COSMIC AND SUBATOMIC PHYSICS REPORT
LUIP 8511,
(LUNFD6/(NFFK-7064)1-38 (1985)).
ISSN 0348-9329

PION PRODUCTION AND PARTICLE CORRELATIONS

A study of particle emission in intermediate energy heavy ion collisions

by

Per Kristiansson

FK, Ld

AKADEMISK AVHANDLING SOM FÖR AVLÄGGANDE AV FILOSOFIE DOKTORSEXAMEN VID LUNDS UNIVERSITETS MATEMATISK-NATURVETENSKAPLIGA FAKULTET OFFENTLIGEN KOMMER ATT FÖRSVARAS I FÖRELÄSNINGSSAL B PÅ FYSISKA INSTITUTIONEN FREDAGEN DEN 11 OKTOBER 1985 KLOCKAN 10^{15}

Organization LUND UNIVERSITY	**Document name** DOCTORAL DISSERTATION
	Date of issue September 1985
	CODEN: LUNFD6/(NFFK-7064)1-38 1985
Author(s) Kristiansson, Per	**Sponsoring organization**

Title and subtitle PION PRODUCTION AND PARTICLE CORRELATIONS A Study of Particle Emission in Intermediate Energy Heavy Ion Collisions

Abstract

Intermediate energy heavy ion collisions have been studied using the carbon-beam produced at the CERN SC-accelerator.
Cross-sections for π^+ and π^- have been measured over a wide range of large angles at 60, 75 and 86 MeV/nucleon. The yields and shapes are compared to a nucleon-nucleon scattering approach, which underestimates the yields by orders of magnitude. The π^-/π^+-ratio observed is close to unity for $^{12}C+^{12}C$, but the enhancement for $^{12}C+^{208}Pb$ is much larger than expected from the neutron excess in ^{208}Pb.
Large-angle light-particle correlations for 86 MeV/nucleon carbon induced reactions on different targets (C, Al, Cu, Au) have been studied. An excess of correlations is observed in the particle-particle scattering plane. The strength of this effect increases with observed particle mass and decreases with target mass.

DOKUMENTDATABLAD
enl SIS 61 41 21

Key words Heavy Ion Collisions, Intermediate Energy, Pion-Production, Two-Particle Correlations, Large-Angle Correlations

Classification system and/or index terms (if any)
LUIP 8511

Supplementary bibliographical information		**Language** English
ISSN and key title 0348-9329		**ISBN**
Recipient's notes	**Number of pages** 38	**Price**
	Security classification	

Distribution by (name and address) Per Kristiansson, Department of Physics, University of Lund,
Sölvegatan 14, S-223 62 LUND, Sweden

I, the undersigned, being the copyright owner of the abstract of the above-mentioned dissertation, hereby grant to all reference sources permission to publish and disseminate the abstract of the above-mentioned dissertation.

Signature ______________ Date 29/8 - 85

PION PRODUCTION AND PARTICLE CORRELATIONS

A study of particle emission
in intermediate energy
heavy ion collisions

by

Per Kristiansson

To EVA

The papers in this thesis have been copied in accordance with the permission given by the copyright owners:

The American Physical Society, New York (paper I)

The North Holland Publishing Company, Amsterdam (papers II and III)

PION PRODUCTION AND PARTICLE CORRELATIONS

A study of particle emission
in intermediate energy
heavy ion collisions

This thesis contains four publications based on work done by the SC83-collaboration at the CERN synchro-cyclotron, during the years 1981-1984. Each paper is a summary of one experiment, and all of them concern studies of interactions between nuclei.

The four publications are:

I. Subthreshold Pion Production in Heavy Ion Collisions at 85A MeV
Phys.Rev.Lett. 48(1982)732

II. Production of Charged Pions in intermediate-energy heavy ion collisions
Nucl.Phys. A423(1984)511

III. Large-Angle Light Particle Correlations in ^{12}C Induced Reactions at 85A MeV
Phys.Lett. 155B(1985)31

IV Large-Angle Correlations observed in Intermediate Energy Heavy Ion Collisions
Cosmic and Subatomic Physics Report LUIP 8505
To appear in Nuclear Physics

The results presented in this thesis have also been presented at a number of international conferences. The pion results were first presented at the 5th High Energy Heavy Ion Study in Berkeley 1981 and later the pion data have appeared at many conferences, often in connection with theoretical calculations. The large-angle correlation data have so far been presented at the LESIP-workshop, Bad Honnef 1984, and at the second international nucleus-nucleus conference in Visby 1985, where the results were presented by myself.

This thesis is divided into a number of subsections.

The first gives a short review of nucleus-nucleus collisions. A more complete presentation can for example be found in references 1-3.

In the second section a summary is given, with some comments, on the results obtained so far by the SC83-collaboration.

The articles presented in this thesis are compactly written, with very little of the experimental details described. I therefore give a more extensive description of the experiments in the third section. Here also a comparison between the different techniques used is made.

The fourth section gives a short description of some theories of nucleus-nucleus interactions relevant for the studies of this thesis. They are presented from an experimentalist's point of view.

The papers included in this thesis are summerized in section five, with some remarks and corrections.

In section six , I discuss the results obtained and make a comparison with results from other experimental groups.

In the last section the papers appear in the same way as they were published.

1. Introduction

Ever since the late forties when heavy ions were found in the cosmic radiation, physicists have shown a great interest in what is happening when two nuclei collide. The only accelerator available in the beginning of these studies was our own Galaxy. It provided a constant low intensity beam with both non uniform energy as well as variable projectile mass. The detection technique available was mainly that of nuclear track detectors and the interest was focused on the chemical and isotopic composition of the radiation. However, some interest was shown for the field of nuclear reactions. This led to a classification of the collisions into two types, peripheral and central. In figure 1, examples of the two types of collisions are shown, as seen in an emulsion exposure. This classification is the first measure of the impact parameter, i.e. the minimum distance between the centers of the projectile nucleus and the target nucleus. Such a classification subsequently led to the introduction of the participant-spectator model for the reactions. According to this model, the participants are thought to be inside a "fireball" with a high temperature, while the spectators appear as low-excited fragments, possibly evaporating light particles.

One of the early observations, which was made, was the approximate energy independence of the reaction cross-section, which was found possible to describe with a simple geometrical formula:

$$\sigma = \pi \cdot r_0{}^2 \cdot (A_P{}^{1/3} + A_T{}^{1/3})^2$$

eventually with some small additional corrections.

In the early seventies, accelerators for high energetic heavy ions began to work around the world, for example in Berkeley and in Dubna. Later, synchro-cyclotrons for less energetic ions were completed at CERN (SC) and in Caen (GANIL). So at the beginning of this decade, accelerators providing heavy ion beams with energies in the interval 30-2000 MeV/nucleon had become available for the experimental physicists.

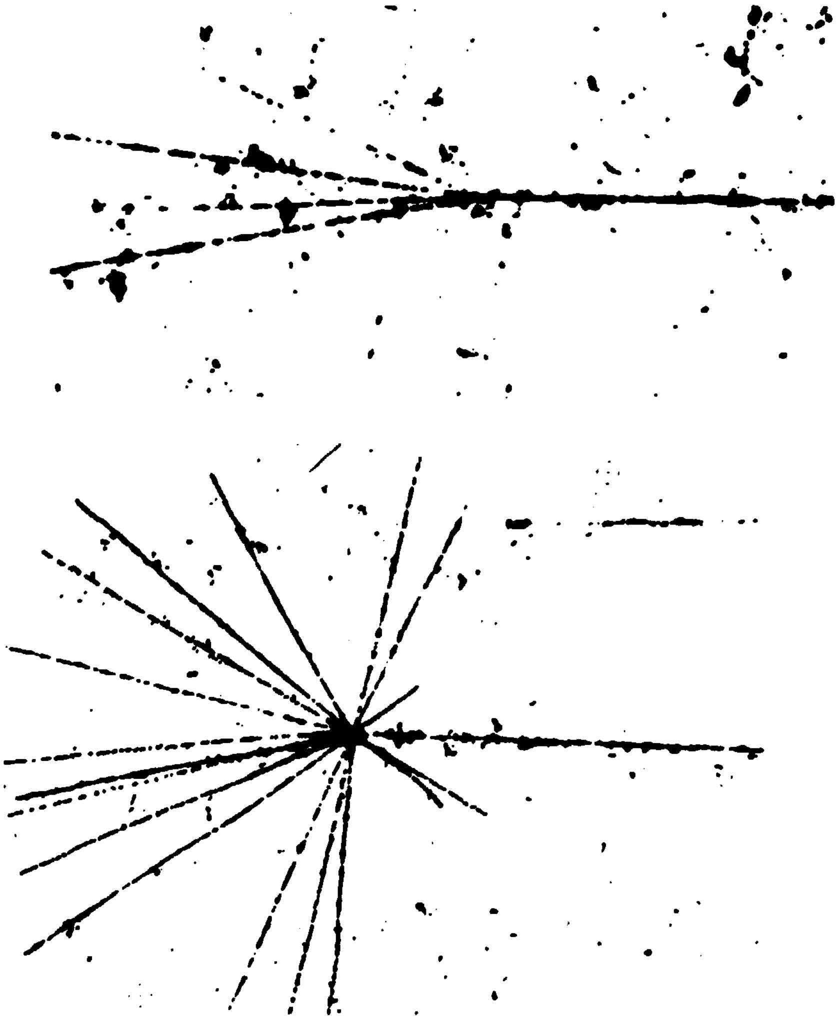


Figure 1: Examples of peripheral (top) and central nuclear reactions, as seen in an emulsion. The projectiles (from the right) are in both cases a ^{12}C-nucleus with an energy of about 100 MeV/nucleon, and the targets are nuclei in the emulsion. In the peripheral collision, the projectile fragments in lighter pieces, which continue with almost the same momentum/nucleon as the initial projectile. In the central collision, particles, coming from both projectile and target, are emitted in all directions, and almost nothing is left in the projectile region.

One of the basic motives for this enormous effort, was the intriguing possibilities that, through nucleus-nucleus collisions, new states of nuclear matter could be reached, for instance high temperature and high density states or even an exotic states like quark-gluon plasma.

The results so far have shown a rather weak dependence on projectile energy. Most of the particle emission, related to the participant part of the reactions, seem to fit a parametrization of the type:

$$\frac{1}{p}\cdot\frac{d^2N}{dE\cdot d\Omega} = \mathrm{Const}\cdot(E+m)\cdot(2\pi mT)^{-3/2}\cdot e^{-p^2/2mT}.$$

Here the parameters p,E,Ω and m have their usual meaning. The slope parameter T, also called the apparent temperature of the source, is supposed to be related to the available excitation energy through $\varepsilon=3/2\cdot T$. This, however, is not in accordance with experimental observations. The observed slope parameters, at the energies concerned in this thesis, give much higher values than what is allowed by energy conservation.

In the late seventies, the CERN synchro-cyclotro was reconstructed to accelerate heavy ions. The rebuilt accelerator produced a stable high flux beam of good quality, which made it possible to measure small cross-sections with fairly simple experimental equipment. At this time, there was a great interest to study nucleus-nucleus collisions at energies around 100 MeV/nucleon, where a poosible encounter between low and high energy was supposed to take place.It was with this assumption and with this accelerator using comparatively simple detector systems the work described in this thesis began.

2. The SC83-experiment

The history of the SC83 experimental serie, began with the approval of a proposal (4) from the CERN-Copenhagen-Grenoble-Lund collaboration in 1978. The experimental goals stated in the proposal were:

1. *Inclusive measurements of the double differential cross-section for lighter fragments up to about the projectile mass.*

2. *Coincidence measurements between light particles and projectile fragments.*

3. *Measurements of the multiplicity dependence of the cross-section for light particles and projectile fragments.*

4. *A study of possible pion production.*

These measurements were intended to be made with simple ΔE-E telescopes and, if necessary, combined with time-of-flight measurements.

The first experimental period was at the beginning of 1980. An 85 MeV/nucleon carbon-beam was used to bombard various targets ranging from carbon to gold. The target thicknesses were about 30 mg/cm^2. Inclusive measurements of projectile fragments (5), light particles at large angles (6) and also some elastic scattering measurements were made (7).

From the projectile fragmentation measurements, it was found that the results showed similarities with observations at higher energies, although deviations from existing fragmentation models were seen. The observation was also made, that the spectral shapes were target independent. At large angles ($>10^0$) a low energy component was seen for the lighest fragments (A<8), similar for all target nuclei, indicating an equal amount of participating nucleons from the projectile and from the target.

In the light particle measurement, at large angles, the same target independent behaviour was observed. The data are presented in ref.6. The cross-sections are underestimated at the lowest energies, due to an omitted correction for multiple scattering. In ref.8 and ref.9 are corrected spectra shown, and in ref.9 is also a more detailed description of the correction given. The procedure of energy calibration of the experimental system was also somewhat uncertain. In the article (6) are temperatures extracted, varying between 12 and 18 MeV. According to data obtained during a later experiment, the lowest temperatures are too low. In figure 2 a $p_{\parallel}$-$p_{\perp}$ plot is shown for the reaction $^{12}C+^{12}C$. This was obtained during the experiment presented in paper IV, and gives a higher value, 20 MeV, for the observed temperature than what is given in ref.6. Also other experimental groups (10 and 11) have obtained temperatures around this value at these beam energies.

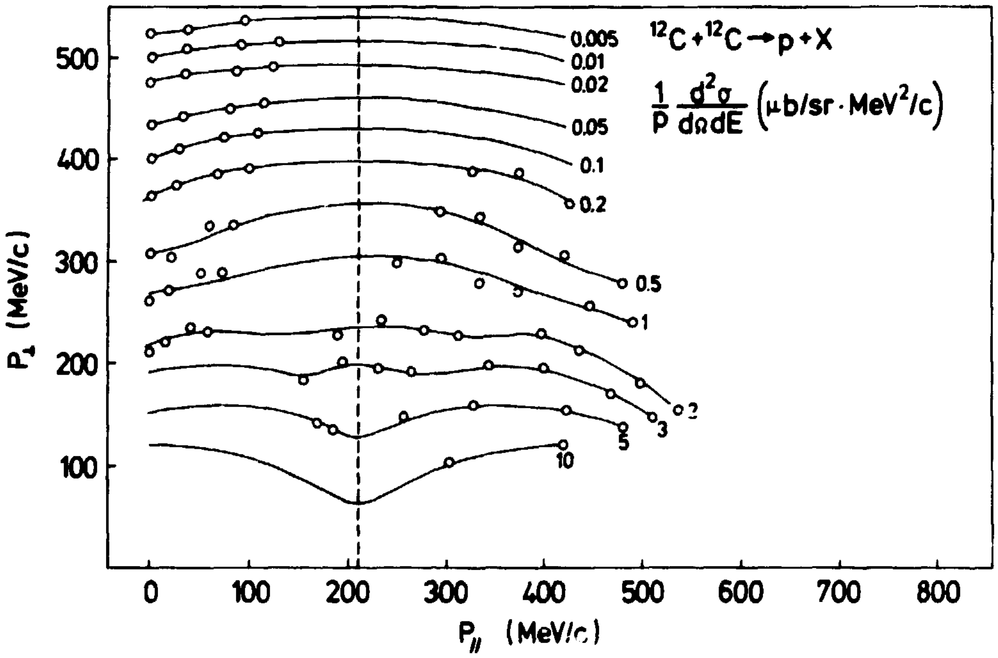


Figure 2: The invariant cross-section for protons emitted from the reaction $^{12}C+^{12}C$, drawn as contours in the $p_{\parallel}$-$p_{\perp}$-plane. The symmetry of the reaction is used to mirror the contour-lines at half the beam energy. A fit to the slope at 90^0 in the cm-system, gives a temperature of about 20 MeV.

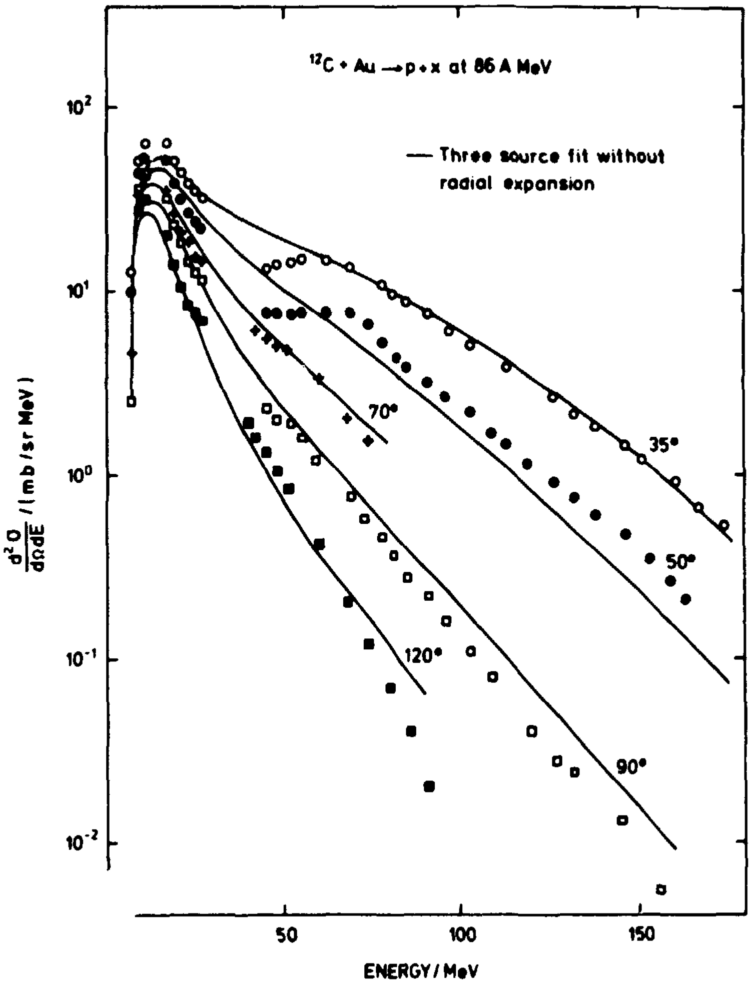


Figure 3: The double differential cross-section for protons versus energy in different laboratory angles for the reaction $^{12}C+^{197}Au$. The curves are from a three source fit, one hot Boltzmann source, "fireball", and two cold evaporation sources. The parameters obtained for the fireball were a temperature of 18.2 MeV and a velocity of 0.14·c.

During the second period of running (1981) complementary data were taken for elastic scattering (12) and some measurements on low energy particles emitted at large angles were also made (9). In figure 3 is a combination between the new low energy light particle data and the old data for the reaction $^{12}C+^{197}Au$ shown. The fitted curve is based on a three source model, with one hot "fireball" Bolzmann-source and two cold evaporating fragments. The peak at the lowest energies comes from the target evaporation.

During this second run and also during the third one later in 1981, the interest was focused on the pion production experiments. The results of these are presented in papers I and II. They will be commented more extensively in section 5.

After the pion-experiments, part of the collaboration joined an experiment at Orsay to study inclusive pion production cross-sections in proton induced collisions on nuclei at 180 and 200 MeV. The experimental set-up used for this experiment was a combination of the technique used at CERN, with range telescopes, and a magnetic spectrometer from Orsay. We measured in the forward direction with the spectrometer and used the range telescopes at backward angles, with an overlapping angle at 90^0. The main purpose of this experiment, for our CERN group, was an efficiency study of the range telescopes, used in our CERN experiment, but absorption studies and a comparison with N-N scattering calculations, were also of interest. The measurements showed that the difference in efficiency of the two detector systems was less than 20%, which is acceptable. Strong absorption effects were also observed. More detailed information about this experiment will be given in a forthcoming report (13).

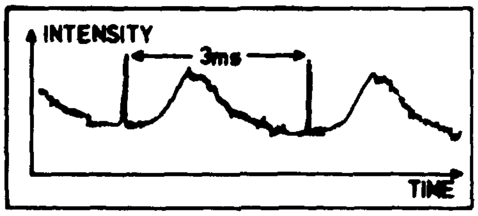
The SC83 program has since 1983 been divided into two categories of experiments, large-angle light particle correlations and correlations between pions and projectile fragments. Some of the results obtained during the two first correlation runs (1983 and 1984) are presented in this thesis (III and IV). In order to better understand the mechanisms involved in nucleus-nucleus collisions at these energies and to be able to differentiate between different theoretical approaches, it was necessary to develop the experiment towards exclusive measurements. The introduction of large-angle correlation measurements in the program, was mostly due to the discussion around the possibility that the pion production data could be explained in terms of nucleon-nucleon scattering (sec.4.1).The possibility to observe quasi-elastic nucleon-nucleon scattering for these correlations was the first aim of the experiment. During the second run we also took some data on small-angle correlations. The results, although still under evaluation, look very similar to what is obtained both at higher (14) and lower (15 and 16) energies. A further extension, included in our last experiment (1985), was the introduction of a plastic wall (paper IV,fig.1) for the study of projectile fragmentation. It will be able to give us information about impact parameter and, hence, participant source size. The data from this experiment are still under evaluation, and so far, no results are ready for presentation.

3.Experimental Tools

3.1 The Accelerator

The accelerator, used in all the experiments presented in the publications in this thesis, is the CERN synchro-cyclotron (SC). It is an old accelerator, constructed for 600 MeV protons. Since 1980, when it was available for heavy ion experimental groups, the SC-machine has been able to produced a stable ^{12}C-beam with an maximum energy of 85 MeV/nucleon and with a duty factor of about 25%. The ions are extracted from a PIG-source, and a rotating condensor (ROTCO) is used to improve the time structure by slow extraction of the beam. Figure 4 shows the beam-structure at the entrance of the experimental site. This picture was obtained during the run described in paper IV. The intensities used in the experiments have varied from $1*10^{8}$ up to $2*10^{10}$ particles/second, the last intensity being close to the upper limit allowed in the beamline due to the neutron background.

Figure 4: The beam-structure at the entrance of the experimental site, measured with a plastic scintillator.



During the years of the experiments other beams have been available, for example oxygen and neon beams, but none with a quality as good as the ^{12}C-beam. The ^{18}O-beam, with an energy of 85 MeV/nucleon, has shown an acceptable performance and this beam has been used in one SC83 fragmentation experiment (1983) and there are also plans to use it in future large-angle correlation experiments.

3.2 The Scattering-chambers

During our experiments two different types of scattering-chambers were used. Figure 1a in paper II shows the first one, originally designed for measuring projectile-fragmentation (5), elastic scattering (7) and light particle emission from the participant-region (6) at the same time. All these simultaneous demands gave unwanted limitations of the kinematical regions that could be measured. For exampel, in ref.6 there is no theoretical reason to measure the inclusive proton-spectra down only to 32°. Neither is there any possibility to make measurements outside the plane defined by the scattering-chamber. These kinematical constraints were of less importance for the pion measurements described in papers I and II, where only inclusive spectra were recorded, and no other experiment ran simultaneously.

For the coincidence measurements described in papers III and IV these constraints were unacceptable, so a new scattering chamber was constructed. In the experiment presented in paper III, a first version of the new scattering-chamber was used (paper III,fig.1). A second, slightly modified, version was used for the experiment described in paper IV (fig.1). This one allows us to measure in three different azimuthal angles (0°, 90° and 180°) at the same time. The available inclusive angular range is also extended down to 15°. In the last version (paper IV,fig.1) the projectile-fragmentation region is also covered, by mounting a conical extension at the front which covers angles between 2° and 8°.

The target-holder in the old chamber was of ladder-type, which made it possible to change target without breaking the vacuum. The limitation was that it was only possible to measure with three targets before the vacuum had to be broken. In the new system there is a target lock chamber, instead of a ladder, which makes it possible to do a complete run without breaking the chamber-vacuum. The disadvantage with this is that each target change introduces a delay due to the pumping of the lock chamber. But this is a comparatively small problem because we measure fairly small cross-sections in the correlation experiments and have therefore few changes of target.

3.3 Targets

In the papers of this thesis, data are taken with different targets. The target used ranges in mass from ^{7}Li up to ^{208}Pb. One of our aims has been to use as thin targets as possible in order not to decrease the velocity of the beam, when it passes through the targets. Limiting factors in the opposite direction are the available beam intensity and the desired counting rate. The effective target thicknesses chosen were for the pion runs 50-100 mg/cm^2, and for the coincidence experiments between 20 and 40 mg/cm^2. For the coincidence experiments the available beam intensity was reduced due to the demands of a good beam-structure. The most commonly used target in these experiments is the ^{12}C-target, due to the symmetry of the ^{12}C+^{12}C reaction. For comparison, one heavy target, ^{197}Au or ^{208}Pb, was always measured.

3.4 Detector-systems

In all four papers presented here, plastic scintillators have been used in different ways in the experimental set-ups. In all the experiments the triggering (see sec. 3.5) is based on signals from such scintillators. In the experiments described in papers I,II and IV plastic scintillators have been used in the range telescopes, as well. The plastic scintillator material most commonly used is of the type NE102, which has a very fast response time and a good efficiency. The risetime is of the order of a few nanoseconds and the response increases approximatly linear with the energy loss of the ionizing particle.

A disadvantage with these scintillators is that the light output for a given energy loss depends both on the charge and the mass of the ionizing particle. The pulse-height dependence of the particle charge is in fact as large as a factor of two between protons and alfa particles, with the largest response for protons. Another disadvantage for the plastic material is the low stopping power, i.e. the specific energy loss per cm. The low stopping power leads to large detectors if they are used as stopping detectors for energy determination. This can give rise to both mechanical problems and problems with light collection and transparency. For more accurate energy determination (papers III and IV) we used a NaI-crystal instead (see below).

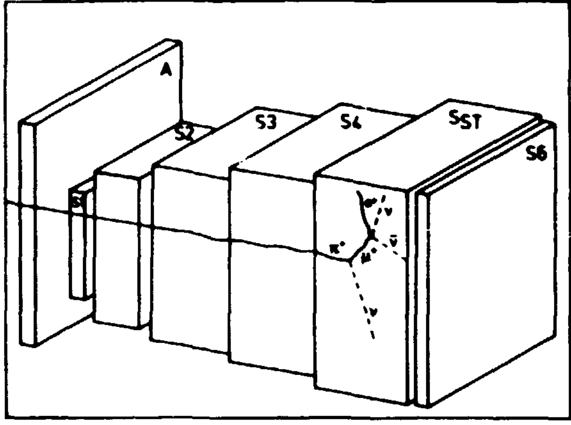
The great advantage with plastic scintillators is the fast response, but the fairly low cost and the simple manufacturing are also parameters of importance. The possibility to choose size and shape practically without limitations is also a valuable property.

The other detector type used in the telescopes is, as mentioned before, a NaI-crystal scintillation detector, which has a somewhat different behaviour than the plastic scintillator. The stopping power is approximatly a factor two better than for plastics and the comparison of the response functions for different particles also behaves in a more satisfactory way. The energy resolution is somewhat better for NaI than for plastic scintillators, but when they are used as E-detectors this is of less importance.

The great disadvantage with sodium-iodide is its very hygroscopic properties which makes it unpractical to handle. The slow response- and recovery-time also create problems. The resolution for instance, is very dependent on the flux hitting the crystal. Especially with those intensities and target thicknesses used in the correlation experiments, problems arose with the slow NaI scintillation detector.

A third type of detectors used, although only for calibration, are the silicon detectors. They are used to calibrate the NaI-crystals (paper III and IV) due to their linear response to energy loss for different particles. The silicon detectors are further discussed in the section about corrections and calibrations, and a detailed description of their use will be given in a forthcoming report (17).

The detector systems used in the experiments are of two different types. In the two pion experiments (paper I and II) and in the second correlation experiment (paper IV) we have used a type of systems called range telescopes. They simply consist of a stack of plastic scintillators, placed in a row behind each other. In figure 5 the telescope from the experiment discussed in paper I is shown. Each scintillator in these telescopes is chosen, so that its thickness corresponds to a suitable interval in energy at the target for the particles to be studied. No external calibration is needed during the



TELESCOPE - DATA

	Thickness (mm)	Area (cm²)	E_{mean} (MeV)	ΔE (MeV)
A	8			
S1	5	6×6		
S2	25	8×8	23.7	13.2
S3	50	9×9	39.6	18.5
S4	50	10×10	56.5	15.4
S5	50	11×11	71.3	14.2
S6	5	11×11		

Figure 5: The range telescope used for pion detection during the first pion experiment. Indicated is a positive pion, which has stoppped in scintillator S_5, and the subsequent decay of it into a muon. The average pion stopping energy for each detector is shown in the table.

run if a range telescope is used and only the number of particles that have stopped in each scintillator has to be counted. This method suffers of course from a limited number of scintillator plates, uncertanties in the range-energy relation, range straggling and experimental errors such as threshold adjustments. On the other hand, the off-line analysis is much easier and this is a practical method especially for measurements of small cross-sections.

The other type of technique used is the ΔE-E-technique with one detector for the energy determination and a thin detector for the particle separation. In paper III and IV we have used plastic scintillators as the ΔE-detectors and NaI-crystals for the energy determination. This method gives a continuous energy determination, but the analysis is more demanding. The calibration method is discussed in section 3.7. Figure 6 shows typical ΔE-E telescopes (from paper III).

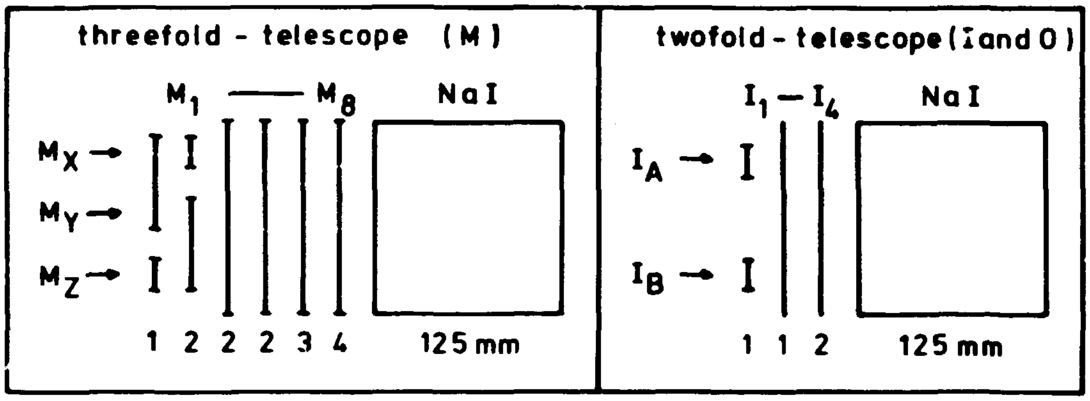


Figure 6: The two types of ΔE-E systems used during the first correlation run. The thin detectors (M_1-M_8 and I_1-I_4) are all plastic scintillators and the thick ones are NaI-crystals. The plastic scintillators were used both for the trigger and for particle identification. The first part of the M-telescope was used as a range telescope as well.

3.5 Electronics

To take advantage of the fast response of the plastic scintillators there is a need for special electronics developed for fast pulse processing. The photomultiplier tubes are of the type Philips XP2020, connected with appropiate bases from Philips. A typical transit time for a signal through this system is of the order of 30 ns, with a timespread of about 1 ns.

The electronic modules are of the fast type, for example those manufactured by the Le Croy Research Systems (18) are very commonly used in the electronic schemes. Typical internal delays in these modules are ot the order of 10 ns. In all the experiments the trigger systems are based on such fast modules, and the pulse-height signals from the plastic scintillators are also processed by such modules. The needs for the NaI-signals are somewhat different. Fast processing are of less importance while high accuracy in the pulse-height determination is vital. For these signals we therefore used amplifiers of the type Ortec 572 or similar ones.

For the energy signals from the silicon detectors the demands are similar to those from the NaI-crystal, and the same type of amplifiers are used for these. The fast timing signal for the trigger is treated in a similar way as the signals from the plastic scintillators.

In the first pion experiment (paper I) we studied the production cross-section for positive pions. In figure 7 an outline of the trigger system for the this experiment is shown. These positive pions decay to positive muons with a mean life time of 26 ns and the muon gets a kinetic energy of 4.2 MeV. A negative pion does not behave in the same way. Instead it is absorbed in a nucleus in the detector, and the time for this process is much shorter than its decay time into a muon, so all the energy is deposited promptly. The first part of the trigger creates a signal, which defines, through a coincidence chain, the element in which the incident particle has stopped. Thereafter, if the particle is a positive pion, there will be a second signal from this detector originating from the pion decay. If this signal comes approximatly between 30 and 200 ns after the first one, and there is no simultaneous signal from the detector in front of it, a second trigger signal will be the result. This signal will in coincidence with the first one, create the master gate for the computer.

During the second pion experiment, the technique with the delayed coincidence as trigger was impossible to use, because we aimed to measure both positive and negative pions. Instead we used a method ot high ΔE-threshold discrimination for the rejection of the large proton background. The basic idea is that a proton-signal in a ΔE-detector two steps in front of the stop detector compared to one from a pion, should always be higher. This, of course, depends on the choice of the detector thicknesses, but it is always possible to use this technique in range telescopes. The main trigger is a simple coincidence chain similar to the one described above and, if no high level ΔE-signal appears, the event is collected. If, on the other hand, such a signal appears it creates a fast clear-signal to the computer, and the event is rejected. The separation between positive and negative pions is done off-line, using, among other things, the information from the positive pion decay.

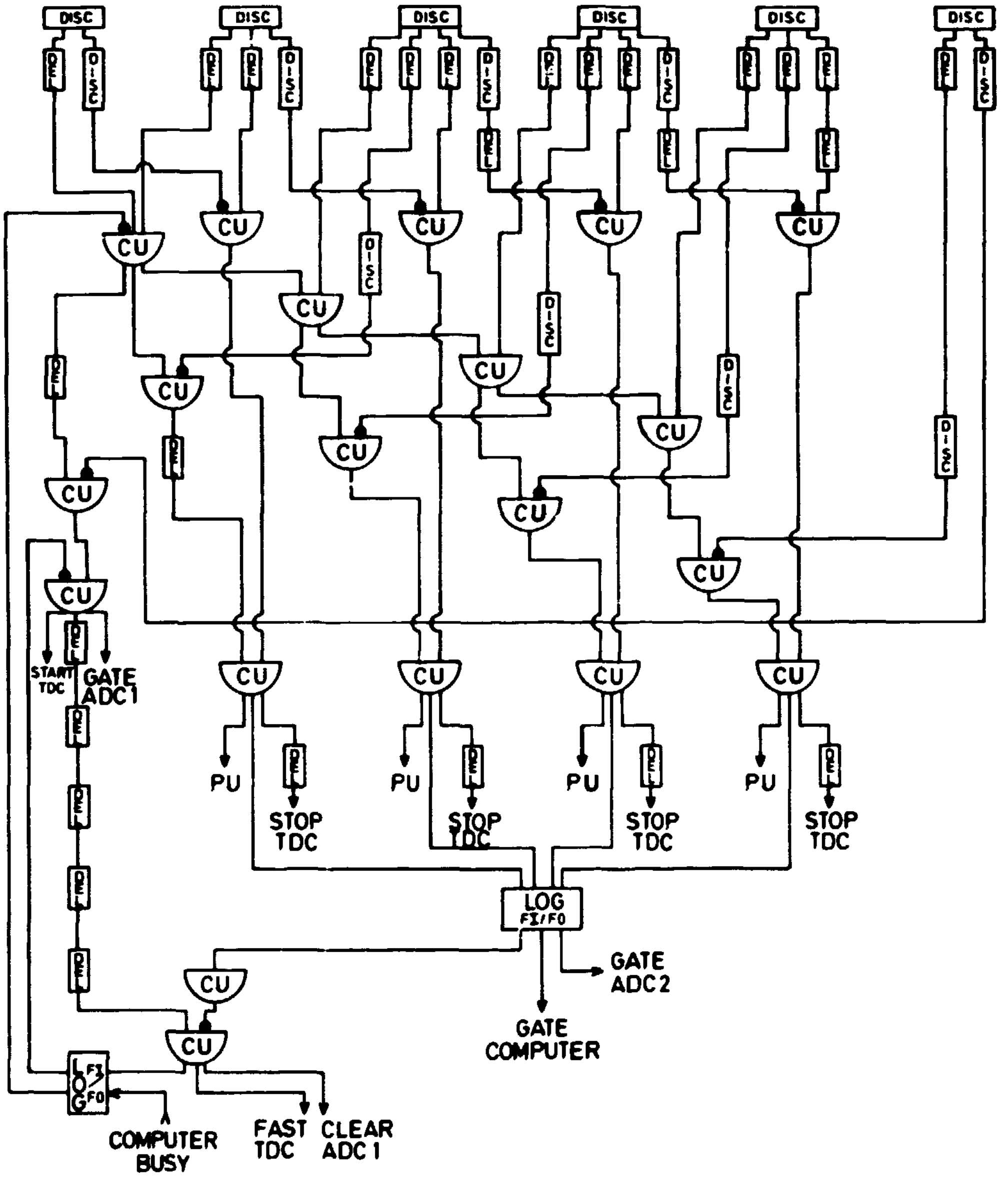


Figure 7: The trigger system for the pion telescope shown in figure 5. It is based on the delayed-coincidence technique.

For the large-angle correlations the following trigger philosophy is used in both experiments. The definition of a triggered telescope is that the three first plastic scintillators are fired within 5 ns. If then two different telescopes have been triggered within 30 ns, a master gate is created. This broad acceptance in time is necessary for the off-line subtraction of random coincidences from the real coincidence peak. The principle of the master trigger is shown in figure 8. This, was the one used in the second correlation experiment (paper IV), and it also has a part designated for small-angle correlations.

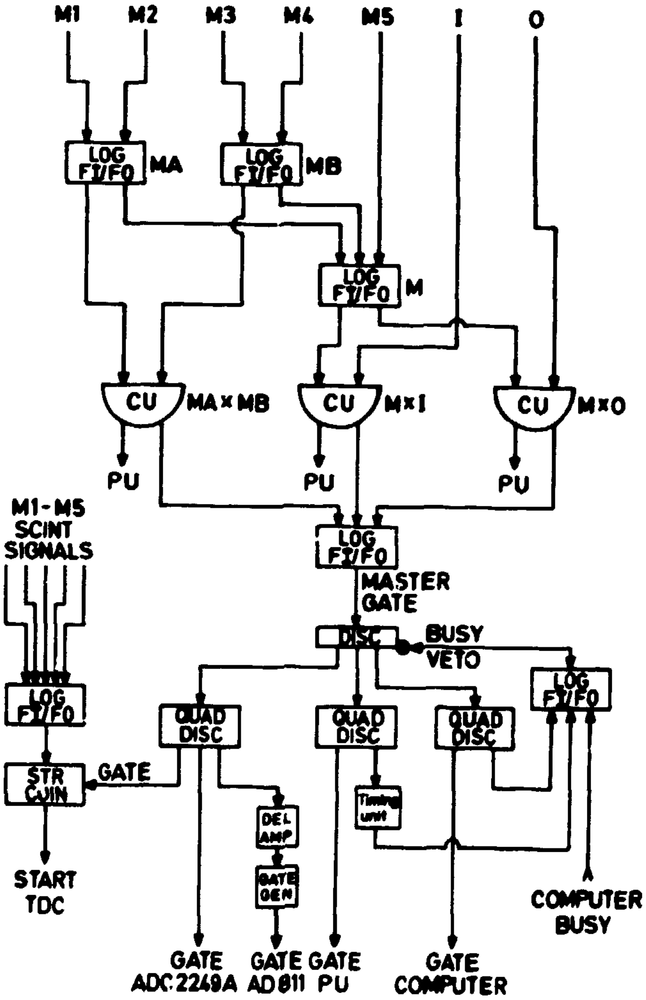


*Figure 8: An outline of the master-trigger used in the correlation experiments. This one is from the second experiment. Three different kinds of coincidences are accepted, M*I and M*O for large-angle correlations and MA*MB for small-angle correlations.*

3.6 Data-aquisition

In all four experiments the data-aquisiton was based on CAMAC read out. In the pion-experiments we used both a PDP-computer (II) and an HP-computer (I and II). It was found to be an advantage to use two computers during the second pion run due to the comparatively long set-up-time needed for four range telescopes. For the correlation experiments (III and IV) we used the PDP-computer combined with a front-end machine (MICE) developed at CERN. It decreased the collection time for one event to about 300 μs, which was an improvement by approximately an order of magnitude. Combined with the duty-factor of the accelerator, this made it possible to collect 30-50 events/second with a reasonable dead-time (~15%).

The CAMAC modules used, were of a type, which matched with the fast electronics. The ADC units for pulse-height measurements and the TDC units for time measurements had an approximate conversion time of about 100 μs.

3.7 The off-line analysis

For all four experiments the off-line data analysis has been performed at a Nord-100 computer in Lund. A schematic outline of the analysing procedure is shown in figure 9. The two basic features of the program are the menu, where it is possible to choose different run options, and the sorter , which is the actual analysing part of the program.

In the sorter the events are deciphered and then treated one at a time with different choosen options. For instance, there is a possibility to check if a signal lies within a certain gate or if the correlation between two signals lies within a given area. There are also possibilities to correlate signals on a display (e.g. a ΔE-E plot) and use this for particle identification. There is also a possibility to save events, either in histograms in the program or on the computer disc for future use in other programs.

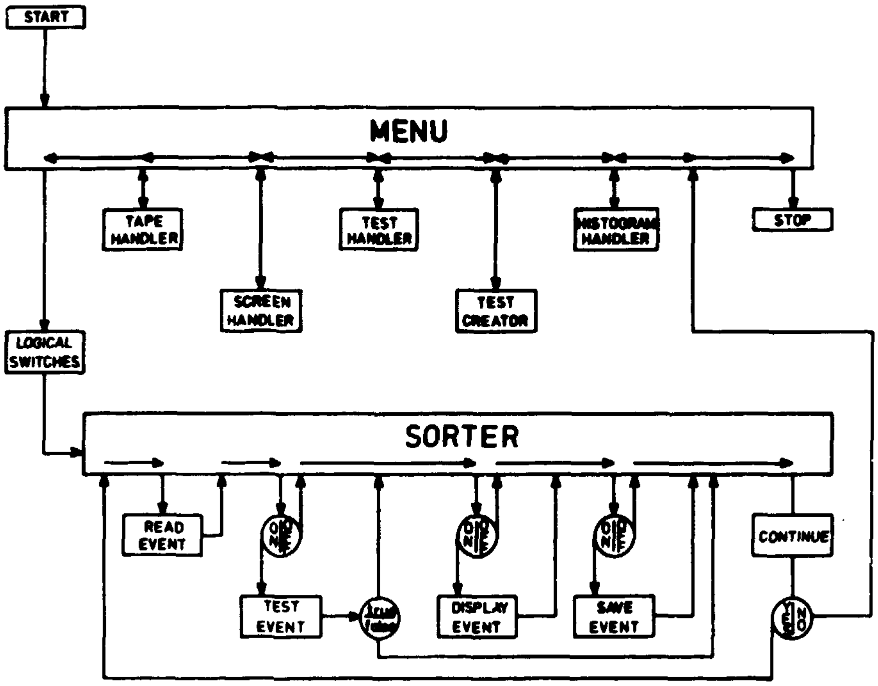


Figure 9: A schematic representation of the off-line program for data analysis.

The menu contains a variety of possible options. There are some directly computer connected, like tape handling and screen handling, and also read and write connections with the computer disc. Other possibilities are the creation of test, for use in the sorter, from the two dimensional plots and display of the stored histograms.

For the pion data the available program was large enough to isolate the pions and calculate the actual numbers. Figure 10 shows a typical fit to a decay spectrum for π^+. From this fit the number of pions produced at the target are extracted. Corrections for decay in flight and nuclear reactions must be applied afterwards (sec.3.8).

In the correlation experiments, the structure of the data is more complicated and the program discussed here is used only as a first raw-sorting program. The identities and energies of the particles were extracted but no extra coincidence requirements were imposted on the events. These events were instead saved on a disc and then a second program was used for background subraction and extraction of correlation data.

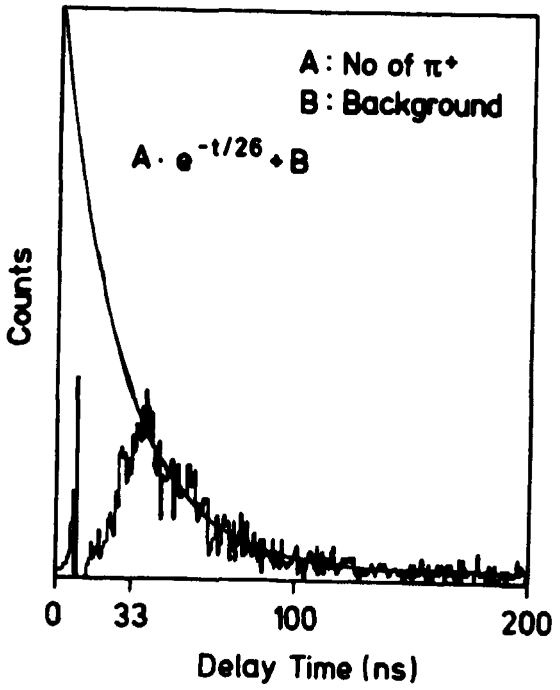


Figure 10: A typical decay spectrum recorded during the first pion run. The curve is fitted in the interval 33-200 ns to obtain the actual number of positive pions stopping in the detector.

3.8 Calibrations and corrections

For the pion measurements with the range telescopes, no real energy calibration is necessary. Instead a calibration of the efficiency for the detection of the decay of positive pions into muons is needed. Such calibrations have been performed both at the SC-accelerator, with a pion beam produced by protons and at Orsay, where data obtained with a range telescope in proton-nucleus collisions have been compared to data obtained by a spectrometer. This comparison gave a fairly good agreement (13) between the two detection methods. Other things that have to be considered in the measurement of charged pions are their decaytime, which is of the same order of magnitude as their flight time between target and detector, and their comparatively large cross-section for nuclear reactions in the telescopes. In figure 11 the corrections applied to the data (paper I) are shown as a function of pion energy. The corrections increase strongly with pion energy, which makes it more or less impossible to increase the width of the measurable energy interval at the high energy cut-off, when this method of measurements with range telescopes is used.

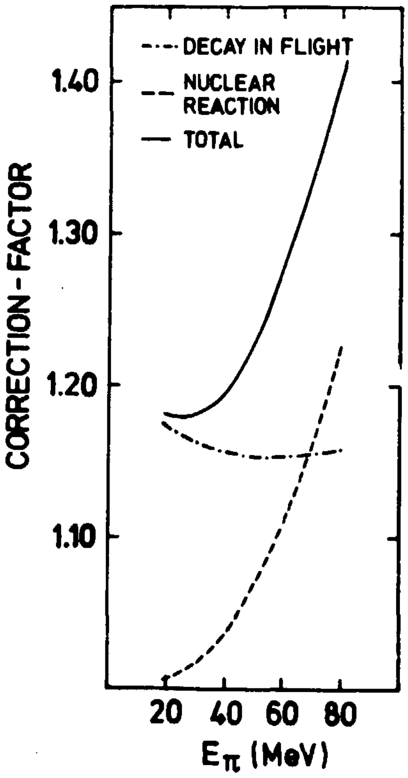


Figure 11: Correction factor versus pion energy, for those pions never reaching the stopping scintillator due to decay in flight and nuclear reactions.

For the correlation experiments (III and IV) the situation is somewhat different. The correction, which could be made, is for the nuclear reactions. But since almost all of these reactions take place in the E-detector most of the incoming energy will be deposited here and only a small change in the observed signal will be the result. So far we have ignored this correction with this argument.

The sodium-iodide crystals used in the experiments reported in papers III and IV have been calibrated, using silicon-detectors, which have a linear response, and reaction products, consisting of light particles, from the target. By placing two silicon-detectors in front of the NaI-scintillators which were to be calibrated and collect data, we obtain relations between the pulse-heights in the Si-detectors and the NaI-crystal for different particle types. Then, by using the well defined "punch-through" points in the correlation between the silicon detectors we are able to calibrate these in a consistent way. The range-energy relation will then give us the relation between the loss of energy in the silicon detectors and the deposite energy in the NaI-crystal, and then, with all three relations combined, we are able to obtain the response functions for the NaI-crystal. Finally, by using the range-energy relation once again, it is possible to get the pulse-height in the crystal as a function of the energy at the target. The calibration will be further discussed in a special report (17).

For the range telescopes, used as tag telescopes during the second correlation experiment (paper IV), the energy intervals are derived from the range-energy relation in the same way as described above. Here, too, the nuclear reaction correction has been neglected. As long as we just compare the counting rates in the two telescopes, this error will be of less importance.

4. Theoretical Tools

In this section the two different theoretical approaches used in the papers are presented. The first is a nucleon-nucleon (NN) scattering model and the second is a statistical or thermal model based on Bolzmann statistics. They are completely opposed to each other, from the point of view that one is without any direct collective effects and one totally collective.

4.1 The NN-model

The nucleon-nucleon scattering model is mainly based on two assumptions. First, nucleons inside two colliding nuclei have the possibility to accomplish nucleon-nucleon (N-N) collisions without any important interactions with the other nucleons in the nuclei. Secondly, nucleons inside a nucleus move according to some momentum distribution, for instance a zero temperature Fermi distribution. The momenta of the two colliding nucleons inside the nuclei are added, giving the reaction an extra "boost" (positive or negative) in addition to what is obtained from the beam energy.

The energy threshold for pion production through free N-N interaction in the laboratory frame is 290 MeV, hence should the threshold for pion production through N-N scattering in nucleus-nucleus collisions without including Fermi motion also be 290 MeV/nucleon. The introduction of Fermi motion strongly reduces the threshold for π-production. For instance, if the momentum components are lined up in the most favourable way in reactions between light symmetric systems, the threshold energy of the beam will be reduced to approximatly 42 MeV/nucleon (19).

Depending on the relative velocity between the colliding nuclei, more or less of the phase-space is available for pion production. At the low energies used in the experiments treated in papers I and II, the available phase-space is reduced to the end-caps of the Fermi spheres (see figure 12). In the calculations performed for the comparison with these experimental results, some other important features had to be

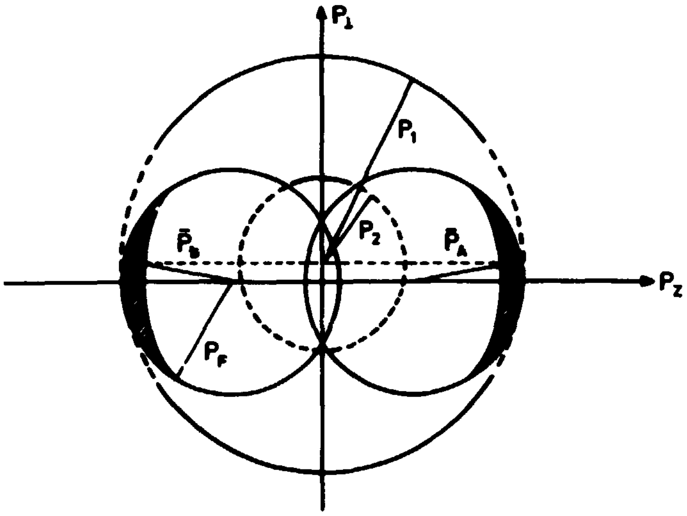


Figure 12: A schematic phase-space picture. The two partly overlapping circles describe the momentum-volumes occupied by the projectile and the target nucleons respectively. The distance between their centers represents the beam velocity. p_A *and* p_B *are the initial momenta of the scattered nucleons.* p_1 *is the radius of a circle corresponding to elastic scattering, while* p_2 *is the radius for pion producing events. The shaded end caps are the space allowed for pion production. Pauli blocking occurs inside the two original Fermi spheres.*

considered. Only the first N-N scattering for each nucleon is accounted for, mainly due to the fact that after this collision there is not enough energy available in the cm-system for π-production, i.e. the relative momentum is too small in the next collision. It is also necessary to apply Pauli blocking, which means that after the pion is produced,the nucleons have to be scattered outside the already occupied phase-space. With this restriction on the model, the production cross-section decreases approximatly by one order of magnitude, but the shape of the spectra changes very little. Finally, the reabsorption of pions in the residual nuclei must be considered. This factor can be calculated under the assumption that the pion is produced in the overlap region of the collision, and has to pass through a certain amount of nuclear matter with an attenuation given by the mean-free-path. To normalize the calculation to absolute cross-sections, the optical limit of Glauber theory was used to calculate the average number of N-N collisions at a certain impact parameter, and finally integration was performed over the impact parameter. The result of such an approach is clearly demonstrated in paper II. It strongly underestimates the pion production cross-section. Since only the highest internal momentum components are useful for pion production, any choice of a diffuse momentum distribution may critically change the conditions. However, it has been demonstrated by Shyam and Knoll (20) that the use of shell model (harmonic oscillator) momentum distributions also gives too small cross-sections, due to the fact that the binding energy in the various shells must be introduced.

In (21) a newer and more extended description of the NN-calculation procedure is presented. Here are also some analytical expressions introduced to shorten the huge Monte-Carlo simulations.

In the QES-calculations for the large-angle correlations the scenario used, is much simpler than that for the pion production. Most of the phase-space is here available and there is no threshold energy for the reaction, which implies that the choice of Fermi distribution is not as critical as for the pions. The Fermi distribution used in our calculations is a zero temperature, hard sphere distribution. Binding potentials and recoil momenta are also introduced in this picture and the Pauli blocking is treated in the same way as for the pions. In this case too, the Pauli blocking puts some restrictions on the allowed collisions. Different angular distributions for proton-proton scattering have been tested, but they do not give any observable difference in the final spectrum. The absolute normalization procedure is done similar to that for pions. Comparisons with experimental data are given in (22) for inclusive spectra and in paper III for large-angle correlations.

4.2 The RTS-model

The recoiling thermal source model (RTS) is a statistical model. It assumes thermal equilibrium in the participant part of the reaction, before any emission of particles takes place. It also assumes that the momentum distribution inside the participant source behaves like a Boltzmann gas.

In the calculations used for the comparison with the data in paper III, we have included some further constraints beyond those introduced by the Boltzmann distribution. The participant source is created through a nucleus-nucleus collision with a straight line geometry, which means that only nucleons in the overlapping part of the collision are participants. This implies that the impact parameter alone determines the number of nucleons participating and the total excitation energy in the participant source. In these calculations we have also implemented the binding energy of the nucleons in the mother nuclei, and subtracted this energy from the total excitation energy. The excitation energy per nucleon is then coupled to the slope parameter (temperature) in a Boltzmann distribution and this distribution is used for the simulation of the particle emission.

The particles are emitted one after the other from the participant volume, and after each emission, the momentum of the remaining participant-nucleus is adjusted for the momentum loss. The excitation energy is reduced by the kinetic energies used in the emission. The procedure is repeated until all the participant nucleons are emitted, or all the excitation energy is used. A small Coulomb correction was also introduced, but it had only a slight effect on the results.

The basic reason for this approach was, to investigate if the momentum conservation constraint was sufficent to create apparent non isotropic correlations in the emission from a participant source. The results of these calculations fit the observed results surprisingly well (paper III). However, one should remember that the emission of composite particles are still not included in the calculations. The slope-parameter given by the model differs from the one experimentally observed (22), which of course is a consequense of the fact, that the excitation energy per nucleon is fixed and directly coupled to the temperature. The deviation may depend on an effect of compression or that the equilibrium conditions are not fullfilled.

5 Summary of Publications

PAPER I

Subthreshold Pion Production in Heavy-Ion Collisions at 85A MeV

T.Johansson, H-Å.Gustafsson, B.Jakobsson,
P.Kristiansson, B.Norén, A.Oskarsson, L.Carlén,
I.Otterlund, H.Ryde, J.Julien, C.Guet, R.Bertholet,
M.Maurel, H.Nifenecker, P.Perrin, F.Schussler,
G.Tibell, M.Buenerd, J.M.Loiseaux, P.Martin,
J.P.Bondorf, O-B.Nielsen, A.O.T.Karvinen and J.Mougey

In this paper the first results from our pion production experiments are discussed. This experiment was inspired by an experiment performed by Benenson et.al. (23) at 0^0 with a 80 MeV/nucleon Ne-beam on NaF. We studied the reactions $^{12}C+^{12}C$ and $^{12}C+^{197}Au$ with a beam energy of 85 MeV/nucleon. The angular range covered was between 55^0 and 145^0 in the laboratory system, where the lower angular cut is set mainly by the large proton background.

Significant pion production is observed in both reactions. The doubly differential cross-sections for the two targets show similar behaviour. They both fall off exponentially with the pion energy and have a slope parameter around 15 MeV. A comparison between the absolute values of the cross-sections for the ^{12}C and ^{197}Au targets, gives approximatly nine times higher value for the gold target.

The angular distributions in different cm-systems are investigated. For the $^{12}C+^{12}C$ reaction we observe a forward peaking in the laboratory system, while forward-backward symmetry is observed in the nucleon-nucleon (same as nucleus-nucleus) cm-system. For the gold target we observe a slight forward peaking in the laboratory system, and for the nucleus-nucleus system this forward peaking remains. In the nucleon-nucleon cm-frame this is changed to a strong backward peaking. This behaviour can be explained by two different approaches, one collective, suggesting cluster collisions between asymmetric clusters, and one pure nucleon-nucleon scattering model, where the asymmetry is explained by absorption effects in the target nucleus.

In the last paragraph in the paper there is a comparison between the apparent temperatures obtained for the pions and for the protons (6). As discussed earlier (sec.2) the observed temperature fcr the carbon target is prersumably too low, so the discussion about a contradictory behaviour compared to higher beam energies is probably not valid. Instead the pion production follows the pattern observed at higher energies.

In the same paragraph a comparison with results from a preliminary calculation on a nucleon-nucleon scattering model is also made. The calculated yield seems to be in agreement with the experimental results. A more refined calculation is done for the results presented in paper II, which indicates that the nucleon-nucleon scattering approach underestimates the measured cross-section very much.

PAPER II

Production of Charged Pions in Intermediate-Energy Heavy-Ion Collisions

V.Bernard, J.Girard, J.Julien, R.Legrain, J.Poitou,
A.Oskarsson, L.Carlén, H-Å.Gustafsson, B.Jakobsson,
P.Kristiansson, B.Norén, I.Otterlund, H.Ryde, T.Johansson,
G.Tibell, R.Bertholet, C.Guet, M.Maurel, H.Nifenecker,
P.Perrin, F.Schussler, M.Buenerd, D.Lebrun, P.Martin,
G.Løvhøiden, J.P.Bondorf, O-B.Nielsen and A.Palmeri

The experimental results described in the second paper are obtained during a pion measurement experiment which was an extension of the one discussed in paper I. The aim of the experiment was to study the production of both positive and negative pions, and therefore it was necessary to change the technique of on-line identification of the particles (sec.3.5). We studied π^+ and π^- emission using three different targets. For the symmetric reaction $^{12}C+^{12}C$ we also studied the beam energy dependence of the production cross-section. Three different energies were used 60, 75 and 85 MeV/nucleon.

The doubly differential invariant cross-sections are compared to those given by a nucleon-nucleon scattering model (sec.4.1). It is quite obvious from this comparison that the model underestimates the production cross-section with orders of magnitude. As in paper I, a comparison is made between the temperatures, i.e. the slope-parameters, for protons and for pions from the reaction $^{12}C+^{12}C$, and the temperature for pions was found to be the largest. If instead the pion temperature is compared to the new proton data for carbon target, (sec.2) with a temperature of 20 MeV, it is obvious that there exists a serious disagreement. It is clear that the arguments based on the temperature estimate in paper II are not valid.

The most interesting new feature presented in this paper is the measurement of the π^-/π^+-ratio, where a comparison is made at 90^0 for the three targets (Li,C,Pb). The deviation from unity in the ratio for the carbon target is interpreted as a result of Coulomb effects, due to the completely symmetric system. If this Coulomb shift is applied to the results for the other targets, the π^-/π^+-ratio will be so large that it is impossible to explain it only with the neutron excess in these targets.

The last part of the article is attributed to a discussion about the velocity of the source of pion emission. The results indicate that the velocity of the system is closer to the nucleus-nucleus cm-system than to the mean-speed system, which could indicate that the production takes place in central collisions. However, the observed symmetry effects are most likely strongly disturbed by reabsorption effects, particularly in heavy targets. Such an effect is for example seen in (14), where a comparison of the π^+ inclusive cross-section from the reactions p+Y and p+Pb is made.

In the text, two small printing errors have appeared. The first one is on page 514, where S_{i+2} has to be substituted with S_{i-2}. The second error is in the figure caption of figure two, where the letters b and c have been reversed.

PAPER III

Large-Angle Light Particle Correlations in ^{12}C Induced Reactions at 85A MeV

P.Kristiansson, L.Carlén, H-Å.Gustafsson, B.Jakobsson,
A.Oskarsson, H.Ryde, J.P.Bondorf, O-B.Nielsen,
G.Løvhøiden, T-F.Thorsteinsen, D.Heuer and H.Nifenecker

The main reason for the experiment presented in this paper was the conviction that the inclusive measurements can not provid enough information for an understanding of the reaction mechanisms in nucleus-nucleus interactions. It was also to some extent a consequence of the possibility discussed in paper I that the observed pion production could be explained by NN-scattering. We measured large-angle correlations between light particles for the reactions $^{12}C+^{12}C$ and $^{12}C+^{197}Au$. Our main interest was focused on pp-correlation measurements, in order to find out if a quasi-elastic component is visible. This is for example claimed to be observed in the reaction $^{12}C+^{12}C$ at 800 MeV/nucleon (24).

In this experiment we observed an in-plane excess of coincident protons, which means an excess of particles simultaneously emitted in a "back-to-back" plane compared to the number of particles emitted "perpendicular" relative each other. This in-plane excess was not only observed for proton-proton pairs, but also in the other correlations studied (pd, dp and dd).

The results obtained were compared with two different theoretical approaches, one quasi-elastic scattering model (QES,sec.4.1) and one using a recoiling thermal source (RTS,sec.4.2). The RTS-model fairly well reproduced the R-function, defined as the ratio between the two types of coincidences measured, whereas the QES approach, as expected, greatly overestimated the ratio. To get a more sensitive test of the models, they were also compared with the absolute cross-section of the excess, i.e. the difference between the coincidence rates. Fairly good agreement was here observed for both approaches.

PAPER IV

Large-Angle Correlations Observed in Intermediate Energy Heavy Ion Collisions

P.Kristiansson, J.P.Bondorf, L.Carlén,
H-Å.Gustafsson, B.Jakobsson, A.Kristiansson,
G.Løvhøiden, H.Nifenecker, O-B.Nielsen,
A.Oskarsson, H.Ryde, T-F.Thorsteinsen and M.Westenius

The last paper in this thesis is a summary of a talk given by myself at the second international conference on nucleus-nucleus collisions in Visby, 10-14 June 1985. It is a presentation of some of the data obtained during the second large-angle correlation run. The experimental set-up was slightly modified for this run, compared to the first, to increase the counting rates. The data are parametrized with the same ratio function R, as in paper III. In this experiment we extended our measurements, because we especially wanted to look for correlations between heavier emitted particles. We also made a comparison between correlations obtained for particles emitted from different targets.

The results show that the strength of the in-plane excess strongly depends on both the mass of the observed particle and the target mass. The ratio function increases when the mass of the observed particle increases and decreases when the target mass increases. These results are qualitatively explained with momentum conservation within the emitting system (compare with the RTS-model). There is an indication of direct alfa-alfa scattering in the reaction $^{12}C+^{12}C$, but the signal is weak and the reaction has to be studied in a specially designed experiment.

6. Concluding remarks

In this section I will comment on some experimental results obtained by other groups, in close connection to those presented in papers I-IV. I have just tried to extract those data that are relevant for this thesis and it is by no means a complete description of these experiments. At the end there are some reflections about some possible experimental directions for the future.

Charged pions at 0^0 have been measured by E.Chiavassa et.al. (25) with a magnetic spectrometer. They have studied both positive and negative pion production from the reaction $^{12}C+^{12}C$ at 85 MeV/nucleon. The energy range covered by the spectrometer was approximatly between 60 and 200 MeV for the pions. The relative yield of positive and negative pions, above the region disturbed by the projectile, shows great similarites with the results presented in paper II. Above 120 MeV the spectra show the same exponential fall-off with approximately the same slope-parameters as we have found.

Neutral pion production in nucleus-nucleus collisions has been measured by H.Noll et.al. (26 and 27) with different projectiles and at different energies. Their results from reactions which, are similar to those reported in the papers I and II, show fairly good agreement in the absolute yield, but there are discrepancies in the slope-parameters, for instans the 90^0 spectra from the reaction $^{12}C+^{12}C$.

Large-angle correlations have been studied by S.Nagamiya et.al. (24 and 2) at high energies, 800 MeV/nucleon, for the reactions $^{12}C+^{12}C$ and $^{12}C+^{197}Au$. They claim that they see a quasi-elastic pp-component for the light system, while there is no indication of such a component for the gold target.

At lower beam energy (20-25 MeV/nucleon), Lynch et.al. (28 and 29) have studied large angle correlations between (Z=1)-particles in collisions between ^{16}O-projectile and light and heavy targets. They have reported results similar to those presented in papers III and IV, i.e. non-isotropic correlations. Conversion of their results to the form used in our papers, indicates the same increase in the in-plane excess with observed particle mass (fig.4,IV). The stong ratio dependence on the target mass reported in paper IV is not at all seen in their results. It seems that the corresponding ratio function instead is completely target independent, but they have observed a large variation with target mass in the azimutal interval 0^0 to 90^0.

For both types of measurements presented in this thesis, inclusive pion production and large-angle correlations, there is a need for an extension of the experimental work to be able to distinguish between different types of collisions. The easiest extension would presumably be the introduction of a measurement of the projectile in coincidence with the other measurement. This would give some information about the size of the participant region, and a definition of the nucleus-nucleus reaction plane.

Such measurements have already been done in combination with the detection of π^0 (30) at 48 MeV/nucleon. The result indicates that the pion is normally produced in a central event, i.e. the whole projectile is involved. The technique used for measuring charged pions with range telescopes, is not very suitable for these types of measurements. The biggest problem is that the maximum solid angle, which is possible to use, is only about 0.1% of the total, which is about a factor ten less than the π^0-experiment. Such a small solid angle leads to a demand of a high flux beam, which in turn reduces the possibility of using a simple projectile-fragmentation detector. One may also question the importance to measure pion-production much below (85 MeV/nucleon) the free nucleon-nucleon threshold, if one considers that the production cross-section decreases very strongly with decreasing beam energy. The possible collective production mechanism, pionic bremsstralung (31) and other cooperative mechanisms (20), ought to be possible to studie at higher energies, without too much disturbance from the nucleon-nucleon scattering.

For the large-angle correlations there is no problem to introduce a plastic wall for the detection of projectile fragments. In the future this will give the possibility to deduce indirectly the size of the participant system, and from this it will hopefully be possible to select among different theoretical approaches. One difficulty with the experiment performed at CERN (SC) is that only light ions are available as projectiles. Heavier projectiles, combined with fragmentation detectors would give much more new information about the reaction mechanism.

Acknowledgements

I wish to express my sincere gratitude to docent Bo Jakobsson, who introduced me to this field of heavy ion physics and acted as my supervisor during these enjoyable years. I have found our work inspiring and our discussions most interesting. I am also grateful to Professor Hans Ryde for his support and interest in my work.

To my colleagues in the SC83-collaboration I send many thanks. What I know today about experimental physics, I have learned from them. Especially my friends (and teachers) Hans-Åke Gustafsson and Anders Oskarsson are acknowledged. I would also like to take this opportunity to thank my two younger co-workers, Anders Kristiansson and Mats Westenius, for their help with the daily routines and for many stimulating discussions during the last year.

My sincere thanks to my colleagues at the Department of Cosmic and Subatomic Physics and all my other friends. These years have been five really good ones!!

I wish to thank my parents for their encouragement and support throughout my studies. I am also extra grateful to my father for not once trying to persuade me into nuclear physics. Now I understand why, it was not necessary.

Finally, I wish to thank my wife for her interest in my work and her patience with my working hours. Especially the nightcalls during the work with this thesis are appreciated.

Thank You very much, all of you.

References

1) D.K.Scott LBL-7727 (1978)

2) S.Nagamiya and M.Gyulassy LBL-14035 (1982)

3) A.S.Goldhaber and H.H.Heckman LBL-6570 (1978)

4) CERN-Copenhagen-Grenoble-Lund collaboration proposal, CERN/PSCC/78-8 (1978)

5) J.Mougey et.al. Phys Lett. 105B(1981)25

6) B.Jakobsson et.al. Phys.Lett. 102B(1981)121

7) M.Buenerd et.al. Phys.Lett. 102B(1981)242

8) H.Ryde Phys.Scripta Vol T5 114-117 (1983)

9) A.Oskarsson Thesis, Cosmic and Subatomic Physics Report LUIP 8303

10) N.Brummund et.al. Contributed Paper to the Second International Nucleus-Nucleus Conference, Visby (1985)

11) G.D.Westfall et.al. Phys.Lett 116B(1982)118

12) M.Buenerd et.al. Phys.Rev. C 26(1982)1299

13) L.Bimbot et.al. IPNO-DRE 84.31 To appear in Nucl.Phys.

14) H-Å.Gustafsson et.al. Phys.Rev.Lett. 53(1984)544

15) W.G.Lynch et.al. Phys.Rev.Lett. 51(1983)1850

16) M.A.Bernstein et.al. Phys.Rev.Lett. 54(1985)402

17) A.Kristiansson et.al. Cosmic and Subatomic Physics Report LUIP 8506

18) LeCroy Research System, Spring Catalog 1983

19) B.Jakobsson Phys.Scripta Vol T5 207-212 (1983)

20) R.Shyam and J.Knoll Phys.Lett. 136B(1984)221

21) C.Guet and M.Prakash Nucl.Phys. A428(1984)119

22) B.Jakobsson et.al. Cosmic and Subatomic Physics Report LUIP 8411

23) W.Benenson et.al. Phys.Rev.Lett. 43(1979)683
Errata Phys.Rev.Lett. 44(1980)54

24) I.Tanihata et.al. Phys.Lett. 97B(1980)363

25) E.Chiavassa et.al. Nucl.Phys. A422(1984)621

26) H.Noll et.al. Phys.Rev.Lett. 52(1984)1284

27) H.Noll Dissertation GSI-85-9 (1985)

28) W.G.Lynch et.al. Phys.Lett. 108B(1982)274

29) M.B.Tsang et.al Phys.Lett. 148B(1984)265

30) A.Oskarsson Contributed Paper to the Second International Nucleus-Nucleus Conference, Visby (1985)

31) D.Vasak et.al. Phys.Scripta 22(1980)25