FOUR HEAVY-ION EXPERIMENTS AT THE CERN-SPS — A TRIP DOWN MEMORY LANE*

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After a brief review of the first steps towards high-energy nuclear beams at CERN, the heavy-ion experiments at the OMEGA Spectrometer, WA85, WA94, WA97, are introduced together with their North-Area successor, NA57. In particular, the experimental solutions adopted to cope with very high-multiplicity events are described, as well as the main results obtained in the pursuit of the Quark-Gluon Plasma. The inspiring role played by Johann Rafelski is underlined.

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1. The beginnings

In October 1980, a Letter of Intent [1] to study Ne–Pb reactions at the CERN Proton-Synchrotron, was submitted by a GSI–LBL Collaboration:

Study of particle production and target fragmentation in central ^{20}Ne on Pb reactions, at 12 GeV per nucleon energy of the CERN-PS external beam
Spokesman of the collaboration: R. Stock, GSI Darmstadt
27 October, 1980
Letter of Intent GSI Darmstadt – LBL Berkeley Collaboration

Abstract: We propose to study in two simultaneous experiments the target fragmentation modes, and π^- , K^0 and Λ production in central collisions of ^{20}Ne with a heavy target nucleus. The acceleration of ^{20}Ne at the PS will be facilitated by a high-charge state ^{20}Ne source, provided by us. Experimental equipment will be *the Plastic Ball and Wall spectrometer, currently employed by us at the Bevalac, LBL Berkeley* and *a streamer chamber now used at CERN by the Munich group.* The experiments require acceleration of about 10^7 Ne ions per PS cycle, and a split in the external beam delivering about 10^4 ions/s to *the streamer chamber* and the main part of the intensity to the *Plastic Ball* and *Wall.* The anticipated time of experiment is about the spring of 1983, with the long lead-time caused mostly by source construction and injector linac acceleration tests.

GSI Darmstadt: R. Bock, H.H. Gutbrod, J. Harris, H.G. Ritter, A. Sandoval, H. Stelzer, R. Stock, H. Ströbele, F. Weik, H. Wiemann
University of Marburg and GSI Darmstadt: M.R. Maier, F. Pülhofer, R.E. Renfordt
LBL Berkeley and Argonne National Laboratory: A.M. Poskanzer, H. Pugh, L.S. Schroeder, A. Warwick, K.L. Wolf

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This initiative triggered a long and eventually successful approval process [2], that resulted in a new CERN programme involving ion beams at energies much larger than those initially envisaged.

Also in October 1980, at the initiative of Rudolf Bock and Reinhard Stock, a Workshop on Future Relativistic Heavy-Ion Experiments [3] took place at GSI Darmstadt. Here is a list of contributions:

1980 GSI Workshop: Heavy-Ion contributions

Future Relativistic Heavy-Ion Experiments; H.G. Pugh, LBL
The determination of Nuclear Matter Temperature and Density; K.L. Wolf, ANL
Evidence for Anomalous Nuclei among Relativistic Projectile Fragments at Bevalac Energies; H.H. Heckmann, LBL
High-Multiplicity Events – ISR Experience; D. Wegener, University of Dortmund
Reactions induced by Very High Energy Cosmic Ray Nuclei; I. Otterlund, University of Lund
Evidence for Two Different Reaction Mechanisms in Heavy-Ion Collisions in the GeV/u Region; E. Schopper, H.G. Baumgardt, E. Friedlander, University of Frankfurt
How to Deal with Relativistic Heavy-Ion Collisions; R. Hagedorn, CERN
Extreme States of Nuclear Matter; J. Rafelski, University of Frankfurt
Approach to Equilibrium in High Energy Heavy Ion Collisions; J. Zimanyi, Central Research Institute for Physics, Budapest
Hadron Chemistry; I. Montvay, University of Hamburg
Collective Behaviour in Hydrodynamic and Microscopic Models; J.A. Maruhn, G. Buchwald, L.P. Csernai, G. Graebner, H. Kruse, H. Stoecker, P.R. Subramanian, W. Greiner, University of Frankfurt
Quark Model and Nucleus–Nucleus Collisions at High Energies; A. Białas, W. Czyz, Jagiellonian University, Cracow
Diogene: A 4pi Detector, Based on a Time Projection Chamber, for studying Central Collisions of Relativistic Heavy Ions; J. Gosset, CEN Saclay
The Hiss Spectrometer at LBL; D. Greiner, LBL
Experiments on Very High Energy Heavy Ions; W.J. Willis, CERN
On The Study of Hard Processes in Heavy Ion Collisions; H.G. Fischer, CERN
Summarizing Panel: Future Experiment; H.J. Specht, University of Heidelberg

The atmosphere was of enthusiasm, since head-on collisions of heavy nuclei were seen as the way to obtain a deconfined state of quarks and gluons, Quark-Gluon Plasma (QGP), in the laboratory, albeit for a very short time. Johann Rafelski — also amongst the contributors [4] — had been the first, in a joint work with Rolf Hagedorn [5], to point out the relevance of strange particles for QGP diagnostic. The idea was then explored and developed with Berndt Müller [6] and in a paper presented at the XVIII Rencontres de Moriond [7]. Detailed predictions — as strange baryon enhancements increasing with their strangeness content — were later published in a classic *Physics Reports* written together with Peter Koch and Berndt Müller [8]. These predictions, which later would be confirmed at CERN, RHIC, and LHC, triggered several major SPS experiments, thus substantially shaping its physics programme.

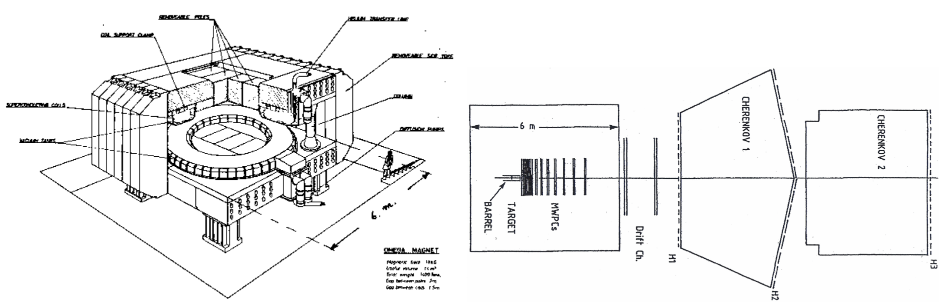
A few years, however, went by before ion beams from the SPS became available! At the time, the CERN top priority was to build LEP with a constant yearly budget. Robert Klapisch, nominated in 1981 Director of

Research for all Non-LEP activities, had the mission to maintain a broad physics program, supplementing the reduced CERN investments by outside contributions. At his initiative [2] a Workshop on the Future of Fixed Target Physics was held in December 1982: a group "Nuclear Beams and Targets" was convened by W.J. Willis and the summary given by M. Albrow [9]. As a result, the SPS community began to take an active interest in heavy-ion physics and, in September–November 1984, seven new experiments were recommended; two of them (NA35 and WA80) being the direct descendants of the 1980 Letter of Intent. Finally, the first beams of oxygen and sulphur nuclei, at energies up to 200 GeV per nucleon, became available in 1986 and 1987 respectively, while the lead beams, up to 158 GeV per nucleon, came only in 1994, following an upgrade of the accelerator complex.

In the meantime, my colleagues and myself had been thinking about how to measure the predicted strangeness enhancements; in particular those of the strange baryons, particles which we had already met in previous experiments [10]. However, a constant budget meaning essentially no new equipment, one had to use existing detectors and magnets, *i.e.* what one had at hand! Our first choice, therefore, was the Omega Spectrometer, which we had been using for hadron spectroscopy.

2. The Omega Spectrometer

This spectrometer [11, 12], located in the West Experimental Area, consisted of a large 1.8 T superconducting magnet, Fig. 1 (a), in which each approved experiment could install the detectors corresponding to its own particular needs. As an example, Fig. 1 (b) shows the layout of the WA72 experiment [13], proposed by the Warsaw group to study the production



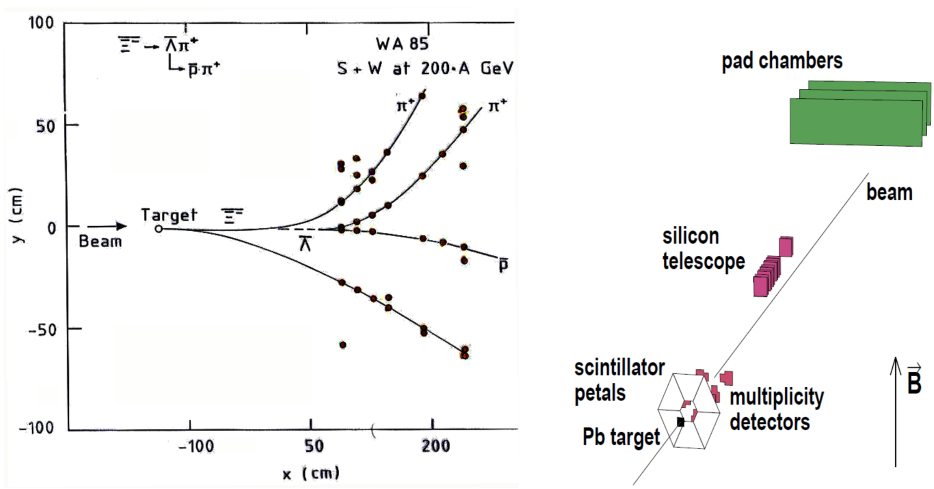
(a) (b)

Fig. 1. The Omega Spectrometer consisted of (a) a 1500 ton superconducting magnet. The inner diameter of the coils was 3 meters and the free gap between poles was 1.5 meters. The maximum field was 1.8 T. (b) Array of MultiWire Proportional Chambers (MWPC) for tracking, and downstream detectors for improved momentum measurements and for particle identification.

of fast protons and antiprotons in the interactions of 30 GeV pions with various target nuclei. It was our first "nuclear" experiment, as the use of nuclear targets had here the specific purpose to study the differences in the A-behaviour of baryon and antibaryon yields. These differences were then related to the final state interactions inside the nuclei [14] using the formation-zone model [15, 16].

3. Heavy-ion experiments

The first two experiments, WA85 [17] and WA94 [18], used the Omega Spectrometer and the 200 A GeV sulphur beam[1]. The standard Omega MultiWire Proportional Chambers (MWPC) however, could only handle up to about fifteen tracks per event — not enough for this kind of experiments. We decided to make these chambers only sensitive to particles emitted in a narrow phase space region, thus reducing the number of tracks to a few out of the several hundreds particles produced in the collision. This was obtained by adequately shaping the chamber's cathode, using a technique developed for a previous experiment [19]. Figure 2 (a) shows a fully reconstructed $\overline{\Xi}$ decay as seen by these so-called "butterfly chambers", sensitive only to charged particles produced with transverse momentum above 0.6 GeV$/c$ and absolute value of c.m.s. rapidity less than 1.



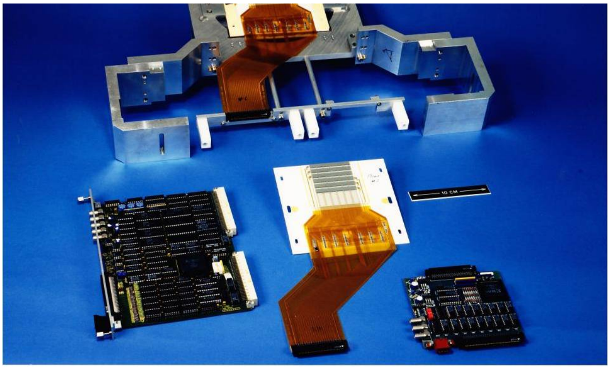
(a) (b)

Fig. 2. (a) WA85: fully reconstructed decay of a $\overline{\Xi}$ produced in a central S–W collision at 200 A GeV. (b) WA97 layout: multiplicity detectors to provide a centrality trigger, compact silicon telescope, lever-arm pixel planes followed by wire chambers with pad cathode readout.

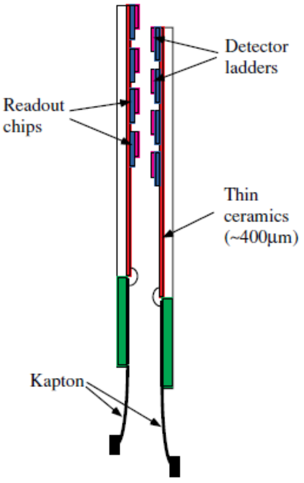
[1] WA85 experiment could finally run with a sulphur beam (1987), thanks to an ingenious splitting scheme invented by Per Grafström.

Silicon Pixel Detectors (SPD) [20] were, instead, the main tracking device for the lead-beam experiments WA97 [21] and NA57 [22]. Their choice was dictated by the necessity to cope with the track multiplicity of the events — much larger than for events from sulphur-beam experiments. The new detectors could determine the space points on a track directly, *i.e.* with a two-dimensional readout, thus avoiding the ambiguities generated from the intersections of wires or strips. In addition, because of their high granularity they could be placed near to the target, thus easing the study of the short-lived strange baryons. Their development began in the framework of the CERN–LAA R&D programme [23, 24] and continued in the CERN RD19 [25], which became progressively intertwined [26, 27, 28, 29, 30] with the WA94, WA97 and NA57 collaborations.

The layout of WA97 in the Omega magnetic field is shown in Fig. 2 (b). Its successor, the NA57 experiment, was instead located in the North Experimental Area and made use of the 1.4 T magnetic field of the Saclay Goliath magnet. Its layout and that of WA97 were conceptually similar [31]. In both experiments, the charged particles were reconstructed in a telescope, made from an array of silicon detector planes of $5{\times}5$ cm^2 cross section, which was placed above the beam line, inclined and pointing to the target. The bulk of the detectors were closely packed in a length of approximately 30 cm. This compact part was used for pattern recognition.



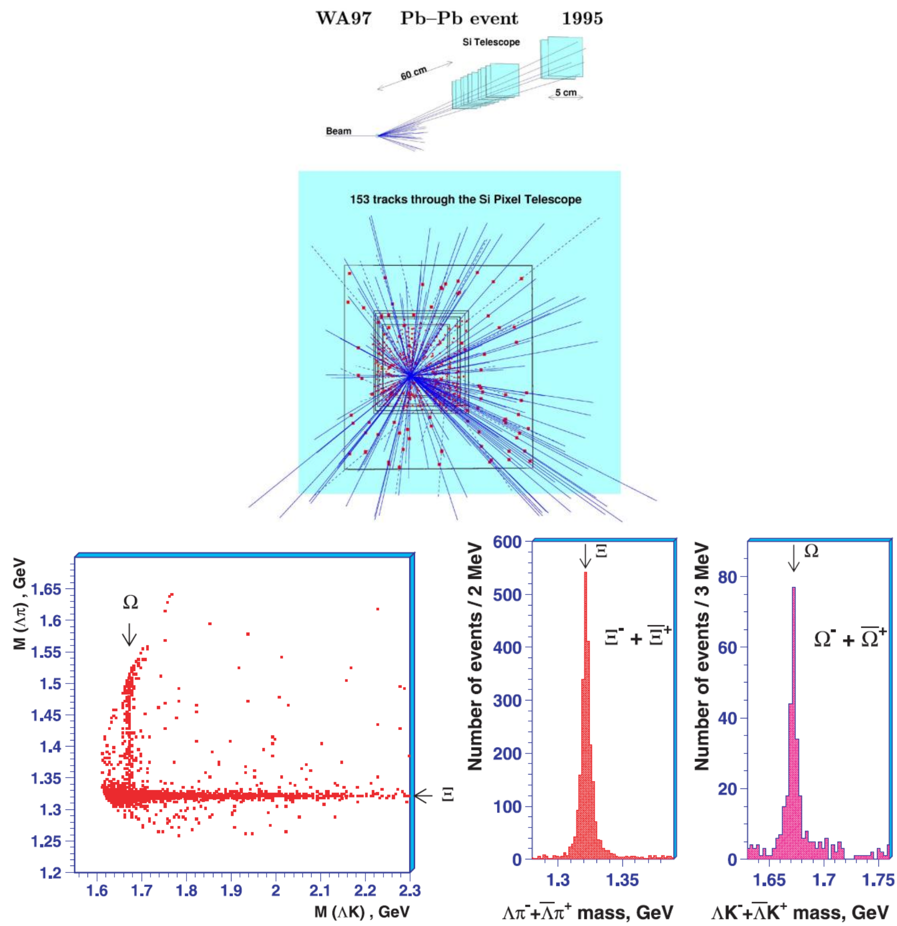
(a)



(b)

Fig. 3. Silicon pixel detectors: (a) Photo of a 6 ladder array (21), mounted on the WA97 support frame, and of the staggered matching array in front of it. To the right: a local card and, to the left the remotely placed VME board readout. (b) Logical plane: two arrays mounted face to face and staggered to give a $5{\times}5$ cm^2 sensitive area.

The WA97 telescope consisted of seven pixel planes, interleaved with ten silicon micro-strip planes providing altogether half a million detecting elements. The NA57 telescope instead, was entirely made of pixel detectors for a total of about one million channels. The basic building block of the pixel telescope was the ladder: a matrix of rectangular diodes (pixels) each one connected to a virtual ground via a front-end amplifier on a readout chip by a Pb–Sn solder bump. The pixel dimensions were 75×500 μm^2 for WA97 and 50×500 μm^2 for NA57. Several ladders were then glued on a ceramic carrier, as shown in Fig. 3 (a). Each plane of the telescope consisted of two such arrays mounted face to face, suitably staggered to hermetically cover a sensitive area of 5×5 cm^2, see Fig. 3 (b).



(a) (b)

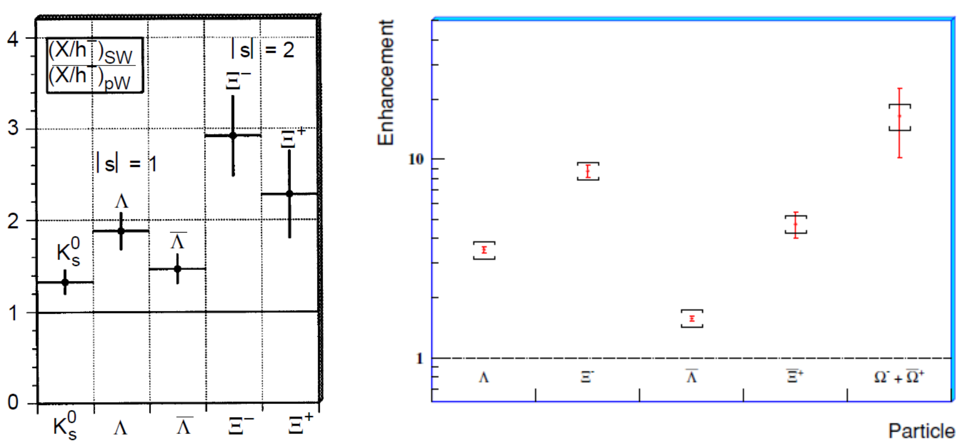
Fig. 4. WA97: (a) A reconstructed Pb–Pb event, recorded in the absence of magnetic field. It contains 153 tracks, *i.e.* an occupancy of about 0.2 % of the channels. (b) Identification of Ξ and Ω hyperons.

These detectors revealed themselves as particularly suitable for tracking in a high-multiplicity environment, as shown in Fig. 4 (a). Hyperon identification was remarkable, even in the most central Pb–Pb collisions, as illustrated by Fig. 4 (b).

It is worth noting that WA97 has been the first experiment in high-energy physics which tested and made use of this new technique [20]. Later, the experience gained there proved to be invaluable in the design of the LHC inner tracking detectors: for example, the ALICE silicon pixel micro-detectors are the direct descendants of those of WA97 and NA57.

4. Physics

It turned out that Rafelski and his collaborators [5, 6, 7, 8] were right! Figure 5 (a) shows the strange-baryon enhancements observed by WA85. From p–W to S–W collisions, the enhancement increased by a factor between 1 and 2 for singly-strange baryons and by a factor between 2 and 3 for the doubly-strange ones [31]. WA94 obtained similar results [32] in the comparison between p–S and S–S collisions. These findings were then confirmed by the data from Pb–Pb collisions, Fig. 5 (b) [33], where the enhancements showed a clear hierarchy, increasing with the strangeness content of the particle, for both hyperons and antihyperons, up to a value of about 20 for the triply-strange Ω^-. A pattern which was consistent with the QGP

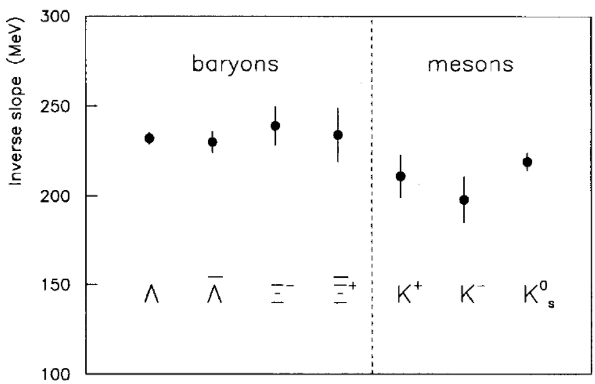


(a) (b)

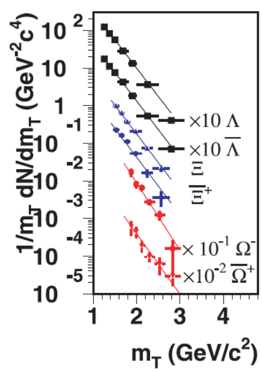
Fig. 5. (a) WA85: Hyperon enhancements, normalized to the yields of negatively charged particles, in central 200 A GeV S–W relative to p–W collisions [31]. (b) NA57: Hyperon enhancements for the 5% most central Pb–Pb collisions at 158 A GeV [33]. Enhancements are defined as the yield per participant in Pb–Pb collisions normalized to the yield per participant in p–Be collisions.

creation hypothesis, but was hard to accommodate into any hadronic microscopic model. These results, therefore, constituted one of the main pieces of evidence for the formation of a new state of matter at CERN-SPS energies.

More evidence for the deconfinement of quarks was obtained from the transverse-mass spectra of the produced hyperons. In 1991, the WA85 results triggered Rafelski [34] to propose a simple model of an explosively disintegrating quark-gluon plasma. His hypothesis of QGP quarks coalescing in a sudden hadronization with negligible re-scattering was corroborated by the observed similarity of the inverse slopes of transverse-mass ($m_{\rm t}$) spectra between strange baryons and the corresponding antibaryons — both in S–W [35] and in Pb–Pb collisions [36, 37, 38] — as shown in Fig. 6. These findings led Rafelski and Jean Letessier to develop a statistical model of QGP hadronization, *e.g.* [39, 40], which has since been used for a consistent analysis of SPS and RHIC results. *Á suivre*!



(a)



(b)

Fig. 6. (a) WA85: Inverse slopes of the transverse-mass distributions for hyperons and mesons produced in S–W interactions at 200 *A* GeV [35]. (b) NA57: Transverse-mass distributions for hyperons produced in Pb–Pb interactions at 158 *A* GeV [37].

5. Conclusion

As a conclusion of this trip down memory lane, I wish to offer to the younger generation of SQM participants the same quote made by Howell Pugh [41] thirty-one years ago, at the beginning of the SPS heavy-ion adventure: “One does not discover new lands without consenting to lose sight of the shore for a very long time”[2].

[2] André Gide, “On ne découvre pas de terre nouvelle sans consentir à perdre de vue, d’abord et longtemps, tout rivage” (1925).

I would like to thank my friends Federico Antinori, Werner Beusch, Giuseppe Bruno, Michael Campbell, Maria Fidecaro, Erik Heijne, Adam Jachołkowski, Karel Šafařík and Orlando Villalobos-Baillie for their help in the preparation of this paper.

REFERENCES

[1] GSI–LBL Collaboration, CERN/PSCC/80-129; PSCC/I-56 (1980).

[2] R. Klapisch, Symposium in honor of A. Poskanzer, preprint LBL30-5, Berkeley 2001.

[3] R. Bock, R. Stock, eds., Workshop on Future Relativistic Heavy-Ion Experiments, GSI 81-6, Darmstadt 1981.

[4] J. Rafelski, in Ref. [3], 282 (1981).

[5] J. Rafelski, R. Hagedorn, in: *Statistical Mechanics of Quarks and Hadrons*, H. Satz, ed., Elsevier, 1981, p. 253.

[6] J. Rafelski, B. Müller, *Phys. Rev. Lett.* **48**, 1066 (1982).

[7] J. Rafelski, *Phys. Rep.* **88**, 331 (1982).

[8] P. Koch, B. Müller, J. Rafelski, *Phys. Rep.* **142**, 167 (1986).

[9] M.G. Albrow, in: Workshop on SPS Fixed-Target Physics in the Years 1984–1989, I. Mannelli ed., CERN Yellow rep. 83-02, Vol. 2, 462 (1983).

[10] M. Baubillier *et al.*, *Phys. Lett.* **B78**, 342 (1978).

[11] W.F. Baker *et al.*, CERN-NP 68-11 (1968).

[12] W. Beusch, CERN/SPSC/84-62/P204 (1984).

[13] WA72 Collaboration, CERN/SPSC/81-54 (1981).

[14] M.G. Abreu *et al.*, *Z. Phys.* **C25**, 115 (1984).

[15] A. Bialas, TH.3765-CERN (1983).

[16] A. Bialas, *Z. Phys.* **C26**, 301 (1984).

[17] WA85 Collaboration, CERN/SPSC/84-76 (1984).

[18] WA94 Collaboration, CERN/SPSLC/91-5 (1991).

[19] W. Beusch *et al.*, *Nucl. Instrum. Methods* **A249**, 391 (1986).

[20] E.H.M. Heijne, *Nucl. Instrum. Methods* **A465**, 1 (2001).

[21] WA97 Collaboration, CERN/SPSLC/91-29 (1991).

[22] NA57 Collaboration, CERN/SPSLC/96-40 (1996).

[23] M. Campbell *et al.*, *Nucl. Instrum. Methods* **A290**, 149 (1990).

[24] F. Krummenacher, *Nucl. Instrum. Methods* **A305**, 527 (1991).

[25] E.H.M. Heijne *et al.*, R&D Proposal RD19, CERN DRDC/90-81 (1990).

[26] H. Beker *et al.*, *Nucl. Instrum. Methods* **A332**, 188 (1993).

[27] E.H.M. Heijne *et al.*, *Nucl. Instrum. Methods* **A349**, 138 (1994).

[28] E.H.M. Heijne *et al.*, *Nucl. Sci. IEEE Trans.* **42**, 413 (1995).

[29] F. Antinori *et al.*, *Nucl. Instrum. Methods* **A360**, 91 (1995).
[30] D. Di Bari *et al.*, *Nucl. Instrum. Methods* **A395**, 391 (1997).
[31] F. Antinori, in: *The Cern Omega Spectrometer — 25 Years of Physics*, M. Jacob, E. Quercigh, eds., CERN Yellow Rep. 97-02, 43 (1997).
[32] J.B. Kinson *et al.*, *Nucl. Phys.* **A590**, 317c (1995).
[33] F. Antinori *et al.*, *J. Phys.* **G32**, 427 (2006).
[34] J. Rafelski, *Phys. Lett.* **B262**, 333 (1991).
[35] D. Di Bari *et al.*, *Nucl. Phys.* **A590**, 307c (1995).
[36] L. Šándor *et al.*, *Nucl. Phys.* **A661**, 481c (1999).
[37] R.A. Fini *et al.*, *J. Phys. G* **27**, 375 (2001).
[38] K. Šafařík *et al.*, *J. Phys. G* **27**, 579 (2001).
[39] J. Rafelski, J. Letessier, *Phys. Rev. Lett.* **85**, 4695 (2000).
[40] J. Rafelski, J. Letessier, *Nucl. Phys.* **A715**, 98 (2003).
[41] H.G. Pugh, in Ref. [3], 1 (1981).