PROTON EMISSION IN 58A AND 86A MeV ^{12}C -INDUCED HEAVY-ION REACTIONS

B. Jakobsson, L. Carlén, P. Kristiansson,
J. Krumlinde, A. Oskarsson, I. Otterlund and B. Schröder
Department of Physics, University of Lund, Lund, Sweden

H.-Å. Gustafsson, T. Johansson and H. Ryde
CERN, Geneva, Switzerland

G. Tibell

The Gustaf Werner Institute, University of Uppsala, Uppsala, Sweden

J.P. Bondorf, G. Fàì, A.O.T. Karvinen and O.-B. Nielsen
The Niels Bohr Institute, Copenhagen, Denmark

M. Buenerd, J. Cole, D. Lebrun, J.M. Loiseaux,
P. Martin, R. Ost and P. de Saintignon
Institut des Sciences Nucléaires, Grenoble, France

C. Guet, E. Monnard, J. Mougey, H. Nifenecker, P. Perrin,
J. Pinston, C. Ristori and F. Schussler
Centre d'Etudes Nucléaires, Grenoble, France

ABSTRACT

Inclusive proton spectra from ^{12}C -induced heavy-ion interactions at 58A and 86A MeV have been obtained by using a ΔE -E time-of-flight telescope. The shapes of the energy spectra above 30 MeV for $32^\circ \leq \theta \leq 142^\circ$ are very similar for five targets ranging from C to Au. The backward spectra can be reproduced both in the picture of a thermalized source characterized by an 11-17 MeV temperature Boltzmann distribution moving with half the beam velocity and in the picture of quasi-elastic nucleon-nucleon scattering from two interacting Fermi spheres. The forward spectra are difficult to reproduce unless a combination of the two descriptions is accepted. The 58A MeV spectra peak substantially closer to the beam energy per nucleon and show significantly steeper slopes than the 86A MeV spectra.

(Submitted to Physics Letters B)

The nucleon emission in heavy-ion collisions slightly above the Coulomb barrier is normally well explained by the statistical decay of moderately excited compound nuclei and deep inelastic fragments. However, some recent experiments show indications of other processes producing a hard proton and neutron component [1-3], explainable in terms of prompt emission [4] or strongly heated subvolumes [5,6]. In relativistic heavy-ion interactions the inclusive proton spectra of Sandoval et al. [7] and Nagamiya et al. [8] can be explained by various participant-spectator models [9,10], where the main sources are the strongly heated participant (fireball) and the weakly heated residual nuclei. However, several other microscopic and macroscopic approaches are able to explain inclusive proton spectra [11].

Our experiment gives inclusive proton data in the intermediate-energy heavy-ion collision region.

The experiment was performed at the CERN Synchro-cyclotron (SC) with 86A and 58A MeV ^{12}C beams of an intensity, for the full energy beam, of 2 to 5×10^9 ions/s, a momentum resolution of 0.5%, and a duty factor around 30%. Targets of C, Al, Cu, Ag, and Au, all of natural composition, with thicknesses of 17-38 mg/cm² received 99% of the beam intensity within an area of 1 cm². Double-differential cross-sections for p, d, t, ^3He , and ^4He were obtained by the use of a telescope consisting of a 1 mm totally depleted Si detector (Si), placed inside a vacuum scattering chamber, and three plastic scintillators with a vacuum pipe in between the first and the second one. The first two scintillators, a 1 mm NE102A (S1) and a 25 mm NE111 (S2) were used for time-of-flight (TOF) and energy-loss measurements. The third one, a 180 mm NE104 (S3), was used for energy-loss measurements only. The TOF distances were 2.2 m ($32^\circ < \theta < 55^\circ$) and 0.6 m ($\theta > 55^\circ$). Particle identification was obtained from the ΔE_{S1} -TOF, ΔE_{S2} -TOF, ΔE_{S3} -TOF and ΔE_{S2} - ΔE_{S3} correlations. The error in the proton yield due to the isotopic resolution is less than 1%. Proton energies were determined from the light output of S2 and S3. The scintillators were calibrated from the energy deposited in the Si detector, resulting in a maximum energy uncertainty of ± 10 MeV. Determinations of the

passing-through point in the ΔE_{S2} -TOF and ΔE_{S3} -TOF correlations were made as a further test of the validity of the energy calibration. The beam intensity was measured with a Faraday cup calibrated by a determination of the ^{24}Na activity produced in the $^{27}\text{Al}(^{12}\text{C},x)^{24}\text{Na}$ reaction [12]. The total error in the cross-sections, including uncertainties from detector efficiencies and nuclear reactions in the detectors, is estimated to be less than 30%. As seen in table 1, the energy-integrated ($30 \text{ MeV} < E_p < 200 \text{ MeV}$) proton cross-sections at $\theta_{\text{lab}} = 32^\circ$, 45° , and 54° are found to be in good agreement with those obtained in a nuclear emulsion experiment [13].

The differential cross-sections $d^2\sigma/d\Omega dE$ of protons are shown in fig. 1. The forward spectra have broad maxima at energies well below the projectile energy per nucleon, changing into exponentially falling spectra at higher energies. A tendency towards a steeper fall-off at the highest energies has been observed. The backward spectra are falling off exponentially in the whole energy region above 30 MeV with an almost constant slope. A strong forward peaking in the angular distribution is found. For $\theta_{\text{lab}} = 3^\circ$, preliminary data of 40-200 MeV protons in $^{12}\text{C} + ^{12}\text{C}$ reactions [14] indicate a narrow peak (the width is about 25 MeV) at an energy close to the beam energy per nucleon. In the low-energy (target evaporation) region one could expect the yield of protons to increase strongly. This has in fact been observed in preliminary data for $^{12}\text{C} + \text{C}$ and $^{12}\text{C} + \text{Au}$ reactions [14]. The general behaviour of the proton spectra is the same for all targets ranging from C to Au. The similarity of the distributions is demonstrated in fig. 2, where 32° and 90° spectra are shown for C, Al, Cu, Ag, and Au targets.

The target-mass dependence of the cross-section is very close to $A^{2/3}$ for the backward spectra as well as for the high-energy part of the forward spectra. In the peak region of the forward spectra the A dependence gets weaker, a tendency which becomes more and more pronounced with decreasing angle. This could be understood as a gradually increasing influence from a fast source in peripheral collisions.

The fact that the inclusive spectra are not very sensitive to the target mass with respect to peak positions, peak widths, and slopes could be qualitatively explained in two ways. One possibility is that quasi-elastic nucleon-nucleon scattering is the dominating source of proton emission, another one is that the parts of the projectile and target volumes which participate in the early phase of the reaction, forming a hot pre-equilibrium system, are always of the same size.

A simple thermal participant-spectator approach has been attempted to parametrize our data. In the symmetric system $^{12}\text{C} + ^{12}\text{C}$ we expect that any participant-(fireball)like source has a parallel velocity of $\beta_L \approx \beta_{\text{proj}}/2 \approx 0.20$ in the laboratory system. The average transverse velocity β_T is expected to be zero. This is in fact supported by the circular shapes we find of the invariant $(1/p)(d^2\sigma/d\Omega dE)$ contours in the p_L - p_T plane centred around $(p_L = p_{\text{proj}}/2, p_T = 0)$ for the protons having large momenta in the centre-of-mass system. The characteristic temperature of this source is obtained by fitting Galilei-transformed classical Boltzmann spectra to the experimental distribution, i.e. for the above-mentioned source ($\beta_T = 0$):

$$\frac{d^2\sigma}{d\Omega d\varepsilon} = C\sqrt{\varepsilon} \exp \left[-(\varepsilon + \varepsilon_{\text{source}} - 2\sqrt{\varepsilon \cdot \varepsilon_{\text{source}}} \cos \theta)/T \right]. \quad (1)$$

Here ε is the proton kinetic energy in the laboratory system, $\varepsilon_{\text{source}}$ the source energy per nucleon, θ the laboratory emission angle, T the characteristic temperature of the source, and C a normalization constant. The least squares fit to the 90° $^{12}\text{C} + ^{12}\text{C}$ spectrum of protons with $E_p > 40$ MeV, where any contribution from a low-temperature spectator source is negligible, gives a temperature of $T = 13.0$ MeV. In order to test the validity of the classical approach, we also used an approximation to the relativistically generalized Boltzmann distribution in the source system. For large m/T values (m is the nucleon mass), one gets

$$\frac{d^2\sigma}{d\Omega d\varepsilon'} = C p' E' \frac{\exp(-\varepsilon'/T)}{(T/m)^{3/2} [1 + (2T/m)]}, \quad (2)$$

where now $E' = \varepsilon' + m'$. Since we do not find any noticeable deviation from the classical approach, we subsequently use eq. (1). Effects of Coulomb repulsion and binding energies are not considered in our first-order approach.

If only the high-energy part of the 90° spectrum is used in the fit, we find lower temperatures (table 2). One reason for this effect could be that quasi-elastic first-order nucleon-nucleon scattering contributes substantially to the proton production cross-section. In fig. 1 the experimental 90° spectrum is compared both with that obtained in the moving Boltzmann source calculation and with the spectrum from the first-order nucleon-nucleon scattering calculation. The latter distribution has been calculated in the framework of two colliding Fermi spheres (the Fermi energy $E_F = 25$ MeV) with inclusion of Pauli blocking. Both calculations reproduce the shape of the experimental distribution.

In table 2 we display the temperatures we find for the 90° distributions for five different targets. All backward spectra are consistent with these temperatures from 11 to 17 MeV and by making two-parameter ($\beta_L^{\text{source}}, T$) fits we find $\beta_L^{\text{source}} \approx \beta_{\text{beam}}/2$ for all targets. The temperature of the participant source increases with increasing target mass. This is a result which does not allow any decreasing projectile-to-target-participant ratio. The forward-angle distributions cannot be explained by the above-mentioned moving Boltzmann source. This may be due to a strong contribution from faster moving "spectator-like" sources. The apparent temperature of the hard proton component is of the same order as (or higher than) the 90° temperatures. In the quasi-elastic nucleon-nucleon scattering approach one can fit these high-energy components if one uses a Fermi energy of about 37 MeV (even for $^{12}\text{C} + ^{12}\text{C}$), i.e. the one normally adopted for heavy nuclei. However, for the "peak regions" the best fits give much lower Fermi energies.

Figure 3 shows $d^2\sigma/d\Omega dE$ distributions for 58A MeV $^{12}\text{C} + \text{Ag}$ collisions compared with the previously presented 86A MeV distributions (solid curves). A significantly steeper slope is found in the hard part of the spectrum and the characteristic temperature is here 11.4 MeV (table 2) compared with 16.6 MeV for the 86A MeV data. Since the ratio of the temperatures at 86A and 58A MeV is nearly the same as the ratio of the beam energies ($T_{86}/T_{58} = 1.46$ and $86/58 = 1.48$), the same projectile-to-target-participant ratio is expected provided that all

energy available for the participants is transformed to heat. Another observation is that the 32° peak is now significantly closer to the beam energy per nucleon, which could indicate that the average impact parameter is larger and that more projectile-fragmentation-like processes contribute to the cross-section, at this laboratory angle. The orbital deflection, discussed by van Bibber et al. [15], is probably an important source for this difference.

In conclusion, we have observed inclusive $d^2\sigma/d\Omega dE$ distributions of protons from intermediate-energy heavy-ion collisions which could not be fully explained by either a simple thermal-source approach or a simple nucleon-nucleon-scattering approach alone. The shapes of the spectra depend very little on the target mass, and the absolute cross-sections are proportional to $A^{2/3}$ except around the maxima for forward angles where the mass dependence is substantially weaker. The projectile-to-target-participant ratio seems to be the same for all targets and furthermore it does not change when the beam energy is increased from 58A to 86A MeV.

We express our gratitude to the CERN SC staff for their outstanding support during our experiment. We wish to acknowledge the excellent work of K. Gudbjerg-Hansen and his staff at the Niels Bohr Institute mechanical workshop as well as that of U. Persson in Lund. The Danish and Swedish Natural Science Research Councils as well as the Nordic Committee for Accelerator-based Research have provided financial support.

REFERENCES

- [1] D.G. Sarantites, L. Westerberg, M.L. Halbert, R.A. Dayras, D.C. Hensley and J.H. Barker, Phys. Rev. C 18 (1978) 774.
L. Westerberg, D.G. Sarantites, D.C. Hensley, R.A. Dayras, M.L. Halbert and J.H. Barker, Phys. Rev. C 18 (1978) 796.
- [2] D.L. Hillis, J.D. Garrett, O. Christensen, B. Fernandez, G.B. Hagemann, B. Herskind, B.B. Back and F. Folkmann, Nucl. Phys. A325 (1979) 216.
- [3] R.M. Lieder, B. Bochev, T. Kutsarova, H. Beuscher, D.R. Haenni, T. Morek, M. Müller-Veggian, A. Neskakis, C. Mayer-Böricke and J.P. Didelez, Proc. Nobel Symposium 50, Nuclei at Very High Spin, 'Sven-Gösta Nilsson in Memoriam', Örenäs, Sweden, 1980 (Eds. G. Leander and H. Ryde), to be published by Physica Scripta.
- [4] J.P. Bondorf, J.N. De, A.O.T. Karvinen, G. Fàì and B. Jakobsson, Phys. Lett. 84B (1979) 162.
- [5] J.P. Bondorf, J.N. De, G. Fàì, A.O.T. Karvinen, B. Jakobsson and J. Randrup, Nucl. Phys. A333 (1980) 285.
P.-A. Gottschalk and M. Weström, Phys. Rev. Lett. 39 (1977) 1250.
- [6] S.I.A. Garpman, D. Sperber and M. Zielinska-Pfabe, Phys. Lett. 90B (1980) 53.
- [7] A. Sandoval, H.H. Gutbrod, W.G. Meyer, R. Stock, Ch. Lukner, A.M. Poskanzer, J. Gosset, J.C. Jourdain, C.H. King, G. King, Nguyen Van Sen, G.D. Westfall and K.L. Wolf, Phys. Rev. C 21 (1980) 1321.
- [8] S. Nagamiya, L. Anderson, W. Brückner, O. Chamberlain, M.C. Lemaire, S. Schnetzer, G. Shapiro, H. Steiner and I. Tanihata, Phys. Lett. 81B (1979) 147.
- [9] G.D. Westfall, J. Gosset, P.J. Johansen, A.M. Poskanzer, W.G. Meyer, H.H. Gutbrod, A. Sandoval and R. Stock, Phys. Rev. Lett. 37 (1976) 1202.
- [10] J. Hüfner and J. Knoll, Nucl. Phys. A290 (1977) 460.
- [11] A.A. Amsden, J.N. Ginocchio, F.H. Harlow, J.R. Nix, M. Danos, E.C. Halbert and R.K. Smith, Jr., Phys. Rev. Lett. 38 (1977) 1055.

- [12] J.W.N. Tuyn, R. Deltenre, C. Lamberet and G. Roubaud, CERN Technical Memorandum HS-RP/TM/80-5 (1980).
- [13] R. Kullberg and A. Oskarsson, unpublished data.
- [14] J. Mougey et al. (CERN-Copenhagen-Grenoble-Lund Collaboration), unpublished data.
- [15] K. Van Bibber, D.L. Hendrie, D.K. Scott, H.H. Weiman, L.S. Schroeder, J.V. Geaga, S.A. Chessin, R. Treuhaft, J.Y. Grossiord, J.O. Rasmussen and C.Y. Wong, Phys. Rev. Lett. 43 (1979) 840.

Table 1

Production cross-sections for protons with $30 \text{ MeV} \leq E \leq 200 \text{ MeV}$ obtained in the present experiment, compared with results from a nuclear emulsion experiment ($\langle A \rangle = 94$, $\langle E_{\text{beam}} \rangle = 85A \text{ MeV}$)

θ_{lab}	$\frac{d\sigma}{d\Omega} \text{ (mb/sr)}, 30 \text{ MeV} \leq E_p \leq 200 \text{ MeV}$		
	32°	45°	54°
$^{12}\text{C} + \text{Cu}$ (this expt.) 86A MeV	540	270	180
$^{12}\text{C} + \text{AgBr}$ (ref. [13]) 50-100A MeV	520 ± 80	410 ± 60	240 ± 50
$^{12}\text{C} + \text{Ag}$ (this expt.) 86A MeV	630	450	-

Table 2

Temperatures found in the Boltzmann least squares fit to 90° spectra. T_{40} is the temperature obtained for $E > 40 \text{ MeV}$ protons and T_{60} for $E > 60 \text{ MeV}$ protons. The source is moving in the laboratory system with half the beam velocity.

Target	T_{40} (MeV)	T_{60} (MeV)	χ^2_{40}	Degrees of freedom
86A MeV				
C	13.0	11.0	7.0×10^{-6}	17
Al	13.8	12.6	9.9×10^{-6}	17
Cu	13.8	12.6	2.6×10^{-5}	19
Ag	16.6	15.4	7.5×10^{-6}	21
Au	17.0	15.8	1.3×10^{-5}	21
58A MeV				
Ag	11.4	10.6	1.5×10^{-5}	15

Figure captions

- Fig. 1 : Differential cross-sections $d^2\sigma/d\Omega dE$ for protons emitted in $^{12}\text{C} + \text{C}$, Cu, and Au reactions at 86A MeV. The solid curve is the result of a moving Boltzmann source with $\beta_L = \beta_{\text{beam}}/2$ and $T = 13.0$ MeV. The dashed curve is the result of the collision of two Fermi spheres with $E_F = 25$ MeV.
- Fig. 2 : Differential cross-sections $d^2\sigma/d\Omega dE$ for protons at $\theta_{\text{lab}} = 32^\circ$ and 90° , emitted in $^{12}\text{C} + \text{C}$, Al, Cu, Ag, and Au reactions at 86A MeV.
- Fig. 3 : Differential cross-sections for protons at $\theta_{\text{lab}} = 32^\circ$ and 90° , emitted in $^{12}\text{C} + \text{Ag}$ reactions at 58A MeV (points) and 86A MeV (solid curves).

Fig. 1

Fig. 2

Fig. 3