Investigation of Pion Absorption in Heavy-Ion Induced Subthreshold π^0 Production

R. S. Mayer,(1) W. Henning,(1),(a) R. Holzmann,(1) R. S. Simon,(1) H. Delagrange,(2) F. Lefèvre,(2) T. Matulewicz,(2),(b) R. Merrouch,(2) W. Mittig,(2) R. W. Ostendorf,(2) Y. Schutz,(2) F. D. Berg,(3) W. Kühn,(3) V. Metag,(3) R. Novotny,(3) M. Pfeiffer,(2) A. L. Boonstra,(4) H. Löhner,(4) L. B. Venema,(4) H. W. Wilschut,(4) D. Ardouin,(5) H. Dabrowski,(5) B. Erazmus,(5) C. Lebrun,(5) L. Sézac,(5) F. Ballester,(6) E. Casal,(6) J. Díaz,(6) J. L. Ferrero,(6) M. Marqués,(6) G. Martínez,(6) H. Nifenecker,(7) B. Fornal,(8) L. Freindl,(8) and Z. Sujkowski(9)

(1)*Gesellschaft für Schwerionenforschung, D-6100 Darmstadt, Germany*
(2)*Grand Accélérateur National d'Ions Lourds, F-14021 Caen, France*
(3)*II. Physikalisches Institut, Universität Giessen, D-6300 Giessen, Germany*
(4)*Kernfysisch Versneller Instituut, NL-9747 AA Groningen, The Netherlands*
(5)*Laboratoire de Physique Nucléaire, F-44072 Nantes CEDEX 03, France*
(6)*Istituto de Fisica Corpuscular, SP-46100 Burjassot Valencia, Spain*
(7)*Institut des Sciences Nucléaires, F-38026 Grenoble CEDEX, France*
(8)*Institute of Nuclear Physics, 31-342 Cracow, Poland*
(9)*Soltan Institute for Nuclear Studies, 05-400 Swierk, Poland*

(Received 27 July 1992)

We present results from an experimental study of reabsorption effects in subthreshold π^0 production in the reaction ^{129}Xe+^{197}Au at 44 MeV/nucleon. Within the picture of pion generation in nucleon-nucleon scattering we deduce, from our data and from a comparison with the systematics of production cross sections available for lighter reaction systems, information on the π^0 absorption length in nuclear matter. For the π^0 kinetic-energy range $\simeq$5–100 MeV the energy-averaged λ_{abs} and its momentum dependence are obtained, and compared with optical-model calculations.

PACS numbers: 25.70.−z

Like hard-photon emission, the production of pions has been shown to be a sensitive probe of reaction dynamics in nucleus-nucleus collisions [1,2]. In that respect, particularly subthreshold π^0 production has been extensively studied over the last decade. While at beam energies in excess of $\simeq$200 MeV/nucleon pions are thought to be emitted mostly from the hot and compressed participant zone [3], at very low projectile energies collective or cooperative effects have been considered as a possible production mechanism [1,4]. In the intermediate-energy regime relevant to this paper, namely, at $\simeq$35–150 MeV/nucleon, the systematics of data, as well as dynamical phase-space calculations suggest that the pions are generated mainly in incoherent nucleon-nucleon (N-N) collisions [2], in analogy to the production of hard photons in proton-neutron (p-n) collisions [5]. Here the energy necessary to create pions is provided through an appropriate coupling of the nucleon Fermi momenta with the momentum of relative motion of the colliding nuclei. Pions, however, interact strongly with the nuclear medium, i.e., they rescatter and are reabsorbed with high probability. These effects decisively influence experimental observables, like production yields, energy spectra, and angular distributions, as has been shown, e.g., by Grosse [6]. For a deeper understanding of pion-production mechanisms, detailed knowledge of the pion final-state interactions is therefore essential, and it is in particular of prime interest to the investigation of the nuclear equation of state.

For kinetic energies above 50 MeV the pion mean free path in nuclear matter is dominated by the Δ resonance and has been studied extensively in $\pi^{\pm}$-nucleus reactions with charged-pion beams [7]. At lower energies, important in subthreshold production, absorption data for charged pions are scarce and the situation is complicated by the Coulomb interaction. Although direct measurements are impossible for neutral pions because of their short lifetime, an average absorption length of $\lambda_{\mathrm{abs}} \leq 4$–6 fm has been estimated from the shadowing effect observed in heavy-ion induced subthreshold pion emission [6,8,9]. Photoproduction data rather suggest $\lambda_{\mathrm{abs}} \geq 10$ fm in the kinetic-energy range of 20–30 MeV [2], indicating that for a consistent picture clearly more information on low-energy pion absorption is required. Therefore, we have extended the available experimental systematics of subthreshold π^0 production to a very heavy collision system where final-state effects are expected to be large. In this paper we present first quantitative data on neutral-pion absorption and its momentum dependence far below the Δ resonance.

In an experiment performed at GANIL a 9 mg/cm^2 Au target was irradiated with a 44 MeV/nucleon ^{129}Xe beam of typically 0.4–0.9 particle nA. High-energy γ rays stemming from both bremsstrahlung and the decay of neutral pions were detected in an array of 247 hexagonal BaF^2 scintillators clustered in blocks of 19 crystals each. Placed at a distance of 42 cm from the target, they covered angles from 66° to 156° with respect to the beam axis, with a total solid angle $\Omega \simeq 0.30\times 4\pi$. Seven of the blocks were assembled with BaF_2 crystals of 25 cm length and 5.9 cm inscribed radius, developed for the TAPS (two-arm photon spectrometer) array [10]; for the remaining blocks, crystals of somewhat different sizes were used (20 cm length, 5.1 or 6.7 cm inscribed radius). The scintillators were shielded with 2 cm thick plexiglass plates against charged particles; one block was equipped with plastic veto detectors. The energy calibration of the BaF_2 detectors was done with γ rays from radioactive sources and energy-loss signals from cosmic-ray muons. A typical time resolution of 700 ps FWHM was achieved.

In the off-line data reduction it was possible to identify "photon only" events with a high degree of selectivity through a combined pulse-shape and time-of-flight analysis. For each neutral hit the photon energies deposited in adjacent modules were summed in order to improve the overall energy resolution. The high-energy background events produced by cosmic-ray muons were largely suppressed by cuts on the coincidence time and on the geometry of the hit pattern. Finally π^0 events were identified by an invariant-mass analysis of coincident photons, yielding a FWHM mass resolution of 29% and a kinetic-energy resolution above 35 MeV of 20%, superior to those of lead-glass detectors, typically about 2 times less accurate [4,6]. The energy-averaged efficiency for neutral pions was determined from Monte Carlo shower simulations to be 3.1%.

Our data yield an inclusive cross section of 5.3 ± 1.2 mb for the production of bremsstrahlung photons with $E_\gamma \geq 30$ MeV and, from a moving-source analysis of the latter, a source velocity of $\beta = 0.15\pm 0.01$, i.e., equal to $\beta_{\mathrm{beam}}/2$. Both findings fit well into the systematics of hard-photon data [2,5]. For π^0 production we obtain an inclusive cross section of 9.6 ± 1.7 μb, integrated over the N-N frame angular distribution. The error quoted is the quadratic sum of a 4% statistical and a 17% systematic error mainly from the beam-current normalization. A thermal fit to the π^0 transverse-momentum spectrum p_T, represented in the upper part of Fig. 1, produces a source temperature of $T_0 = 14.6\pm 1.0$ MeV, in good agreement with the systematic study of pion energy slopes of Suzuki *et al.* [11]. From the lower part of Fig. 1 it appears that the π^0 angular distribution displays a distinct minimum at 90° in the N-N center-of-mass (c.m.) frame, reminiscent of the p-wave amplitudes of pion production in free N-N collisions [12]. While this indicates that a sizable fraction of the pions originate from N-N collisions in an early stage of the heavy-ion reaction, the good description of the measured p_T spectrum with a thermal distribution points to a certain degree of thermalization.

Beyond these inclusive results, some impact-parameter selectivity could be achieved by placing cuts on the number of neutrons and protons detected in the BaF_2 array. Correlating the nucleon multiplicity with the impact parameter b through a statistical fragmentation calculation done with the code FREESCO [13], we find that the neutral-pion/hard-photon ratio decreases by a factor of 2-3 going from central ($b \leq 5$ fm) to peripheral ($b \geq 10$ fm) collisions. The decrease of this ratio with larger b is most probably caused by a depletion of the π^0 production. Such a behavior is indeed expected as peripheral reactions probe the softer momentum components in the diffuse nuclear surface and because it takes much more energy to produce a pion than a 30 MeV photon. Within the Fermi-gas model the Fermi momentum is calculated to decrease over the investigated impact-parameter range from 265 to 220 MeV/c.

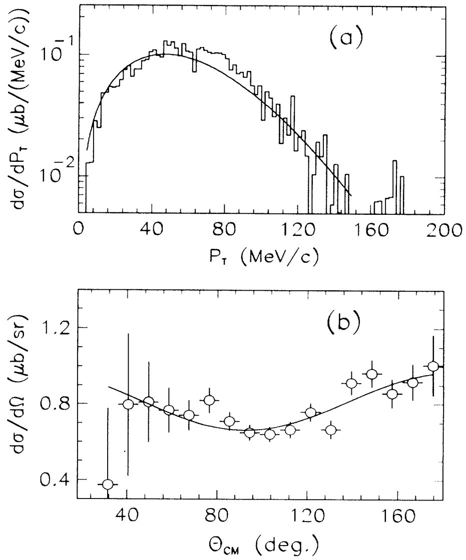

FIG. 1. (a) Response-corrected π^0 transverse-momentum spectrum measured for $^{129}Xe + ^{197}Au$ at 44 MeV/nucleon. The solid line is a thermal fit (see text). (b) Angular distribution in the N-N c.m. frame. Only statistical error bars are shown. A Legendre-polynomial fit (solid line) yields an anisotropy of $A_2 = 0.27\pm 0.07$.

Ultimately our data display many features of π^0 production in mainly leading N-N collisions. Adopting therefore the N-N scattering picture, the π^0 multiplicity per N-N collision $P_{NN}(\pi^0)$ can be expressed dividing the inclusive production cross section by the product $\sigma_{\mathrm{reac}} N_{NN}$, i.e., the total reaction cross section times the impact-parameter-averaged number of first-chance N-N collisions, where N_{NN} is computed in a Glauber approach [8]. The value found for $^{129}Xe + ^{197}Au$ collisions can be compared with the body of inclusive data available for beam energies around 44 MeV/nucleon [4,6] and extending from $^{12}C + ^{12}C$ to $^{86}Kr + ^{90}Zr$. Beforehand two corrections are, however, necessary: (1) Because of the strong energy dependence of subthreshold pion production, we choose to scale the various data points to a common energy of 40 MeV/nucleon available above the Coulomb barrier. The scale factors were determined with the aid of a polynomial fitted to the doubly logarithmic representation of the systematics of $P_{NN}(\pi^0)$ vs $(E_{\text{beam}} - V_{\text{Coulomb}})/A_{\text{beam}}$ between 30 and 60 MeV/nucleon (see, e.g., Fig. 5.17 of Ref. [2]) and range from 0.28 to 14. The error bars have been scaled accordingly and an additional 10% systematic error has been applied to the Stachel data, measured at 35 MeV/nucleon, i.e., furthest away from the 44 MeV/nucleon used in our experiment. Corrections due to different energy losses in the targets are small and have been neglected. (2) Furthermore, one expects the pion production to be depleted at low bombarding energies more strongly in light collision systems because of their reduced Fermi momenta. In order to compensate this we have applied an empirical correction estimated from the ratio of π^0 cross sections measured by Noll *et al.* in light and heavy systems over a range of beam energies [14]. Between 48 and 84 MeV/nucleon the rise of this ratio, after correction for the Coulomb barrier, amounts to a factor of 2.0 for $\sigma_{\pi^0}(\text{C+C})/\sigma_{\pi^0}(\text{C+U})$ and 1.5 for $\sigma_{\pi^0}(\text{C+Ni})/\sigma_{\pi^0}(\text{C+U})$. The π^0 yields of the three lightest systems included in the systematics have been corrected with these numbers, i.e., by a factor of 2 for C+C, and 1.5 for C+Ni and N+Al, the latter being comparable in size to the C+Ni system. The average Fermi momentum probed in the C+C system is only 221 MeV/c [15], in contrast with the saturation value of 265 MeV/c in heavy nuclei, which is similar to the momenta probed in the most peripheral Xe+Au collisions. The correction factors deduced from the data of Noll *et al.* are indeed consistent with the impact-parameter variation of the pion yield discussed in the previous paragraph.

The corrected $P_{NN}(\pi^0)$ is shown in Fig. 2 as a function of the average distance D_{mean} the pions propagate in the nuclear medium before they can escape. Following Ref. [8], D_{mean} has been calculated in a simple geometric model in which the pions are emitted uniformly and isotropically from the overlap region of the two colliding nuclei. A maximal geometric overlap of 3 fm and an overlap density of $1.25\rho_0$ has been assumed, as suggested by Boltzmann-Uehling-Uhlenbeck calculations [2], and the result has been averaged over all impact parameters. We attribute the observed decrease of $P_{NN}(\pi^0)$ with increasing system size, characterized by D_{mean}, to pion reabsorption and, fitting an exponential attenuation law to the data, we find an energy-averaged absorption length of $\lambda_{\text{abs}} = 5.5^{+2.5}_{-1.5}$ fm. This value agrees well with the former estimate of ≤ 4–6 fm by Grosse deduced from the shadowing effect observed in π^0 angular distributions [6].

The momentum dependence of the π^0 absorption can be deduced from a comparison of the measured c.m. energy-differential cross section $(pE)^{-1}d\sigma/dE$ with a primary distribution, which we take as a Boltzmann distribution [Fig. 3(a)]. Primary is understood here in the sense of antecedent to any final-state interactions. The above assumption seems to be at odds with the picture of pion production in mainly leading collisions. A reconciliation might, however, be given by microscopic transport

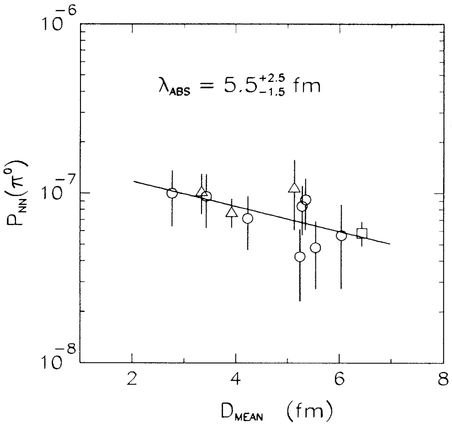

FIG. 2. Inclusive π^0 multiplicity per N-N collision as a function of the pion mean path to the nuclear surface; the square point is ^{129}Xe+^{197}Au; other data are from Refs. [4] (triangles) and [6] (circles). The solid line is a fit of $P_{NN}(\pi^0) = P_0 \times \exp(-D_{\text{mean}}/\lambda_{\text{abs}})$ to the data, where P_0 is the π^0 multiplicity without absorption.

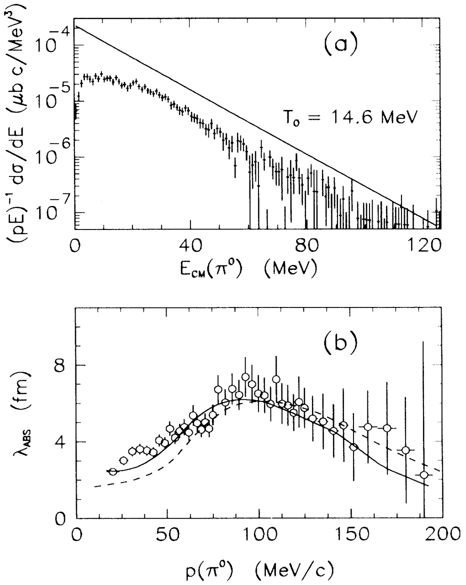

FIG. 3. (a) π^0 kinetic-energy distribution in the N-N c.m. system (histogram) compared to a Boltzmann distribution (solid line) with $T_0 = 14.6$ MeV. (b) π^0 absorption length as a function of the pion c.m. momentum, normalized to an average of 5.5 fm (see text for details). Error bars are statistical; the normalization error is not included. The dashed line is an optical-model calculation from Hecking (parameter set II [17]) and the solid line is obtained by adjusting the potential of Ref. [18] to our data; for the latter calculation the finite experimental energy resolution has been folded in, giving a better agreement at low pion momenta.

models which show that, while leading N-N collisions dominate pion production in the energy regime considered here, second- and higher-chance collisions contribute to some extent [2]. Furthermore, from cascade calculations [16] it is known that the mere folding of the nucleon Fermi distribution with the differential cross section of the elementary N-N production process results in a phase-space occupation close to Maxwellian. Pion data from light collision systems [9,11,14], where final-state effects are much weaker than in the Xe+Au system, show indeed that the production mechanism, whatever it is, leads to a Boltzmann-like primary energy spectrum. This is also supported by the shape of the π^0 p_T spectrum measured in the present work [see Fig. 1(a)]. With these arguments in mind we have calculated the π^0 escape probability f_{esc} as a function of the pion c.m. kinetic energy $E_{\text{c.m.}}$, dividing the experimental energy spectrum by a primary spectrum approximated with a Boltzmann distribution of temperature $T_0 = 14.6$ MeV. The parameter T_0, fitted to the pion p_T spectrum, is itself not very sensitive to reabsorption effects, as any given value of p_T corresponds to an average over a whole range of pion energies. Using $f_{\text{esc}} = \exp(-D_{\text{mean}}/\lambda_{\text{abs}})$ and $E_{\text{c.m.}} = (p^2 + m^2)^{1/2} - m$, where m is the π^0 rest mass, we finally obtained the π^0 absorption length as a function of the (asymptotically observed) pion c.m. momentum, i.e., $\lambda_{\text{abs}}(p)$ shown in Fig. 3(b). In this procedure the absolute normalization of the primary distribution was chosen such that the momentum average of the absorption length is 5.5 fm.

The overall trend of $\lambda_{\text{abs}}(p)$, with a pronounced absorption minimum around momenta of 100 MeV/c, is reproduced by a pion-propagation calculation of Hecking [17] based on an optical potential adjusted simultaneously to charged-pion scattering and pionic-atom data. A better description of the data can be achieved by adjusting the potential of Carr (taken from Ref. [18]) to $\lambda_{\text{abs}}(p)$. One should, however, realize that these potentials are not very strongly constrained by our π^0 data. From the momentum dependence one can now understand the apparent discrepancy between estimates of λ_{abs} from heavy-ion data (≤ 6 fm) and photoproduction data (≥ 10 fm): While the former correspond to an average over a thermal pion spectrum, the latter yielded λ_{abs} for pion kinetic energies in the range of 20–30 MeV [2], i.e., close to the absorption minimum. The nuclear translucence observed around 50 MeV in pion charge-exchange reactions has been recently interpreted in a similar way within optical-model calculations [19].

In summary, we have measured inclusive π^0 production in the reaction ^{129}Xe+^{197}Au at 44 MeV/nucleon. Our data support the picture of π^0 and hard-photon production in incoherent nucleon-nucleon collisions. A quantitative analysis of the π^0 multiplicity per N-N collision yields an average π^0 absorption length of 5.5 fm. The momentum dependence of λ_{abs} is deduced for pion kinetic energies reaching from the threshold to below the Δ resonance region.

We would like to thank Oak Ridge National Laboratory for making 57 BaF$_2$ detectors available for this experiment, the GANIL technical staff for efficient support, the GANIL accelerator crew for delivering the stable ^{129}Xe beam, and finally the GSI target laboratory for producing the Au targets. Very fruitful discussions with E. Grosse and B. Jakobsson are gratefully acknowledged. This work was supported in part by BMFT under Contract No. 06 GI 464 I, by GSI Darmstadt under Contract No. Gi Met K, and by the Stichting voor Fundamenteel Onderzoek der Materie (FOM).

(a)Present address: Argonne National Laboratory, Argonne, IL 60439.

(b)Permanent address: Warsaw University, Warsaw, Poland.

[1] P. Braun-Münzinger and J. Stachel, Annu. Rev. Nucl. Part. Sci. **37**, 1 (1987).
[2] W. Cassing, V. Metag, U. Mosel, and K. Niita, Phys. Rep. **188**, 365 (1990).
[3] R. Stock, Phys. Rep. **135**, 259 (1986).
[4] J. Stachel *et al.*, Phys. Rev. C **33**, 1420 (1986).
[5] H. Nifenecker and J. A. Pinston, Prog. Part. Nucl. Phys. **23**, 271 (1989).
[6] E. Grosse, in *Proceedings of the International School of Physics "Enrico Fermi," Course CIII*, edited by P. Kienle, R. A. Ricci, and A. Rubbiano (North-Holland, Amsterdam, 1987).
[7] D. Ashery and J. P. Schiffer, Annu. Rev. Nucl. Part. Sci. **36**, 207 (1986).
[8] W. Cassing, Z. Phys. A **329**, 487 (1988).
[9] A. Badalá *et al.*, Phys. Rev. C **43**, 190 (1991).
[10] R. Novotny, IEEE Trans. Nucl. Sci. **38**, 379 (1991).
[11] T. Suzuki *et al.*, Phys. Lett. B **257**, 27 (1991).
[12] S. Stanislaus *et al.*, Phys. Rev. C **44**, 2287 (1991).
[13] G. Fai and J. Randrup, Comput. Phys. Commun. **42**, 385 (1986).
[14] H. Noll *et al.*, Phys. Rev. Lett. **52**, 1284 (1984).
[15] E. J. Moniz *et al.*, Phys. Rev. Lett. **26**, 445 (1971).
[16] J. Randrup and C. M. Ko, Nucl. Phys. **A343**, 519 (1980).
[17] P. Hecking, Phys. Lett. **103B**, 401 (1981).
[18] R. Mehrem, H. Radi, and J. O. Rasmussen, Phys. Rev. C **30**, 301 (1984).
[19] W. R. Gibbs, W. B. Kaufmann, and J.-P. Dedonder, Phys. Lett. B **231**, 6 (1989).