Collective nuclear flow and shadowing by spectator matter
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3. The Au + Au experiment at 1 GeV/u

In the early eighties it was decided at the GSI to enter into the field of relativistic heavy-ion physics while first pioneering studies had been done at the Lawrence Berkeley Laboratory (LBL). At that time a linear accelerator UNILAC had already been successfully operated at GSI for studies at energies close to the Coulomb barrier. For the investigation of relativistic heavy-ion reactions a second accelerator was required to reach energies of $E/mc^2 \approx 1$, the energy domain, which is interesting for the study of collective behaviour of nuclear matter. Because of the high multiplicities of reaction products at these energies, in comparison to experiments in the more classical fields of nuclear physics ($E/mc^2 \ll 1$), specialized and highly granulated detector systems are required.

In this chapter the accelerator combination at GSI and the detector facilities used for the experiment are described. Only a few necessary details of the accelerators are given. The detector components are examined more closely. Finally the electronics and data acquisition are discussed.

3.1 Layout of the Experimental Setup

The newly designed accelerator SIS (Schwerionen Synchrotron) came into operation in 1990. For the nuclear physics investigations in the intermediate-energy regime SIS is used with UNILAC as a pre-accelerator (figure 3.1). This combination allows to accelerate projectiles up to the mass of $^{238}$U. With uranium ions energies of 1 GeV/u can be reached. Less-heavy ions can be studied at energies up to 2 GeV/u. Furthermore, the high particle-current density and very good energy resolution of the facility are necessary features for the experiment described in the present work.

The position of the detector system involved in this experiment is marked in figure 3.1 as “Cave B”. Figure 3.2 represents a schematic view of the experimental setup. The main instrument utilized for the work described in this thesis is the Two-Arm Photon Spectrometer (TAPS). The TAPS spectrometer is developed and employed mainly for hard-photon and neutral-meson measurements. For the purpose of reconstruction of neutral mesons by their invariant mass, TAPS had to be optimized for photon detection. A series of experiments with TAPS at GSI was already analysed emphasizing this aspect (table 3.1). In the context of this the-
The charged-particle aspects of these heavy-ion collisions are analysed. These aspects are: collective charged-particle flow, charged-particle ratios, the distribution of charged particles in phase space and the study of shadowing effects of participants by spectator matter. The present work completes the earlier research on $^{197}$Au + $^{197}$Au reactions at 1 GeV/u in the charged-particle analysis domain. Detailed technical information on TAPS is given in [Gab94, Nov91, Sch90, Tap87].

TAPS was employed at GSI in a combined setup with the Forward Wall of the FOPI collaboration [Fop88, Gob93]. On the right hand side of figure 3.2 the Outer Plastic Wall (OPW) of the Forward Wall is sketched. The technical description of the OPW will be given in section 3.3. The 1 GeV/u Au run is the only experiment from the list above exploiting the full hit information of the Forward-Wall detectors (see section 4.2). Earlier experiments utilized only
Figure 3.2: Experimental setup. Top: spatial presentation of the main detector positions. Bottom: a top view sketch of the setup with two TAPS towers at $45^\circ \leq \vartheta \leq 59^\circ$ (the tower axis is defined by the angle $\theta_{TAPS} = 52^\circ$) including two blocks of 64 BaF$_2$ modules each (see presentation on top: the angle of inclination per block within one tower is illustrated there), the OPW of the Forward Wall with 512 plastic scintillator strips at laboratory angles from $7^\circ$ to $30^\circ$, the start detectors (scintillation counter and finger detector in the target region) and a beam monitor (beam counter).
### Table 3.1: Experiments with TAPS at GSI in the period 1990–1991.

<table>
<thead>
<tr>
<th>reaction system</th>
<th>energy [GeV/u]</th>
<th>period</th>
<th>references</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{20}$Ne+$^{27}$Al</td>
<td>0.35</td>
<td>May 1990</td>
<td>[Ber90, Ber91, Pfe93]</td>
</tr>
<tr>
<td>$^{40}$Ar+$^{40}$Ca</td>
<td>1</td>
<td>August 1990</td>
<td>[Ber91, Ber93, Ber94]</td>
</tr>
<tr>
<td>$^{40}$Ar+$^{40}$Ca</td>
<td>1.5</td>
<td>December 1990</td>
<td>[Bru92, Pfe93, Sch94]</td>
</tr>
<tr>
<td>$^{86}$Kr+nZr</td>
<td>1</td>
<td>April 1991</td>
<td>[Ber93, Ber94]</td>
</tr>
<tr>
<td>$^{197}$Au+$^{197}$Au</td>
<td>1</td>
<td>July 1991</td>
<td>[Ber94, Sch93, Sch94]</td>
</tr>
<tr>
<td>$^{209}$Bi+$^{208}$Pb</td>
<td>1</td>
<td>August 1991</td>
<td>[Ven93, Ven94]</td>
</tr>
</tbody>
</table>

Most analyses are neutral-meson studies, except for [Bru92, Kug94a, Kug94b, Kug94c, Kug95], which describes charged-particle aspects, [Rit93a, Rit93b] investigating the double giant dipole resonance and [Kug94a, Kug94b, Kug94c, Kug95, Pac94a, Pac94b], which are dealing with neutron analyses.

Hardware-derived multiplicity information from the Forward Wall. This information is mainly used for event characterization and in particular for determining the impact parameter (subsection 4.2.2).

A 1 GeV/u $^{197}$Au beam from the SIS accelerator of GSI was used to bombard a $^{197}$Au target with a thickness of 0.1 mm (0.188 g/cm$^2$) corresponding to 0.1% nuclear interaction length. The beam intensity was $\approx 10^6$ particles per spill with a duty factor of 44% at a total spill time of 9 s. A start detector provided the start trigger and the time-zero signals. This detector consisted of an in-beam plastic-scintillator foil and a ring-shaped scintillator to veto the beam halo. A plastic-scintillator beam counter completed the setup. The beam counter serves as a reference counter to monitor the number of beam particles. The beam pipe, made of aluminum with a thickness of 2 mm, passed through the center of the Forward Wall. The subdetector systems are described in the following sections. The acceptance in phase space for the detector systems, which are used to produce the particle spectra of chapter 5, is shown in figure 3.3.
3.2 The Two-Arm Photon Spectrometer (TAPS)

The TAPS spectrometer was designed to detect photons in a large energy range from 20 MeV to 2 GeV. Meanwhile experiments with a dynamic range of 15 GeV have been done successfully at the SPS accelerator complex of the European nuclear research laboratory CERN (Conseil Européen de la Recherche Nucléaire).

The TAPS spectrometer has the following properties:

**mobile:** TAPS is a highly granular and efficient photon spectrometer with high investments in the BaF$_2$ detector material. This apparatus is shared by several research institutes of the European TAPS collaboration. With a mobile construction TAPS can be moved to different accelerators covering complementary energy regions. In the meantime TAPS has been used at accelerators at the University of Mainz, the French national laboratory GANIL (Grand Accélérateur National d’Ions Lourds), at CERN and the KVI (Kernfysisch Versneller Instituut).

**modular:** The modularity allows a flexible reconfiguration of the experimental

---

Figure 3.3: Acceptance in phase space for TAPS and the OPW. Target rapidity has the value $Y_{REL} = -1$ and midrapidity is at $Y_{REL} = 0$ on the scale of relative rapidity (see section 1.3).
setup, e.g., from the four blocks setup described in this work (see figure 3.2) to a “super-cluster” setup (all modules arranged in one large block with a hexagonal configuration) which was used during the CERN experiment and one of the KVI runs. Furthermore, the position resolution depends on the granularity of the detector and the active area of the individual detector modules.

movable: TAPS consisted during the 1 GeV/u Au + Au experiment of four blocks with 64 BaF$_2$ detectors each$^1$. Two towers with two TAPS blocks each were positioned on either side of the beam covering $45^\circ < \theta_{lab} < 59^\circ$

$^1$The present (1997) TAPS configuration consists of 6 blocks.
with respect to the beam direction at a distance of 2 m from the target (figure 3.2). The total azimuthal acceptance was $\Delta \varphi = 43.2^\circ$.  

In figure 3.4 a 3-dimensional sketch of one TAPS block is shown. The basic lattice of the modular arrangement is an $8 \times 8$ array shown with its dimensions in figure 3.5. Every BaF$_2$ module has an individual plastic scintillator veto detector in front of it. For details of the BaF$_2$ and the Charged-Particle Veto (CPV) modules see subsections 3.2.1 and 3.2.2, respectively.

### 3.2.1 The TAPS-BaF$_2$ Crystal and the Single Detector Modules

As mentioned above, the TAPS spectrometer is optimized for neutral meson measurements. It, however, also allows for charged-particle detection. This feature is exploited for light baryons in this thesis. The chosen inorganic detector material BaF$_2$ [Bir64, Lav83, Nov88] has a number of properties that make it especially suited for this task:

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2A large geometric acceptance is necessary for coincident detection of meson-decay photons. The block positions can be optimized per experiment depending on the bombarding energy and the physics of the decay of mesons into $\gamma$'s. From these decay photons an invariant-mass analysis allows the reconstruction of the neutral mesons $\pi^0$ and $\eta$. For more details on invariant-mass analysis see references [Ber93, Loh86, Sch93, Pfe93, Ven94].
Figure 3.6: Pulse shape of a BaF$_2$ detector signal. The area shaded gray originates from a photon emitted by a $^{137}$Cs source. The $\alpha$ activity of the BaF$_2$ crystal is responsible for the charged-particle pulse. The pulses are acquired by a digital oscilloscope. Integration of the signal within the indicated gates allows for discrimination between photons and charged particles [Röb95].

- Possibility to discriminate between neutral and charged particles via the two different decay components of scintillation light (figure 3.6 and subsection 4.1.2); this is done in combination with the CPV detector described in subsection 3.2.2;

- Good time resolution for separation of hadrons via their Time Of Flight (TOF) from target to the detection position (subsection 4.1.1);

- Good energy resolution for a large dynamic range for particle identification (subsection 4.1.1);

- No activation by thermal neutrons;

- Good radiation hardness;

- Low hygroscopic material

- And good mechanical stability.

Furthermore, the BaF$_2$ detectors have to fulfill some design requirements:

- Good position resolution; mainly for neutral meson reconstruction (subsection 4.1.3);
3.2. The Two-Arm Photon Spectrometer (TAPS)

- Sufficient detector volume:
  - The crystal diameter should be smaller than the BaF$_2$-Molière radius $R_M$ to allow a precise position reconstruction for photons; at least 90% of the energy of the electromagnetic photon showers [Loh83] is dissipated within a diameter of $2 \times R_M$. Therefore, one mostly gets clusters of responding modules for detected photons. This arrangement allows for a very satisfactory position reconstruction.
  - Charged particles and photons should deposit their energy in a large energy range mainly in the active detector volume; this fact leads to the detector length which is related to the radiation length.

For more details on the Molière radius

$$R_M = X_0 \frac{E_S}{E_C}$$  \hspace{1cm} (3.1)

with

$$E_S = \sqrt{4\pi/\alpha \cdot m_e c^2} = 21.2\text{MeV}$$  \hspace{1cm} (3.2)

see [Agu94, Par94, Leo87]; $X_0$ is the radiation length, $m_e$ stands for the electron mass, $\alpha$ for the fine-structure constant and $E_C$ represents the critical energy$^3$;

- Because of the projectile energy and the resulting high particle multiplicity the detector system needs to be highly granular to assure low multiple hit rates in a single module.

The properties of BaF$_2$ scintillator crystals are given in table 3.2.

The TAPS-BaF$_2$ crystals$^4$ are hexagonally shaped with an inscribed diameter of 59 mm which is 1.7 times the Molière radius $R_M$. The module length of 25 cm corresponds to 12 radiation lengths $(X_0)$ and is sufficient, e.g., to detect the energy of 400 MeV protons and 92% of the energy of 1 GeV photons. The rear end of the scintillator modules is cylindrically shaped over the length of 2.5 cm for an optimal coupling to a photomultiplier (Hamamatsu R2059-01 [Ham88]). Next to this cylindrical end a light fibre is fed in for gain control and calibration measurements. These tasks are accomplished by a nitrogen laser$^5$ system [Ven94]. The laser light is detected by the photomultipliers of the detector modules and causes a cathode current which is comparable to that one caused by particle detection. Therefore, with the laser detector signals can be simulated. Figure 3.7 depicts the dimensions of a single detector module.

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$^3$Material specific energy at which the radiation loss equals the collision loss.

$^4$Made by company Dr. Karl Korth, Kiel, Germany.

$^5$VSL-337, LSI Laser Scientific, Inc., Cambridge, MA, USA. Wavelength $\lambda = 337$ nm.
Chapter 3: The Au + Au experiment at 1 GeV/u

### Table 3.2: Properties of BaF<sub>2</sub> scintillator crystals [Leo87, Mer87, Agu94, Par94, Lec92].

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>4.89 g/cm&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>Index of refraction</td>
<td>1.49</td>
</tr>
<tr>
<td>Light output</td>
<td>20 % anthracene</td>
</tr>
<tr>
<td>Wavelength maximum I</td>
<td>310 nm</td>
</tr>
<tr>
<td>Wavelength maximum II</td>
<td>195; 210 nm</td>
</tr>
<tr>
<td>Decay time I</td>
<td>620 ns</td>
</tr>
<tr>
<td>Decay time II</td>
<td>0.6 ns</td>
</tr>
<tr>
<td>Radiation length X&lt;sub&gt;0&lt;/sub&gt;</td>
<td>2.05 cm</td>
</tr>
<tr>
<td>Molière radius R&lt;sub&gt;M&lt;/sub&gt;</td>
<td>3.4 cm</td>
</tr>
<tr>
<td>Critical energy E&lt;sub&gt;C&lt;/sub&gt;</td>
<td>12.7 MeV</td>
</tr>
</tbody>
</table>

#### 3.2.2 Charged-Particle Veto Detector (CPV)

The Charged-Particle Veto detector (CPV) consists of 256 plastic scintillator [Sch63] hexagons which are read out via perspex lightguides and 1 inch Philips-Valvo XP2972 photomultipliers (Valvo GmbH, Hamburg, Germany [Phi87]). Figure 3.8 shows the CPV module setup. Every BaF<sub>2</sub> module has an individual CPV detector in front of it. The CPV is mainly used to distinguish charged particles from photons detected in the BaF<sub>2</sub> modules of TAPS in order to perform an efficient online photon analysis. Therefore, the average photon conversion probability in the CPV has to be low (2.5%) [Kle84, Leo87]. The thickness of the NE102A (Nuclear Enterprises Limited, Berkshire, Great Britain [Nuc]) plastic-scintillator modules is the result of a compromise between low photon conversion on one the hand and sufficient energy loss for charged particles in the veto detector material on the other. Tests described in [Ras89] led to a 5 mm thick scintillator which corresponds to 0.012 X<sub>0</sub>. In figure 3.4 the arrangement for the plastic scintillator modules in three levels and the lightguides for one TAPS array consisting of 64 modules is shown. A one-to-one correspondence of BaF<sub>2</sub> to CPV modules is realized to provide each BaF<sub>2</sub> module with an individual coincident “veto” signal. With an overlap of about 5 mm among the CPV modules the detection efficiency is increased. With this construction an efficiency of nearly 100% for charged-particle detection is achieved at target distances larger than 1 meter.

The individual CPV modules are made light tight by black plastic tape. To obtain optimal light collection and thus minimal light loss the reflectivity at the edges of the scintillator and light guide has to be optimal. To achieve diffuse
Figure 3.7: Dimensions and components of a single TAPS module. B: BaF₂ crystal, PmB: Hamamatsu R2059-01 photomultiplier tube, BaB: active voltage-divider base, Sh: μ-metal shielding, Lf: quartz light fibre. C: CPV plastic scintillators, Lg: light guides, PmC: CPV photomultiplier tube with magnetic shielding, BaC: voltage-divider base (for CPV details see subsection 3.2.2). All dimensions are given in millimeters.

reflectivity the detector hexagons and the perspex lightguides are wrapped in teflon foil⁶. The NE102A scintillator slices, machined from Nuclear Enterprises material, are glued to the lightguide. The glue, Ruplo 410 on cyanacrylat basis⁷, is transparent in the region of the produced scintillation light. The coupling of the lightguides to the photomultiplier tubes is efficiently done by pads of silicon rubber made from Silgel⁸ 601 A+B fitted to the phototube window. Due to the compressibility of the 3 mm thick pads a compensation of small inaccuracies of the dimensions of the lightguides resulting from the manufacturing process is achieved. During the experiment a maximum magnetic field of $B_{\text{outside}} = 100$ G is expected. The photocathodes have to be shielded from that field. Individual μ-metal cylinders, one per each photomultiplier, reduced the outside field to $B_{\text{inside}} = 1$ G next to the photocathode. These shieldings are employed in the detector design. Furthermore, groups of 32 phototubes are arranged inside a soft-iron housing. This material of 1 to 2 mm thickness once more reduces the magnetic field by a factor of 7. Mainly this soft-iron housing is used to decouple the photomultiplier tubes from the influence of high-frequency fields from the outside. A detailed description of the CPV detector is given in [Ras89]. In [Nov91] the features of the detector components are explained.

⁶Made by Tetratec Corporation, Feasterville, PA, USA.
⁷Ruplo Glues, Ten Boer, The Netherlands.
⁸Wacker Chemie, Munich, Germany.
Figure 3.8: Dimensions of a single CPV module.

The energy-loss signal of the CPV modules can be used to perform particle identification in combination with the signals from the BaF$_2$ modules. This method complements the particle identification which is described in detail in chapter 4. In the experiment described in this thesis only one of the four TAPS blocks was equipped with electronics to register the CPV energy-loss signal. In a previous experiment the ΔE-E information was used for charged-particle analysis [Bru92]. For this kind of analysis an energy-loss signal with only a small position dependence is necessary. In [Ras89] and [Bru92] the position dependence of the CPV signal was investigated.

3.2.3 TAPS Electronics

In figure 3.9, a sketch of the electronics per TAPS-BaF$_2$ detector module is shown. The abbreviations of the electronics modules used in this section are given in table 3.3. The recorded data should be suitable for the analysis of cluster separation and particle identification which is to be discussed in chapter 4. To achieve these results TAPS uses the three methods of

1. Pulse-Shape Analysis (PSA),
2. Time-Of-Flight (TOF) measurement and
3. Charged-Particle Vetoing (CPV)

(for details see chapter 4). To obtain this information the following electronic modules are employed:
Figure 3.9: TAPS-electronics diagram. The abbreviations of the electronics modules are given in table 3.3.

**PSA:** Pulse-Shape Analysis is based on the two different scintillation light components of the BaF$_2$ detector material (see subsections 3.2.1 and 4.1.2). These components are extracted by integrating the analog detector signal within two different timing gates. In the TAPS-BaF$_2$ case a single analog signal is split by the AAS (Active Analog Split). The three outputs of the AAS are employed for 1) the energy signal, 2) the gating and 3) the trigger information (via a Leading-Edge Discriminator (LED)). The gate and delay generator (RDV; in the gating branch (2)) provides the individual gate timing per detector module, derived from a Constant-Fraction Discriminator (CFD). The charge integration by the Charge-to-Digital Converter (QDC) is performed within a narrow gate of 30 ns and a wide gate of 2 $\mu$s. To achieve sufficient resolution in the narrow gate signal each detector module is equipped with individual gate timing. For the data acquisition of the digitized output see section 3.4.

**TOF:** The BaF$_2$ TOF information is taken from the gating branch (2); see the description for the PSA electronics above. The exact time signal is derived
Table 3.3: List of electronic modules per TAPS-detector module with the abbreviations used in the text and in figure 3.9. The modules are manufactured by:

- **Univ. Gießen**: II. Physikalisches Institut, Electronics Workshop, University of Gießen, Germany.
- **GAN’ELEC**: GAN’ELEC Company, Caen, France.
- **GSI**: GSI, Department of Experiment Electronics, Darmstadt, Germany.
- **LeCroy**: LeCroy Research Systems Corporation, Spring Valley, NY, USA.

from the CFD and is used to stop the Time-to-Digital Converter (TDC). The common start of all TDC’s is provided by the event trigger.

**CPV**: The CPV electronics have to provide fast charged-particle trigger information. In front of each BaF$_2$ module an individual CPV module is placed. The CPV photomultiplier output delivers a fast analog signal, which is processed by a LED. In the trigger and multiplicity box (MB) these CPV signals are combined with the corresponding BaF$_2$ detector module signals. Photon identification is mainly based on this veto signal processing. Such setup allows to count BaF$_2$ signals from neutral or charged particles on a fast trigger level. In addition, this feature is employed for the charged-particle analysis in this thesis. The CPV detector covers the BaF$_2$ completely at target distances larger than 1 m. Consequently, the CPV electronics provide veto and charged-particle signals with an efficiency of almost 100%.

Because of slightly different gains of the BaF$_2$ photomultipliers a good energy resolution (subsection 4.1.1) is achieved by adjusting the low energy thresholds individually per TAPS module. The threshold energy is set just above the detec-
tor noise and corresponds to an average photon energy of 3 MeV. This threshold does not affect the charged-particle identification since the light baryons can be separated only at energies above several tens of MeV (chapter 4). However, this threshold setting is crucial for the neutral-meson reconstruction [Sch93, Ven94]. Triggering of reaction events aims at a pre-selection of the data to optimize the offline data analysis. Therefore, the LED thresholds were set to 10 MeV photon-equivalent energy to select events with high energy photons.

3.3 The Forward Wall

The Forward Wall was made available by the FOPI collaboration to obtain centrality and reaction-plane information. The detector is described in the following except for the most forward part, the Inner Plastic Wall (IPW), which is not used in this data analysis. Details are published in [Fop88, Gob93].

Figure 3.10: The OPW with its 8 sectors and 64 plastic scintillator strips per sector [Gob93].
3.3.1 The Outer Plastic Wall (OPW)

The outer part of the Forward Wall (OPW) covers laboratory angles from $\phi=7^\circ$ to $\phi=30^\circ$ with a nearly symmetric acceptance in $\varphi$. The OPW is built from 512 BC408 plastic scintillator strips\textsuperscript{9}, which are arranged in 8 radial sectors of 64 strips each (figure 3.10). Figure 3.2 shows the setup used at GSI with the 4 TAPS blocks arranged outside the coverage of the Forward Wall. Each of the 45 cm – 165 cm long strips has a rectangular cross section (1.8 cm thick, 2.4 cm high) and is equipped with one phototube Philips–Valvo\textsuperscript{10} XP2972/01 on either side. For the OPW the same 1 inch photomultiplier is applied as for the CPV design but with a different voltage divider. The difference in length of the scintillator parts of the detector modules is compensated within a subgroup of modules by light guides. These light guides and the photomultiplier tubes are arranged in such a way that they are hidden behind the active areas of the two neighbouring sectors. All strips are positioned with their front face exactly perpendicular to the individual target-strip axes. The outer diameter of the OPW is 4 m. The distance from the target is 440 cm and 360 cm for modules arranged at 7$^\circ$ and 30$^\circ$, respectively. The technical report [Gob93] gives details on the overall construction of the OPW as well as on the single detector strips.

The features of the OPW which are important for the physics of particle identification used in this thesis are summarized here. The time resolution depends on the strip length. With the short strips 80 ps resolution has been achieved, whereas for the longest strips a value of 120 ps was obtained. However, the time resolution also depends on the position along the strip. Variations of the order of 45 ps have to be taken into account. The effective signal velocity in the scintillator is determined to be $v_{\text{eff}} = (15.1 \pm 0.1) \text{ cm/ns}$. These properties result in a position resolution along a strip better than 1.8 cm.

An UV light nitrogen-laser\textsuperscript{11} control system is used for stability monitoring and for the time and energy calibration. From the energy and time information per strip the following particle information is derived:

1. position along the strip

$$POS \propto \frac{1}{2}(t_{\text{left}} - t_{\text{right}}) \quad \text{or}$$
$$POS \propto \ln (E_{\text{left}} / E_{\text{right}})$$

(3.3)

with time ($t$) and energy ($E$) signal from both ends of the strips (left and right),

\textsuperscript{9}Bicron Corporation, Newbury, USA [Hur85].
\textsuperscript{10}Valvo GmbH, Hamburg, Germany [Phi87].
\textsuperscript{11}LSI Laser Scientific, Inc., Cambridge, MA, USA. Wavelength $\lambda = 337 \text{ nm}$. More details in [Gob93, Wie93].
Figure 3.11: OPW electronics diagram. The abbreviations of the electronics modules are given in table 3.4.

2. energy loss

\[ \Delta E \propto \sqrt{E_{\text{left}} E_{\text{right}}} \]  \hspace{1cm} (3.4)

and

3. time of flight or particle velocity \( v \)

\[ TOF \propto \frac{1}{2}(t_{\text{left}} + t_{\text{right}}). \] \hspace{1cm} (3.5)

From \( \Delta E \) and \( v \) the element identification (\( Z \)) is obtained. In a two-dimensional representation of \( \Delta E \) versus \( v \) element branches can be separated. The polar angle is given by the strip position with the accuracy of the strip front height of 2.4 cm corresponding to an average \( \Delta \theta = 0.36^\circ \).
Table 3.4: List of electronic modules per OPW-detector module with the abbreviations used in the text and in figure 3.11. The modules are manufactured by:
LeCroy: LeCroy Research Systems Corporation, Spring Valley, NY, USA.
GSI: GSI, department of experiment electronics, Darmstadt, Germany.

### 3.3.2 OPW Electronics

Figure 3.11 gives an overview of the electronics per FOPI-OPW detector module. A list of abbreviations for the electronics modules used in this section can be found in table 3.4. As described in chapter 4 the OPW is used in the analysis to determine per event the reaction plane and the charged-particle multiplicity. The first requires knowledge about the particle position and its transverse momentum. The latter quantity can be deduced from the hit information, i.e., the information on the total number of hits per event. All this information is derived from two energy and two time signals per OPW strip.

The OPW requires three branches with electronics modules:

1. for the energy signals,
2. for the time signals and
3. for the trigger signals.

The corresponding electronics modules are described here:

**energy:** the analog signal from the OPW photomultiplier is split by the Split-Card and Linear-Delay module (SC/LD) into an energy and a time (see next topic) signal by a charge ratio 1:3, i.e., 75% of the signal charge is employed for generating the time information and 25% for the energy information. The energy signal is delayed by the SC/LD (500 ns) and fed into the charge-sensitive Fastbus Analog-to-Digital Converter (ADC).
time: the time-signal output from the SC/LD is directed into a CFD. The outputs of the CFD, which are used for the time signals, are delayed by 500 ns (DL). They are fed into the Fastbus Time-to-Digital Converter (TDC).

trigger: an additional output of the CFD generates an independent leading-edge time signal with a separately adjustable threshold. A valid time output on this channel requires an internal coincidence of the left and right photomultiplier signals of the individual OPW strips. From these leading-edge time signals the Multiplicity Box (MB) generates an analog sum-signal per OPW sector. The MB output serves as trigger on the charged-particle multiplicity.

3.4 Data Acquisition

While in earlier experiments with TAPS the hardware-derived rough charged-particle multiplicity information was fed into the TAPS data stream, this experiment intended to exploit the full information of the Forward-Wall detectors. The hardware-derived multiplicity was realized by the multiplicity box (MB) output per OPW sector (see subsection 3.3.2). To get the full information the two independent data-acquisition systems of TAPS and the OPW had to be combined. This is explained in subsection 3.4.3. But first the individual data-acquisition systems are described here.

3.4.1 TAPS

The TAPS data-acquisition system exploits the detector signals converted inside the CAMAC (Computer Automated Measurement And Control) modules (figure 3.12). Two separate CAMAC branches are equipped for

1. acquisition and
2. control

purposes. These branches write to a VME Subsystem Bus (VSB) which is read out by two microprocessors (VME-CPU-0 and CPU-1), one for each purpose. These CPUs communicate to VME. The acquisition microprocessor fulfills the tasks

1. readout control and
2. pack data into buffers.

The VME master CPU (MCPU) sends the buffers via a Direct Memory Access (DMA) link to the TAPS VAX computer. The TAPS MicroVAX-3200 stored the buffers on magnetic 8 mm video tapes (EXAbyte). The average data length per
event is 400 bytes. CAMAC control of adjustable electronics modules, as CFDs, LEDs and RDVs, was done by the processor in the other branch (VME-CPU-1) via an independent VSB branch. The HV control was realized via the same branch. Ethernet connected the TAPS VAX to the local TAPS cluster as well as to the GSI computer cluster. This allowed online monitoring of the experiment via the VME-CPU-2 processor.

In experiments like those described in this thesis the data acquisition is always a limiting factor. The TAPS system was able to record 500 events/s. With up to $2.5 \times 10^8$ beam particles/s, which corresponds in our case to about 2500 reactions/s, one needs selective triggers to focus on the events of interest. The data analysed here are taken with the “central-event trigger”. Three conditions are added in this trigger. A signal from the start detector is required. Two neutral hits in TAPS are demanded and the central-trigger condition of the OPW is required.

### 3.4.2 OPW

The general data-acquisition concept for the OPW is similar to that of TAPS with respect to the usage of two processors which have complementary tasks (figure 3.13). They are named

1. Event Builder (EB; acquisition) and

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**Figure 3.12:** Scheme of the TAPS data-acquisition system.
2. Setup Controller (SC).

These microcomputers differ both in hardware (Eltec E5/E6) and in their operating system (OS-9) [Mic89] from those used in the TAPS data acquisition. The digitized detector signals are transported via a VSB bus to the EB. The SC uses its own VSB bus to control the CFDs, all HV channels and to address the logic matrix unit, which combines pre-trigger information to triggers. The EB manages the data readout and sends all data via SCSI bus and VME onto magnetic EXAbyte tapes. The FOPI data-acquisition system, in which the OPW data are handled as a subset, was able to record up to 250 events per second with an average event length of 2 kbyte. The GSI Online Offline SYstem (GOOSY) [Goo87] data format was used. The OPW “central-event trigger” demands at least 30 hits in the OPW.

3.4.3 Combined Data Acquisition

The two independent VME-based data-acquisition systems were combined to one data stream using a VME-VME coupling processor (figure 3.14). The combined OPW and TAPS data are written to EXAbyte tapes by the FOPI data acquisition. Therefore, the TAPS event-data were sent via VME to a dual-ported-memory (DPM) module, which makes the connection via the EB VSB bus to the
FOPI EB microcomputer. From that point on the TAPS data were handled like the OPW data as a subevent within one FOPI event. Through this procedure the TAPS data-acquisition microprocessor (VME-CPU-0) became a slave CPU to the FOPI EB microcomputer.

**Figure 3.14:** Scheme of the combined data-acquisition system of TAPS and the Forward Wall.

However, a problem is caused by combining the individual dead times of the two systems. The coupling processor is idle during the wait time for the next event. This waiting is caused by the asynchronous transmission of the corresponding TAPS subevent. The synchronization process consequently causes a reduced data-storage rate. Beyond that the storage rate is reduced because of the 20% longer FOPI event including the TAPS subevent.