *np* collisions occurring in the overlap region.

In Fig. 2 the average proton multiplicity is reported as a function of the number of nucleons participating $A_{\rm part}(b)$ in the collision for different energy bins in the *NN* reference frame {60–80 MeV [$M_p(60)$], 100–120 MeV [$M_p(100)$], 130–150 MeV [$M_p(130)$]}. The experimental proton multiplicity (full squares) displays the expected linear dependence on $A_{\rm part}(b)$ [5] for energy close to the kinematical limit [$60 \leq E_p^{NN} \leq 80$ MeV (Fig. 2a)], while a stronger dependence is observed with increasing proton energy. In particular, the multiplicity of extremely energetic protons [$M_p(130)$] exhibits an almost quadratic increase with $A_{\rm part}$ (Fig. 2c). Only protons emitted in the angular range $75° \leq \theta_{\rm lab} \leq 138°$ were considered. Within this angular range the contribution of double hits is reduced due to the focusing of the emitted particles at forward angles. In particular, for the most energetic protons $130 \leq E_p^{NN} \leq 150$ MeV, where this effect is expected to be larger, an upper limit for this contribution of about 7% has been estimated in the *b* range investigated.

The BNV calculations, filtered with the experimental apparatus, are also reported in Fig. 2 (open circles). The

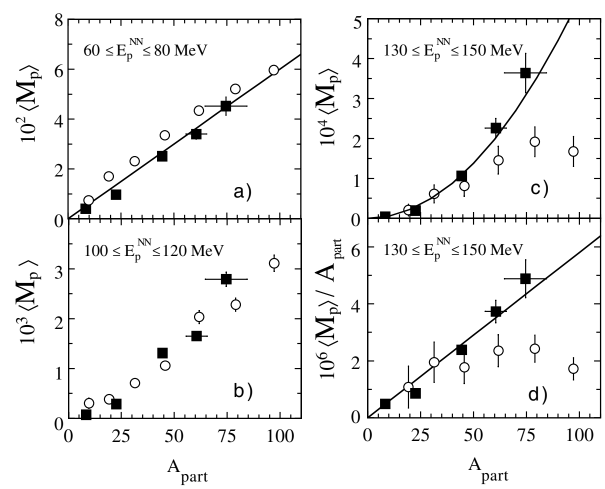

FIG. 2. Proton multiplicities versus $A_{\rm part}$ for different energy bins. Experimental values (solid squares) and momentum dependent BNV calculations (open circles) scaled by a factor of 0.6 (see text) are reported (a),(b),(c). In panel (d) the points of panel (c) are divided by $A_{\rm part}$ and reported versus $A_{\rm part}$. A linear [panels (a) and (d)] and a quadratic dependence [panel (c)] are reported (solid lines).

$A_{\rm part}(b)$ assignment relies on the hypothesis of a geometrical correlation between b and $A_{\rm part}(b)$ [19]. The calculations have been scaled by a factor of 0.6 to allow a better comparison with the data. This scaling is consistent with the yield reduction needed to account for complex particle emission. Within this assumption, a good agreement with the data is observed in Figs. 2a and 2b, confirming that the energetic proton production is described with good accuracy up to $\approx$ 110 MeV. On the other hand, BNV calculations fail in the most energetic bin [$M_p(130)$, Fig. 2c] where the almost quadratic dependence on $A_{\rm part}$ observed experimentally is not reproduced. It is interesting to notice that a nonlinear dependence is observed, both experimentally and theoretically, also for $M_p(100)$. The calculation can account for this behavior due to the increasing importance of multistep two-body collisions in the production mechanism of protons with energy higher than the kinematical limit similarly to the trend observed for high transverse mass π^0 [8]. However, this mechanism seems not to be able to explain the almost quadratic behavior observed for $M_p(130)$. Indeed, for extremely energetic protons, this multistep process is associated with larger time scales. 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). To emphasize the difference between data and BNV multiplicity per participant nucleon $\frac{M_p(130)}{A_{\rm part}}$ is reported in Fig. 2d. The experimental value (full squares) is found to increase linearly with $A_{\rm part}(b)$, as expected since $M_p(130)$ scales as $A^2_{\rm part}(b)$, in contrast with calculations (open circles) which exhibit a different trend. This discrepancy indicates the onset of effects beyond the mean field and two body collisions.

The observed behavior of the multiplicity of very energetic protons on the number of participant nucleons (Figs. 2c and 2d) puts constraints on the mechanism responsible for the production of extremely energetic protons. We have found that multistep two-body collisions, which play an important role in the production of protons with energy between 100 and 120 MeV, do not reproduce the trend of the most energetic protons ($E_p^{NN} \geq 130$ MeV) which exhibits a stronger dependence on $A_{\rm part}(b)$. Dynamical fluctuations [23] are not expected to lead to the $A_{\rm part}$ quadratic behavior 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 ($E_p^{NN} \geq 130$ MeV). This behavior 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.

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[1] W. Cassing *et al.,* Phys. Rep. **188**, 365 (1990).
[2] C. Gelbke, Prog. Part. 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).
[9] E. Migneco *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. A **314**, 31 (1992).
[10] I. Iori *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. A **325**, 458 (1993).
[11] A. Del Zoppo *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. A **327**, 363 (1993).
[12] P. Sapienza *et al.,* Nuovo Cimento Soc. Ital. Fis. **111A**, 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**, 2930 (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 comunications).