Chapter 5

Results

In this chapter the results will be presented in three steps. First the inclusive data, i.e. the data for a given detector without any constraint from the other detectors, will be presented for the TAPS detector system, the KVI Forward Wall and the spectrograph. Then the primary projectile-like fragment distributions will be presented which are reconstructed according to the method described in the previous chapter. Finally, the reconstructed mass distributions and the photon data will be combined in a correlated study.

5.1 Inclusive data

5.1.1 Photon energy spectra

In subsection 1.3.1 it has been shown that the hard-photon energy spectrum exhibits an exponential behaviour for energies larger than 30 MeV. One has to note here that the slope of the energy spectrum as well as the threshold energy are uniquely defined only in the source frame. It is therefore essential to know the velocity of the source frame before one can determine the inverse slope parameter $E_0$. The velocity of the source frame is determined via a source velocity fit of the angular distribution data (see subsection 1.3.2 and the following section) after which the photon energy in the source frame is calculated with this new value for the source velocity. As will be shown in one of the following sections, the source frame is found to be the nucleon-nucleon center of mass, in accordance with previous measurements.

In figure 5.1 the inclusive photon spectrum (in the nucleon-nucleon center of mass) is shown which is obtained with a minimum bias trigger. The
Results

Figure 5.1: Inclusive photon spectrum obtained with TAPS.

The inclusive spectrum was fitted for energies larger than 30 MeV, assuming an exponential shape. The drawn line is the result of this fit. An inverse slope parameter of $E_0 = 11.7 \pm 0.1$ MeV is found. To correct the measured photon spectrum for the detector response, GEANT calculations for energy spectra with different inverse slope parameters were done. Assuming that this response is only little energy dependent one can make a linear conversion from the measured inverse slope parameter to the actual inverse slope parameter. In figure 5.2 the slope parameter as originally inserted into the calculation ($E_0^{\text{actual}}$) is plotted versus the slope parameter determined from an exponential fit to the photon energy spectrum calculated by GEANT ($E_0^{\text{measured}}$).

From this figure it can be seen that in the range of inverse slope parameters of interest, the dependence is linear, allowing for a simple conversion from the measured inverse slope parameter to the actual value. For the slope
parameters quoted in the following, this correction has been applied.

The corrected slope parameter for the spectrum shown in figure 5.1 has a value of $E_0 = 13.4 \pm 0.1$ MeV which is in good agreement with the previous work of Riess et al. [Rie92] who found an inverse slope parameter $E_0 = 13.3 \pm 3.0$ MeV for a similar system, however, with a much larger uncertainty. Furthermore, also a good agreement with the general systematics is found (see figure 1.3).

5.1.2 Photon angular distribution

As already discussed in subsection 1.3.2 the angular distribution of the hard photons is expected to consist of an isotropic and a dipole term. In the laboratory frame this can be parametrized by equation 1.8
$$\left( \frac{d^2\sigma}{dE\,d\Omega} \right)_{\text{lab}} = \frac{K}{X} \left( 1 - \alpha + \alpha \frac{\sin^2 \Theta_{\text{lab}}}{X^2} \right) e^{-XE_{\text{lab}}/E_0}$$

where $X = \gamma(1 - \beta_s \cos \Theta_{\text{lab}})$, $\beta_s$ is the source velocity, $E$ and $\Theta_{\text{lab}}$ are the energy and the laboratory angle of the photon, respectively, $\alpha$ is a measure for the anisotropy and $K$ is an overall constant.

![Inclusive data](image)

**Figure 5.3:** The photon angular distribution. The full curve represents a source velocity fit to the data, for the dashed curve the anisotropy parameter ($\alpha$) has been fixed at 0.

In figure 5.3 the photon angular distribution is shown. A fit of the angular distribution with the parametrization described above yields a value $\beta_s = 0.149 \pm 0.005$ for the source velocity of the emitting frame and a value of $\alpha = -0.26 \pm 0.06$ for the anisotropy. The anisotropy parameter $\alpha$ is found to be less than zero. This is an unexpected value, because the dipole and
isotropic components of the angular distribution are believed to add incoherently. Therefore, a second fit has been applied to the data where the $\alpha = 0$. The dashed curve represents this fit yielding a value of $\beta_s = 0.141 \pm 0.005$.

The source velocity of the nucleon-nucleon center of mass for the $^{36}{\text{Ar}} + ^{159}{\text{Tb}}$ system at 44 MeV/nucleon is, $\beta_{NN} = 0.151$. Note that the value obtained for the source velocity is sensitive to the relativistic corrections for these energies. The usual assumption that $\beta_{NN} = \frac{1}{2} \beta_{\text{beam}}$ can therefore no longer be used ($\frac{1}{2} \beta_{\text{beam}} = 0.148$). The fact that the source velocity of the hard photon source is in agreement with that of the nucleon-nucleon center of mass supports the generally accepted picture that the hard photons originate from individual nucleon-nucleon collisions.

### 5.1.3 Photon production probability

The inclusive photon production probability ($P_{\gamma}^{pn}$) can be determined in two ways. In the literature usually the photon production cross section ($\sigma_{\gamma}$) is measured and then converted to a photon production probability making use of the relation

$$ P_{\gamma}^{pn} = \frac{\sigma_{\gamma}}{\sigma_R < N_{pn} >_b} 
$$

The disadvantage of this method is that it relies on the reaction cross section ($\sigma_R$) and on the value taken for the impact parameter averaged number of proton-neutron collisions ($< N_{pn} >_b$). The choice of the parametrization of $\sigma_R$ influences the value of $P_{\gamma}^{pn}$. This is discussed in appendix C.

A different method to determine the photon production probability employs minimum bias data, i.e. data obtained with a trigger that occurs with equal probability for each event. $P_{\gamma}^{pn}$ is then obtained from

$$ P_{\gamma}^{pn} = \frac{M_{\gamma}}{< N_{pn} >_b} 
$$

$$ M_{\gamma} = \frac{N_{\gamma}}{N_{total}} 
$$

where $N_{total}$ is the number of minimum bias events and $N_{\gamma}$ is the number of photons detected for these minimum-bias events. The advantage of this method is that the photon production probability no longer depends on the expression taken for the reaction cross section which makes it less model dependent.
In the experiment described in this thesis both methods were used. For the minimum-bias trigger the "Forward-Wall" trigger was used, demanding at least three light-charged particles in the Forward Wall. Therefore, it is not a real minimum bias trigger since the demand for three particles in the Forward Wall biases the reaction type. A good measure to determine whether a trigger is minimum bias is to compare the cross sections. A true minimum bias trigger has $\sigma(\text{trigger}) \approx \sigma_R$. In the present case the trigger cross section is 80% of the reaction cross section. The values obtained for $P_{pn}$ using the two methods are listed in table 5.1 and shown in figure 5.4.

The fact that the two values obtained for the inclusive photon production probability differ has two reasons. First the minimum-bias trigger used was a quasi-minimum bias trigger which therefore might underestimate the actual inclusive probability. Based on the difference between the measured reaction cross section for the minimum-bias trigger and the calculated re-

Figure 5.4: Systematics for the photon production probability. The full line represents the fit as written in the figure.
5.1 Inclusive data

Table 5.1: Values obtained for the inclusive photon production probability. (\(^a\) is a calculated reaction cross section and \(^b\) is the reaction cross section measured for the minimum-bias trigger.)

<table>
<thead>
<tr>
<th>method</th>
<th>(\sigma_\gamma) (mbarn)</th>
<th>(P_{pn}^{\gamma}) (10^{-5})</th>
<th>(\sigma_R) (barn)</th>
</tr>
</thead>
<tbody>
<tr>
<td>inclusive</td>
<td>2.17(\pm)0.34</td>
<td>7.8(\pm)1.2</td>
<td>4.3(^a)</td>
</tr>
<tr>
<td>min.-bias trigger</td>
<td>1.17(\pm)0.12</td>
<td>5.2(\pm)0.1</td>
<td>3.5(\pm)0.5(^b)</td>
</tr>
</tbody>
</table>

action cross section, and considering that the reaction cross section scales with the impact parameter squared \((\sigma_R \propto b^2)\), one can estimate the coverage in impact parameter assuming either central or peripheral collisions. Furthermore, one can calculate the average number of pn-collisions for the given impact-parameter range, making use of equation 1.10, and use this value to calculate the photon production probability. The results are shown in table 5.2.

Table 5.2: Recalculated photon production probability per proton-neutron collision corrected for the impact-parameter range \((r_p\text{ and } r_t\text{ are the radii of projectile and target, respectively})\).

<table>
<thead>
<tr>
<th></th>
<th>(b_{\text{min}}) (fm)</th>
<th>(b_{\text{max}}) (fm)</th>
<th>(&lt;N_{pn}&gt;)</th>
<th>(P_{pn}^{\gamma}) (10^{-5})</th>
</tr>
</thead>
<tbody>
<tr>
<td>peripheral</td>
<td>5.04</td>
<td>(r_p + r_t = 11.33)</td>
<td>3.2</td>
<td>10.5</td>
</tr>
<tr>
<td>central</td>
<td>0</td>
<td>10.15</td>
<td>8.0</td>
<td>4.2</td>
</tr>
</tbody>
</table>

From the comparison of \(P_{pn}^{\gamma}\) given in table 5.2 with the systematics one can conclude that the value of \(P_{pn}^{\gamma}\) for peripheral reactions is the closest to the systematics. Therefore, the Forward-Wall trigger selects mainly peripheral reactions.

Secondly it should be noted that the difference between the photon production probabilities calculated via the minimum bias trigger and via the measured \(\gamma\)-cross section may in part be due to the fact that the latter depends on the prescription used for the reaction cross section (see appendix C).
5.1.4 Light charged particles

In figure 5.5 the light-charged-particle (LCP) multiplicity distribution for masses up to Li is shown as a function of the charge of the detected projectile-like fragment. This presentation is chosen to compare with the LCP data available in the literature [Ste89]. From this figure one can directly see that the multiplicity for Li isotopes is already very small compared to that of H and He isotopes and therefore the restriction to $Z \leq 3$ is justified.

![Diagram showing multiplicity distribution as a function of charge]

**Figure 5.5:** The light-charged-particle multiplicity distribution as a function of the charge of the detected projectile-like fragment.
The shape of the total multiplicity distribution as well as the magnitude of the multiplicity are in very good agreement with the fast LCP distribution obtained by Steckmeyer et al. [Ste89]. In the work of Steckmeyer the LCPs were separated into fast (projectile-like) and slow (target-like) particles. In our experiment only fast LCPs were measured mainly as a consequence of the aluminum absorber in front of the Forward Wall which stops slow LCPs. Furthermore, the Forward Wall being positioned at forward angles has a larger acceptance for projectile-like LCPs than for target-like LCPs.

![Figure 5.6: Velocity diagram for α-particles in coincidence with $^{32}S$ projectile-like fragments. The arrow indicates the dividing angle between the small and big detectors.](image)

In figure 5.6 the parallel versus perpendicular component of the velocity distribution for α-particles in coincidence with $^{32}S$ projectile-like fragments is shown (the figure is shown two times, where the difference is that for
the lower graph an upper and a lower limit have been set to the number of
counts in the spectrum). The arrow indicates the dividing angle between the
small, inner, detectors and the big, outer, detectors (see subsection 3.2.1).
From the figure the two different detection thresholds can be seen clearly
due to the different absorbers placed in front of the small and big detectors.

\begin{equation}
N(E) = C^*(E-V_c)^{-0.5} \exp\left(-\frac{E-V_c}{T}\right)
\end{equation}

\[ V_c = 1.84 \pm 0.03 \text{MeV} \]
\[ T = 4.18 \pm 0.02 \text{MeV} \ (E^* = 69 \text{MeV}) \]

**Figure 5.7:** Kinetic energy of $\alpha$-particles in coincidence with $^{32}S$ projectile-like fragments, plotted in the PLF center of mass. The dotted and dashed spectra are the distributions for the small and big detectors, respectively. The solid curve is a fit to the experimental data.

Assuming that the $\alpha$-particles originate from the statistical decay of
a moving projectile-like fragment, the velocity distribution should have a
Maxwellian-shape independent of the emission angle in the center of mass
of the projectile-like fragment. In the two-dimensional picture this should
show up as a ring around the velocity of the projectile-like fragment which is
estimated to be approximately 97% of the beam velocity [Blu86, Bor86]. In the lower graph a clear ring can been seen around the projectile-like fragment velocity (the circle is plotted to guide the eye). It should be noted that it is important to select a specific projectile-like fragment since the difference in Coulomb barrier and velocity for the different PLFs would diffuse the effect.

In figure 5.7 the energy distribution of the light charged particles in the PLF center of mass is plotted. The results of a Maxwellian-fit to the data are shown in the figure. The temperature (T) can be converted to the excitation energy (E*) by the following expression: 

\[ T = \sqrt{\frac{8E^*}{A_{plf}}} \]

where \( A_{plf} \) is the value taken for the level-density parameter. The obtained excitation energy of the system, \( E^* = 69 \text{ MeV} \), is in good agreement with the expected values around 60-70 MeV [Ste89]. The fitted Coulomb barrier, \( V_C = 1.84 \text{ MeV} \), is much smaller than the expected value (\( V_{calc} = 5.57 \text{ MeV} \)). However, it is assumed that the PLF moves along the beam direction and deviations from this due to recoils, resulting from the emission of light charged particles, are ignored. This effect will cause a spread in the detection angle and therefore introduce tails on the low and high energy side. Furthermore a dip can be seen in the spectrum compared to the fit. An explanation for this can be found when looking at the spectra for the small and big detectors separately (the dotted and dashed spectra in the figure). This “dip” region corresponds to the transition region from the small to the big detectors. The acceptance in this region is smaller and therefore the yield is underestimated.

5.1.5 Projectile-like fragments

Projectile-like fragments were measured with the GANIL spectrograph at three rigidity settings: 91%, 96% and 105% of the beam rigidity, respectively. In figure 5.8 the fragment distributions are shown for all three rigidity settings. Note that the most likely velocity of the projectile-like fragment is approximately 97% of the beam velocity [Blu86, Bor86]. Thus, a rigidity setting less than 97% will select proton-rich fragments while a rigidity setting greater than 97% will select neutron-rich fragments. From these figures one can draw a number of conclusions:

1. Although the spectrograph was set to observe proton rich fragments (N-Z<0) in the first setting, the actual fragment distribution is in fact neutron rich. This is presumably a result of the isotope matching of projectile and target. Since the projectile is symmetric and the target has an N/Z ratio of 1.45 the produced fragments will be mainly neutron
Results

rich. In the last setting, where neutron rich fragments are selected, indeed a clear neutron rich fragment distribution is measured.

2. The distributions are narrow in N-Z and broad in mass. Model calculations show that this is caused by the light particle evaporation which tends to draw the nuclei to the valley of stability.

3. Finally one can also observe in this figure (specially for the second setting) that for the α-nuclei \(^{28}\text{Si}, \ ^{32}\text{S}, \ ^{36}\text{Ar}, \text{etc.}\) peaks occur in the fragment distribution. This is a consequence of the strongest binding of the α-type nuclei (see also the previous point).

Figure 5.8: Inclusive projectile-like fragment distribution for the three measured rigidity settings, 91%, 96% and 105% of the beam rigidity, respectively. The spectra have been normalized with respect to the cross section.

The velocity distribution for all projectile-like fragments is shown in figure 5.11 for all three rigidity settings: 0.91% (dashed curve), 0.96% (full curve) and 1.05% (dotted curve). Note that the proton rich fragments are plotted on a much smaller scale. From these pictures one can conclude that with the three measured rigidity settings most of the dynamic range of the projectile-like fragments is covered. In figure 5.9 the velocity distribution for the \(^{28}\text{Si}\) projectile-like fragment is shown together with a Gaussian fit of the distribution. A momentum width of \(\sigma_p = 250\ \text{MeV}/c\) is obtained. Assuming a Goldhaber momentum width, one can calculate the mean square momentum \(\sigma_0^2\) by making use of equation 2.10. The value thus obtained for
5.1 Inclusive data

Figure 5.9: *Velocity distribution of the $^{28}$Si projectile-like fragment. The data for all three rigidity settings has been combined. The curve represents a Gaussian fit to the data.*

$\sigma_0 = 99$ MeV/c comparing well to the value $\sigma_0^{\text{calc}} = 118$ MeV/c used for the model calculations in section 2.2.

Figure 5.10: *Inclusive primary projectile-like fragment distribution for the three measured rigidity settings, 91%, 96% and 105% of the beam rigidity, respectively. The spectra have been normalized with respect to the cross section.*
After the reconstruction procedure has been applied to the data (see the previous chapter for details) one obtains the primary projectile-like fragment distributions. These are shown in figure 5.10, again for all three rigidity settings. The most striking difference after the reconstruction is the large spread in $N-Z$ which is a result of the evaporation effect as explained above. Also the $\alpha$-nuclei can not be distinguished anymore in this plot. It is not completely clear whether this is an effect of the resolution of the reconstruction method which might wash out these structure effects, or whether the origin of this structure indeed lies in the light-particle evaporation.
Figure 5.11: *Velocity distribution for all detected projectile-like fragments.* The data for the three rigidity settings, 91%, 96% and 105%, are represented by the full, dotted and dashed curve, respectively.
5.2 Exclusive data

5.2.1 Photon energy spectra

The photon spectrum shown in figure 5.12 was obtained by requiring a projectile-like fragment in coincidence and it therefore selects peripheral reactions. For this spectrum a corrected (see subsection 5.1.1) inverse slope parameter of $E_0 = 12.0 \pm 0.1$ MeV is found. The fact that this value is smaller than the slope parameter from the inclusive data ($13.4 \pm 0.1$) can be understood if one considers that the energy of the photon is directly correlated to the energy available in the center of mass of the two colliding nucleons. This center of mass energy consists of the beam energy and the respective Fermi energies of both nucleons. For peripheral reactions the average Fermi
energy of the nucleons is less than for central reactions. Therefore, on the average the energy available in the center of mass is smaller for peripheral reactions than for central reactions and thus the photon energy is smaller. This dependence on impact parameter should appear also when plotting the inverse slope parameter as a function of the mass of the primary projectile-like fragment (figure 5.13).

\[ E_0 = 13.71 \pm 3.13 - (0.07 \pm 0.1) \times A_{\text{PPLF}} \]

**Figure 5.13:** Dependence of the inverse slope parameter \((E_0)\) on the mass of the primary projectile-like fragment.

In figure 5.13 an increase of the inverse slope parameter with a decreasing primary projectile-like fragment mass can be seen, which is in agreement with the discussed behaviour and with results from previous works [Rie92, Mar94a]. However, due to the limited range of fragments measured (peripheral events were selected) and the lack of sufficient statistics, no definite conclusion about the mass dependence can be drawn. A constant value of \(E_0\) would also be in agreement with the data.
5.2.2 Photon angular distribution

In figure 5.14 the exclusive photon angular distribution is shown. A fit of the angular distribution with the parametrization as given in subsection 5.1.2 yields a value $\beta_s = 0.150 \pm 0.005$ for the source velocity of the emitting frame and a value of $\alpha = -0.02 \pm 0.05$ for the anisotropy. In subsection 5.1.2 the source velocity of the nucleon-nucleon center of mass for the $^{36}$Ar + $^{159}$Tb system at 44 MeV/nucleon is calculated to be $\beta_{\text{beam}} = 0.151$. And also for the exclusive data we find that the source velocity of the hard photon source is equal to that of the nucleon-nucleon center of mass supporting the generally accepted picture that the hard photons originate from individual nucleon-nucleon collisions.

**Figure 5.14:** The photon angular distribution. The full curve represents a source velocity fit to the data, whereas the dashed curve is a fit through the data with a fixed anisotropy parameter (this is explained in greater detail in the text).
The anisotropy parameter $\alpha$ is found to be consistent with zero. This fact seems to contradict the picture described in subsection 1.3.2 where it was assumed that the angular distribution consists of an isotropic and a dipole component. However, it should be noted that the source velocity $v$ is not sensitive to $\alpha$. The dashed curve in figure 5.14 shows a fit for which the anisotropy parameter has been fixed at a value of 0.15, a typical value for $\alpha$ quoted in previous works [Sch94, Mar94, Mar94a]. As can be seen from the comparison between the full and the dashed curve, the angular distribution is only at small angles sensitive to the anisotropy. Our observation therefore relies on the validity of the first data point. More conclusive evidence for the absence of a dipole component can be found when measuring at even smaller angles.

### 5.2.3 Projectile-like fragments

In figure 5.15 the velocity distribution of the $^{28}$Si projectile-like fragments measured in coincidence with a photon is shown (lower figure). For comparison also the velocity distribution for the inclusive data is plotted (upper figure). In this picture the data for all three spectrograph settings has been combined.

From this figure one can conclude that for the inclusive data (upper figure) as well as for the coincidence data all projectile-like fragments are detected with an exception for those fragments that have a velocity equal to the beam velocity (the gap in the velocity distributions). Therefore, the ratio of the coincident and the inclusive yield, which will be calculated in the following section, is not biased by the selection on the projectile-like fragments.

Furthermore one can see that the velocity distribution for fragments detected in coincidence with a photon peaks at a slightly lower velocity compared to the inclusive velocity distribution. The difference in velocity is $\Delta v = 0.13$ cm/ns which corresponds to an energy difference of 36 MeV. This is consistent with the fact that the produced photon takes away at least 30 MeV.

### 5.2.4 Photon multiplicity

In subsection 1.3.4 the definition of the photon multiplicity already has been introduced. The photon multiplicity will be determined as a function of the mass of the primary projectile-like fragment. It is defined by
**Results**

![Graph](image.png)

**Figure 5.15:** Velocity distribution of the $^{28}$Si projectile-like fragment. The data for all three rigidity settings has been combined. The upper picture shows the inclusive spectrum while the lower picture shows the coincidence spectrum.

$$M_\gamma(A) = \frac{\sum Z N_{\gamma\text{-coincidences}}(A, Z)}{\sum Z N_{\text{singles}}(A, Z)} \quad (5.5)$$

Note that the primary projectile-like-fragment reconstruction procedure for the yield in equation 5.5 has been done independently for the nominator and the denominator, so that the lower excitation energy expected when a photon is emitted does not influence the result.

The photon multiplicity for all rigidity settings is shown in figure 5.16 as a function of the mass of the primary projectile-like fragment. Two regions can be distinguished in this figure, the region to the left of the projectile mass ($A_p = 36$) where the projectile has lost mass and the right region where the projectile has gained mass. We will refer to these regions as stripping and pick-up, respectively. The first point of interest in this figure is the linear
dependence of the photon multiplicity on the removed mass confirming the importance of two-body dissipation. The photon production probability per removed (or added) nucleon is given by the slope of the photon multiplicity.

\[ P_\gamma = \frac{dM_\gamma(A)}{dA} \] (5.6)

Which gives a value for the photon production probability per removed nucleon of \( P_\gamma^- = (1.08 \pm 0.03 \pm 0.27) \times 10^{-6} \); the minus index stands for stripping. The first error quoted is the statistical error and the second error quoted is the systematic error due to the reconstruction procedure. For the pick-up branch the photon production probability is much larger. A value of \( P_\gamma^+ = (2.85 \pm 0.07 \pm 0.34) \times 10^{-5} \) has been obtained, where the plus stands for pick-up. Before discussing the origin of the difference between the two

**Figure 5.16:** Photon multiplicity as a function of the mass of the primary projectile-like fragment.
Results

photon production probabilities we can compare them to the systematics by making the assumption that the number of nucleon-nucleon collisions is equal to the transferred mass. In addition two modifications are needed:

1. The photon production probability per removed (added) nucleon has to be converted to a probability per pn-collision. For this the conversion as described in chapter 1 is used.

\[ P_{\gamma,\text{pn}} = \frac{A_p A_t}{Z_p N_t + Z_t N_p} P_\gamma = 2P_\gamma \] (5.7)

2. To compare to the inclusive systematics the photon production probability has to be corrected for the \( E_0 \) dependence. Making use of the fact that \( P_\gamma \propto \exp(-E_t/E_0) \) one can derive the equivalent inclusive photon production probability as \( (E_t = 30 \text{ MeV}) \)

\[ P_{\gamma,\text{eq.in}} = \frac{\exp\left(\frac{-E_t}{E_0^{+}}\right)}{\exp\left(\frac{-E_t}{E_0^{+}}\right)} P_{\gamma}^{\text{pm}} = 1.30 P_{\gamma}^{\text{pm}} \] (5.8)

In the following we will omit the correction indices, so \( P_{\gamma}^{+} \) and \( P_{\gamma}^{-} \) refer to the values that have been corrected in the above-mentioned way. These values are shown in figure 5.17 next to the inclusive data point (see insert). The difference between the photon production probability for stripping and pick-up can be explained in terms of the different contributions of one- and two-body dissipation to both processes. In section 5.3 it will be shown that the mean field (one-body dissipation) causes a net drift of nucleons from projectile to target i.e. on the average nucleons are removed from the projectile. For two-body dissipation there is no preference for the direction where the nucleons go. Therefore adding nucleons to the projectile is always associated with a two-body dissipation mechanism while removing nucleons from the projectile can be attributed to one- and/or two-body dissipation. Subsequently there will be more photons associated with the reaction channels contributing to the pick-up branch than to the stripping branch and also the photon production probability for pick-up will be larger than that for stripping.

In figure 5.18 the results for all three spectrograph settings \( (B\rho = 91\%, 96\% \text{ and } 105\% \text{ of the beam rigidity}) \) are shown separately. From this figure one can conclude that all three investigated settings exhibit the same dependence of the multiplicity on the primary projectile-like fragment mass.
5.2 Exclusive data

Figure 5.17: Systematics of the photon production probability per pn-collision, including the exclusive probabilities measured for stripping and pick-up (see inset).

The values obtained for the photon production probabilities are listed in table 5.3. From the values for $P^-_\gamma$ and $P^+_\gamma$ obtained from the first two settings, one can conclude that these values are independent of the spectrograph setting. The last setting gives lower values for both photon production probabilities. But in this setting the spectrograph detectors could not be completely shielded from the beam which means that the spectrograph data were partly contaminated and therefore certain isotopes, mainly for $Z>17$, ...
could not be detected. Due to this deficiency also the statistics is very poor for the third setting and we will base our conclusions mainly on the first two settings.

**Table 5.3:** *Results for the photon production probabilities for all three rigidity settings.*

<table>
<thead>
<tr>
<th>$B\rho$</th>
<th>$P_{\gamma^-}$ ($10^{-5}$)</th>
<th>$P_{\gamma^+}$ ($10^{-5}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>all</td>
<td>2.82±0.07</td>
<td>7.40±0.19</td>
</tr>
<tr>
<td>0.91</td>
<td>2.76±0.16</td>
<td>7.16±0.34</td>
</tr>
<tr>
<td>0.96</td>
<td>2.73±0.19</td>
<td>6.57±0.43</td>
</tr>
<tr>
<td>1.05</td>
<td>2.08±0.21</td>
<td>5.06±0.75</td>
</tr>
</tbody>
</table>

At this point it is important to note that the reconstruction of the primary projectile-like fragment is essential in deriving the values for the photon production probability. This argument is supported by figure 5.19 where the photon multiplicity is plotted as a function of the mass of the detected projectile-like fragment, i.e. the light-particle evaporation is ignored. Also from these figures values for $P_{\gamma^-}$ can be obtained as indicated by the solid curve (the values are listed in table 5.4). However, two important aspects need to be considered: the obtained photon production probability for strip-
Figure 5.19: Photon multiplicity distributions for all three spectrograph settings when no reconstruction of the primary projectile-like fragment is done.

ping is 2.5 times smaller than the value obtained for the reconstructed, primary projectile-like fragment. Although for this method an almost linear dependence of the photon multiplicity on the fragment mass is obtained, the value for the photon production probability is severely underestimated by relying only on the measured masses. Furthermore, it is not possible to extract values for $P_\gamma^+$ as pick up does not survive the evaporation stage.

Table 5.4: Results for the photon production probabilities, when no reconstruction is done, for all three rigidity settings. For completeness the values for the photon production probability when the mass has been reconstructed are added in the table.

<table>
<thead>
<tr>
<th>$B\rho$</th>
<th>without reconstruction $P_\gamma^- (10^{-5})$</th>
<th>with reconstruction $P_\gamma^- (10^{-5})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>all</td>
<td>1.09±0.02</td>
<td>2.82±0.07</td>
</tr>
<tr>
<td>0.91</td>
<td>1.12±0.15</td>
<td>2.76±0.16</td>
</tr>
<tr>
<td>0.96</td>
<td>1.07±0.16</td>
<td>2.73±0.19</td>
</tr>
<tr>
<td>1.05</td>
<td>1.14±0.16</td>
<td>2.08±0.21</td>
</tr>
</tbody>
</table>

Photon production probabilities in peripheral reactions can also be calculated from data obtained in previous work. In figure 5.20 the multiplicity
distributions are shown from two previous experiments [Rie92, Mar94a]. A direct comparison of the absolute values for $P^-_{\gamma}$ is difficult since the systems and beam energies are different. Therefore, we will compare for each experiment the values for $P^-_{\gamma}$ and $P^{pn}_{\gamma}$. In table 5.5 these values are listed, together with the measured system. From this table one can see that the measured value of $P^-_{\gamma}$ is always smaller than the inclusive photon production probability $P^{pn}_{\gamma}$. For the last two experiments listed, the ratio is approximately 1.7. Considering the error bars, the first experiment does not contradict this conclusion. The large difference between the results for the two Ar-experiments, which are performed at the same beam energy per nucleon, can be explained by considering that in the Ar + Gd experiment a photon threshold of 25 MeV was used, while the threshold was 30 MeV in the Ar + Tb experiment. Furthermore, the value of $P^-_{\gamma}$ is scaled with the inclusive inverse slope parameter $E_0$ obtained from the inclusive data (see the correction procedure above) in order to compare it with the inclusive value. Therefore the result is very sensitive to $E_0$ which in the Ar + Gd experiment was determined with a large uncertainty.

Figure 5.20: Photon multiplicity distribution taken from previous work by Riess et al. [Rie92] and Martínez et al. [Mar94a]. The dashed line is the result of the fit to the data and the arrow indicates the mass of the projectile.
Table 5.5: Comparison of $P^m_\gamma$ and $P^-_\gamma$ for different experiments.

<table>
<thead>
<tr>
<th>system</th>
<th>$P^m_\gamma (10^{-5})$</th>
<th>$P^-_\gamma (10^{-5})$</th>
<th>ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{30}\text{Ar} + ^{158}\text{Gd}$ (44 MeV/nucleon)</td>
<td>17.7 ± 7.</td>
<td>12.1 ± 4.</td>
<td>1.46 ± 0.48</td>
</tr>
<tr>
<td>$^{86}\text{Kr} + ^{nat}\text{Ni}$ (60 MeV/nucleon)</td>
<td>12.0 ± 0.9</td>
<td>7.46 ± 0.15</td>
<td>1.61 ± 0.12</td>
</tr>
<tr>
<td>$^{96}\text{Ar} + ^{159}\text{Tb}$ (44 MeV/nucleon)</td>
<td>5.20 ± 0.05</td>
<td>2.82 ± 0.07</td>
<td>1.88 ± 0.19</td>
</tr>
</tbody>
</table>

5.2.5 Photon multiplicity for different N–Z

In the previous subsection the photon multiplicity is shown as a function of the primary projectile-like fragment mass averaged over all (N–Z). It is very interesting to study the (N–Z)-dependence of the photon multiplicity and production probability since this might be directly correlated to the N/Z-ratio of projectile and target. It should be noted that the (N–Z)-dependence is very sensitive to the reconstruction method since this method has to fully correct for the neutron evaporation which directly influences the (N–Z) dependence.

Table 5.6: Results for the photon production probabilities for different values of N–Z.

<table>
<thead>
<tr>
<th>N–Z</th>
<th>$B\rho=0.91$</th>
<th>$B\rho=0.96$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P^-_\gamma (10^{-5})$</td>
<td>$P^-_\gamma (10^{-5})$</td>
</tr>
<tr>
<td>-3</td>
<td>2.21±0.47</td>
<td>2.33±0.66</td>
</tr>
<tr>
<td>-2</td>
<td>2.51±0.32</td>
<td>2.37±0.40</td>
</tr>
<tr>
<td>-1</td>
<td>3.26±0.27</td>
<td>2.88±0.33</td>
</tr>
<tr>
<td>0</td>
<td>2.90±0.27</td>
<td>2.78±0.31</td>
</tr>
<tr>
<td>1</td>
<td>2.03±0.27</td>
<td>1.71±0.40</td>
</tr>
<tr>
<td>2</td>
<td>1.69±0.49</td>
<td>2.28±0.50</td>
</tr>
<tr>
<td>3</td>
<td>2.22±0.76</td>
<td>3.04±0.60</td>
</tr>
</tbody>
</table>

In figures 5.21 and 5.22 the photon multiplicity is plotted for values of N–Z ranging from −3 to 3. The fitted values for $P^-_\gamma$ and $P^+_\gamma$ are listed in table 5.6. The data are shown for the first two rigidity settings (0.91% and 0.96%) only, since the statistics of the last setting does not allow this analysis. A clear dependence of the photon production probability on the value of (N–Z) can be recognized. For the proton-rich isotopes (N – Z < 0)
Figure 5.21: Photon multiplicity distribution for different values of $N-Z$ for the first setting ($B_\rho = 0.91$). The full lines are fits to the data whereby it is assumed that the minimum lies at $A = 36$.

A clear asymmetry is found between the photon production probability for stripping and pick-up, while for the neutron-rich isotopes the behaviour is symmetric and nearly flat.

This is shown in greater detail in figure 5.23 where the ratio of the photon production probability for pick-up and stripping is plotted as a function of $(N-Z)$. The dotted curve is the ratio for the case when no isotope selection
has been made. In the following reasoning two assumptions are made which will be justified afterwards. It is assumed that the bremsstrahlung photons originate from proton-neutron collisions (and not from neutron-neutron or proton-proton collisions) and that there is a net drift due to the one-body dissipation from projectile to target. Based on this, figure 5.23 can be understood in the following way:

1. As has been argued in the previous section, the removal of nucleons
from the projectile can be caused by a one-body and/or a two-body mechanism while the pick-up of nucleons by the projectile is mainly due to two-body dissipation. Consequently there will be more photons associated with the pick-up channels than with stripping channels since the photons originate from nucleon-nucleon collisions (two-body dissipation). The result of this is that \( P^+_{\gamma} \) will always be greater than or almost equal to \( P^-_{\gamma} \).

2. Since the target (\(^{159}\)Tb) is neutron rich and the projectile is symmetric there will be relatively more pn-collisions in which the proton comes from the projectile than from the target. Thus, there will be a larger chance to add a neutron to the projectile than a proton. Turning the argument around, in order to add a proton to the projectile more pn-collisions are needed. This is indeed what is observed in figure 5.23, the proton-rich isotopes show a larger ratio of \( P^+_{\gamma} \) to \( P^-_{\gamma} \) than the neutron-rich isotopes. If no isotope selection is done one would expect an average behaviour as indicated by the dotted line. The value is obtained from the ratio of \( P^+_{\gamma} \) to \( P^-_{\gamma} \) in figure 5.16.

![Figure 5.23: Ratio of the photon production probability for pick-up and stripping as a function of N-Z for two different rigidity settings. The dashed line represents the ratio when no selection is made on N-Z.](image)

The second argument justifies the assumption that hard photons originate from proton-neutron collisions. If this were not the case there would have been no difference in the photon multiplicity between proton-rich and
neutron-rich isotopes. Our data thus support the assumption that proton-neutron collisions are, for these energies, the main source of the hard photons. The other assumption, the net drift to the target, will be discussed on basis of model calculations in section 5.3.

5.3 BUU results

In this section the results of the performed BUU calculations will be presented and used to interpret the experimental results. However it is important to note some limitations of the calculations first.

1. The BUU model is a deterministic model, i.e. given the initial phase space density the model will produce one single trajectory. Thus, the BUU calculations can not predict the pick-up branch as observed in the photon multiplicity spectra, which can be viewed upon as fluctuations with respect to the average trajectory. Recently transport models are under development that include these fluctuations (see e.g. [Bur95, Ran94, NPA545] and figure 5.24).

2. Due to the semi-classical nature of the BUU model the nuclei will disintegrate, given sufficient time. Therefore we defined that the reaction stops after 75 fm/c (the time at which the projectile has passed the target).

3. The nature of the model does not allow the definition of a projectile-and target-like fragment. For the present calculations a simple geometrical cut was used to identify those nucleons belonging to the projectile-like fragment.

5.3.1 One-body dissipation

Nucleons that move from projectile to target or vice versa and do not collide dissipate their energy via a one-body mechanism. In figure 5.25a the number of transferred nucleons from projectile to target and vice versa is plotted as a function of impact parameter in the absence of collisions. This figure reveals a preference of mass transfer from the projectile to the target. The transfer is shown separately for protons and neutrons in figure 5.25b. This figure shows only a small difference in the number of transferred protons and neutrons when going from projectile to target while for the other direction the transfer of neutrons is preferred. This observation reflects the fact that the projectile has an equal number of protons and neutrons while the target
Figure 5.24: Time evolution of the one-particle phase-space density $f$ for three different treatments of the dynamics. The left figure shows a pure one-body model (there are no collisions), the middle figure shows the treatment of the BUU model (after every time step the ensemble averaged mean field is calculated) and the right figure shows a true dynamical treatment according to the Boltzmann-Langevin theory. The figure is taken from ref. [Ran94]

has many more neutrons (94) than protons (65). The explanation for the preference of transfer to the target can be found in the driving force of the mean field. In figure 5.26 the average potential energy is plotted as a function of time. The full line is the average over protons and neutrons, the dashed and dotted line are the potential energies for protons and neutrons, respectively.

It can be seen that the potential energy of the target nucleons is only very little modified due to the contact of projectile and target while the potential energy of the projectile nucleons changes drastically. Furthermore, a nucleon moving from target to projectile has to cross a high energy barrier while for
5.3 BUU results

Figure 5.25: The left figure (a) shows the number of nucleons transferred from target to projectile and vice versa without collisions (one-body dissipation) as a function of the impact parameter. In the right figure (b) the mass transfer has been drawn separately for protons and neutrons.

the nucleons moving from projectile to target this is much lower. The origin of the different potential barriers lies in the different volume-to-surface ratios of projectile and target and offer an explanation for the net drift of nucleons to the target: in the surface region nucleons feel a weaker potential.

5.3.2 Two-body dissipation

One can now consider only those nucleons that collided at least once and see whether also these nucleons have a preference to go from projectile to target. In figure 5.27a the number of nucleons that have collided at least once is shown as a function of impact parameter and for the transfer from projectile to target and target to projectile separately. Again we observe a clear preference for transfer to the target. However, one has to consider that the drift of nucleons from projectile to target is larger than vice versa (see previous subsection). Therefore, integrated over the collision time, there will be more projectile nucleons in the overlap zone than there are target nucleons. Assuming that after the collision both particles have a random direction one would still observe a net preference for nucleons to go from projectile to target. In figure 5.27b the transferred nucleons have been separated into protons and neutrons. As already seen in the previous subsection,
Figure 5.26: The full line shows the average potential energy as a function of time for nucleons that moved from projectile to target (top) or vice versa (bottom) without collisions, the dashed and dotted lines show this dependence for protons and neutrons, respectively.

also here the difference in N/Z-ratio of projectile and target can clearly be seen.

5.3.3 Interpretation of the BUU results

As indicated in the beginning of this section BUU does not include fluctuations and, therefore, predicts only the trend of the processes playing a role. The interpretation of the data in terms of the BUU results should thus be treated with care. From the BUU calculations one can draw the following conclusions:

1. BUU predicts a net drift of nucleons from the smaller projectile to the heavier target. This is in agreement with models used at energies much smaller than the Fermi energy, that predict a net drift caused by the different volume-to-surface ratios of projectile and target.

2. In figure 5.27 a nearly linear dependence is shown of the number of transferred nucleons that have collided on the impact parameter. This
5.3 BUU results

![Graph showing nucleon transfer](image)

**Figure 5.27:** The left figure (a) shows the number of nucleons transferred from target to projectile and vice versa with collisions (two-body dissipation) as a function of the impact parameter. In the right figure (b) the mass transfer has been drawn separately for protons and neutrons.

3. Considering the first point, BUU can only predict the "stripping" branch of the measured data. The "pick-up" branch, therefore, is a manifestation of statistical fluctuations along the average trajectory. This also supports the interpretation of the difference between the photon production probabilities for pick-up and stripping as given in subsection 5.2.4 where it was said that adding nucleons to the projectile is associated with two-body dissipation (collisions) while removing nucleons from the projectile can either be attributed to one- or to two-body dissipation.