CHARGE EXCHANGE OF VERY HEAVY IONS IN CARBON FOILS
AND IN THE RESIDUAL GAS OF THE GANIL CYCLOTRONS

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**Abstract**

The results of several years of operation with heavy to very heavy ions in the GANIL accelerators, along with specific measurements concerning stripping through carbon foils, led to a set of valuable recipes for predicting the charge state distributions generated by the accelerators. A series of measurements was also set up to evaluate the beam losses during acceleration in the three cyclotrons; with the help of existing models for charge exchange cross-sections, it is shown that vacuum requirements can be fairly accurately determined.

1. **Introduction**

Since the O.A.E. modification of GANIL, an extensive list of ions, ranging from carbon to uranium, have been routinely accelerated; the energy domain for each of the three cyclotrons is large enough to cover a wide range. The charge state distributions at the output of SSCI and SSC2, is shown on figure 1. The charge state Q obtained with the ECR source cover a wide range, reaching Q = 24 for uranium ions. These beams are accelerated in CO and SSC1 before being stripped by a carbon foil previous to their injection in SSC2.

The charge state Q2 to be accelerated after the stripper has to be chosen between narrow limits due to the constraints imposed by the RF frequency (which is common to the two SSCs), the ratio of their harmonic numbers (h1/h2 = 2.5) and the available range of magnetic field levels; if for example, the field levels are identical in both SSC1 and SSC2, the stripping ratio Q1/Q2 has to be exactly equal to h1/h2 = 2.5.

This ratio was chosen as optimum for the acceleration of heavy ions on the basis of prediction formulas for the stripping process; some discrepancies for the heavy ions led us to measure the charge state distributions generated by Ar, Ni, Kr, Xe, Gd, Ta, Pb and U traversing carbon foils in the 3.8 to 10.6 MeV/amu energy range, and eventually to correct the predictions.

The combination of high charge states with low velocities and a long path leads to beam losses by charge exchange with the molecules of the residual gas when the pressure in the machines is not suitable low; transmission measurements were achieved for Xe, Pb and U ions. The comparison of the results with semi-empirical cross-section estimates proposed by Betz and Schmelzer allows rather accurate predictions, at least for the velocities corresponding to the first two stages of the machine.

2. **Charge state distributions**

2.1. **Previous state of the art**

Since the beginning of operation of GANIL, we had used a home-made formula to predict the average charge state Q of heavy ion beams traversing carbon foils thick enough for the distributions P(Q) to reach equilibrium:

\[
\bar{Q} = Z_i (1 - C \exp (-83.275 \beta / Z i^{0.7}))
\]

where \(Z\) is the projectile atomic number, \(\beta\) is its velocity with respect to that of light, \(C = 1\) for energies \(W > 1.3\) MeV/amu and \(C = 0.9 + 0.0769 W\) below this limit.

Supposing that no significant shell effect is present and that \(Q\) is not too close to \(Z\), the distributions are assumed to be gaussian with a standard deviation \(d\) as proposed by Nikolaev and Dmitriev:

\[
d = 0.5 \left( \frac{\sqrt{Q(1-Q/Z)^2}}{Z} \right)
\]

Up to krypton, this prediction was accurate enough for preparation of the machine operation; however, when GANIL became able to accelerate high atomic number elements, it appeared that the available intensities after stripping were not as expected; therefore, a series of measurements was undertaken.

2.2. **Experimental set-up**

No specific device was designed to measure the charge state distributions at the output of SSCI: the existing beam lines are adequate enough to permit a good analysis of the spectra, either with the charge separator located just behind the stripper or with the high resolution spectrometer which can be reached through a short cut allowing the beam to skip SSC2. The upstream beam intensity is measured by a non-interpretative capacitive monitor calibrated versus a conventional Faraday cup and used as a monitor; the stripped beam components are measured one at a time by a second Faraday cup located after the analyser, while a third one which can be inserted just behind the carbon foil is used as a cross-check for the intensity of the total distribution.

In all cases, carbon was used as a stripper and the incoming and outgoing energies were precisely measured with the spectrometer, allowing the estimate of the thickness within a few \(\mu\) g/cm\(^2\). In some occasions, different thicknesses were used to determine the equilibrium value.

2.3. **Results**

The results are presented in tables 1 to 7 for Ar, Ni, Kr, Xe, Gd and Pb (two other results related to Xe and Ta were already published in [12]); the mean charge \(Q_m\) and the second moment \(d_m\) of the experimental distributions are calculated as usual by:

\[
\bar{Q}_m = \frac{\sum Q F(Q)}{\sum F(Q)} \quad \text{and} \quad d_m = \frac{\sum (Q - \bar{Q}_m)^2 F(Q)}{\sum F(Q)}
\]

only for the thickness which is considered as sufficient for equilibrium so settle. The measurements concerning U ions
are not shown in the tables, because the maximum magnetic rigidity of the analysers is too low to reach the lower charge states; however, a value of 54 for the mean charge \( \bar{Q} \) was measured at \( W = 3.814 \text{ MeV/amu} \) with a fair accuracy. A comparison between the predicted and the measures values, in mean charge as well as in standard deviation, exhibits differences increasing with the projectile atomic number \( Z \). Therefore, a new fit was performed on the above-mentioned measurements as well as for values from other authors \([5, 6, 7, 8, 9, 10]\), leading to the following correction formulae:

\[
\bar{Q} = \bar{Q}_p \{ 1 \cdot \exp(-12.905 + 0.2124Z - 0.00122Z^2) \}
\]

where \( \bar{Q}_p \) is given by (1) and in the range: \( Z \approx 54, W > 1.3 \text{ MeV/amu} \).

Table 8 shows the results for both the "old" and the "new" predictions, where \( \bar{Q}_p \) is the output energy; apart from the poor agreement for Xe at 1.39 MeV/amu and for Au, which remain unexplained, the mean charge is predicted within at most half a unity and the distribution width within one-third.

3. Beam losses during acceleration

3.1 Estimate of the beam transmission

If only the losses due to charge exchange between the ions and the residual gas are considered, the transmission efficiency \( T \) of any accelerator over a pathlength \( L \) is given by:

\[
T = \exp \left(-2.69 \cdot 10^{-16} \int_0^L \alpha(p) \, dl \right)
\]

where \( p \) is the pressure in mbars, \( dl \) is an element of the pathlength in cm and \( \alpha \) is the sum of all the relevant capture and loss cross-sections (in \( \text{cm}^2/\text{molecule} \)); these cross-sections, which depend not only on the velocity, but also on the atomic number and charge state of the projectile as well as on the nature of the target (residual gas) are unknown and it is therefore necessary to rely on some reasonable estimate.

Betz and Schmelzer\[^{[3]}\] approximated the cross section for capture of one electron in a gas like \( \text{N}_2 \) or air by:

\[
\sigma_{0,0,1} = 2.10^{-15} Q^3 (137\beta)^2 \exp(-Q(-0.25 + 0.32 W - 0.14 W^2 - 6.1 \cdot 10^{-17}))
\]

with the mean value \( \bar{Q} \) approximated by:\[
\bar{Q} = Z \{ 1 \cdot \exp(-137\beta) \}
\]

where \( C = 1 \) has a very weak dependence on \( Z \), \( \delta = 0.3443 - 0.667 \log(Z) \) and with the standard deviation given by: \( \delta = 0.27 \sqrt{Z} \).

Using just the sum: \( \sigma_{0,0,1} + \sigma_{0,0,1} \) as \( \sigma \) this model was found to be in fair agreement with Erb's measurements\[^{[7]}\] on cross-sections for Kr, Xe, Pb and U for \( 0.2 < W < 1.4 \text{ MeV/amu} \). In addition, we fitted Erb's values (with \( \text{Ar} \) as the residual gas) by an empirical law:

\[
\sigma = 6.1 \cdot 10^{-17} \exp(-Q(-0.25 + 0.32 W - 0.14 W^2 - 0.0123 W^3))
\]

in order to get easier comparison with our transmission measurements.

For higher energies, Franzke\[^{[11]}\] proposed analytical formulas extrapolated to \( W = 100 \text{ MeV/amu} \).

With these models in hand, it is easy to calculate the integral of equation (5) along the path in any cyclotron, given the following characteristics: input and output energy, number of accelerating gaps along with their energy gain, and extraction radius.

3.2 Experimental method

For each cyclotron, the method is the same: shutting one or several valves, between the pumps and the vacuum chamber, the pressure increases due to outgassing with little variation in the composition of the gas, as was controlled with a gas analyser; at intervals, the pressure and the intensities of cyclotron input and output beams are measured simultaneously. Plotting the ratio of the variation in the two currents versus pressure leads to extrapolation to the ultimate cyclotron yield if the vacuum were perfect and therefore provides the normalisation factor for the beam transmission.

The question of proper pressure measurements must be treated separately for the injector and the two SSC. In the first case, the reference gauge (Bayard-Alpert type) is located in a region of reduced fringe field: therefore, measurements were made without magnetic field with a gauge located at the center of the cyclotron and indicated readings about half the values of the reference. For the SSC, an average was made on the readings of the four gauges located in the valleys, followed by a correction for partial pressures.

3.3 Results

A series of measurements was carried out with \( \text{Xe}^{18+}, \text{Pb}^{23+} \) and \( \text{U}^{24+} \) in the injector, \( \text{Pb}^{23+} \) in SSCI and \( \text{Pb}^{56+} \) in SSC2. Some results are illustrated on figures 2 to 4. Concerning the injector, in all three cases, the results lie between the two predictions described above. At energies higher than 1.4 MeV/amu, the fit (8) should not be extrapolated and only the prediction based on the Betz-Schmelzer approximation was used, providing as good agreements for SSCI as for the injector. It is only above 5 MeV/amu that all estimates fail. On figure 6, the estimated pressure for \( \text{Pb} \) ions in SSC2 based on \([11]\) is 5 times higher than indicated by the measurements.

4. Conclusion

In the absence of detailed knowledge on charge exchange cross-sections for heavy ions traversing solids or gases, simple measurements over a wide range of projectile masses and velocities allow predictions which are significant for the design of injectors and boosters in coupled accelerator systems.

Acknowledgements

The authors wish to thank P. Bricault, P. Gudewicz and B. Lenoble for their participation to the various campaigns.
References

### Table 1: Charge state distribution measurements $^{40}$Ar$^{6+}$, $W_1 = 5.62$ MeV/amu

<table>
<thead>
<tr>
<th>Foil thickness (µg·cm$^{-2}$)</th>
<th>Charge State Fraction (%)</th>
<th>$\bar{Q}_m$</th>
<th>$d_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>1.76 13.69 45.40 32.39 6.74</td>
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</tr>
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<td>84</td>
<td>1.26 10.57 39.64 37.86 10.58</td>
<td>16.44</td>
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<tr>
<td>120</td>
<td>0.96 8.17 35.11 40.54 14.92</td>
<td>16.55</td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>0.85 7.95 32.47 42.26 16.78</td>
<td>16.71</td>
<td></td>
</tr>
<tr>
<td>215</td>
<td>0.55 5.53 26.55 43.79 23.59</td>
<td>16.84</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>0.04 3.81 25.70 45.21 25.25</td>
<td>16.92 0.812</td>
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</tr>
</tbody>
</table>

### Table 2: Charge state distribution measurements $^{58}$Ni$^{10+}$, $W_1 = 10.63$ MeV/amu

<table>
<thead>
<tr>
<th>Foil thickness (µg·cm$^{-2}$)</th>
<th>Charge State Fraction (%)</th>
<th>$\bar{Q}_m$</th>
<th>$d_m$</th>
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</thead>
<tbody>
<tr>
<td>130</td>
<td>0.16 1.53 9.92 35.28 46.22 6.59</td>
<td>0.29 25.46</td>
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<tr>
<td>203</td>
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<tr>
<td>232</td>
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<td>269</td>
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<td>320</td>
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<td>349</td>
<td>- 0.16 2.16 18.24 52.34 24.27</td>
<td>2.88 26.08 0.798</td>
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</table>

### Table 3: Charge state distribution measurements $^{86}$Kr$^{13+}$, $W_1 = 7.965$ MeV/amu

<table>
<thead>
<tr>
<th>Foil thickness (µg·cm$^{-2}$)</th>
<th>Charge State Fraction (%)</th>
<th>$\bar{Q}_m$</th>
<th>$d_m$</th>
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</thead>
<tbody>
<tr>
<td>225</td>
<td>1.02 5.51 17.89 33.05 30.86 11.42</td>
<td>0.25 32.22 1.108</td>
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### Table 4: Charge state distribution measurements $^{86}$Kr$^{14+}$, $W_1 = 9.314$ MeV/amu

<table>
<thead>
<tr>
<th>Foil thickness (µg·cm$^{-2}$)</th>
<th>Charge State Fraction (%)</th>
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<tr>
<td>115</td>
<td>8.43 14.10 26.04 29.13 17.76 4.54</td>
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<tr>
<td>168</td>
<td>5.22 17.78 33.65 31.07 12.06</td>
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<td>225</td>
<td>2.00 10.33 28.31 38.52 20.34</td>
<td>0.49 32.66</td>
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<td>300</td>
<td>1.41 8.53 25.61 39.61 23.95</td>
<td>0.89 32.79 0.977</td>
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### Table 5: Charge state distribution measurements $^{129}$Xe$^{18+}$, $W_1 = 6.785$ MeV/amu

<table>
<thead>
<tr>
<th>Foil thickness (µg·cm$^{-2}$)</th>
<th>Charge State Fraction (%)</th>
<th>$\bar{Q}_m$</th>
<th>$d_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>241</td>
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<td>2.38 0.56 43.54 1.631</td>
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<tr>
<td>Foil thickness (µg·cm⁻²)</td>
<td>Charge State Fraction (%)</td>
<td>Qm</td>
<td>dm</td>
</tr>
<tr>
<td>-------------------------</td>
<td>---------------------------</td>
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<td>----</td>
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<td>44</td>
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<td>46</td>
</tr>
<tr>
<td>149</td>
<td>4.43</td>
<td>10.41</td>
<td>16.23</td>
</tr>
<tr>
<td>196</td>
<td>4.51</td>
<td>9.15</td>
<td>16.39</td>
</tr>
</tbody>
</table>

Table 6: Charge state distribution measurements ¹⁵⁷Gd⁺⁹⁺, W_j = 5.465 MeV/n

<table>
<thead>
<tr>
<th>Foil thickness (µg·cm⁻²)</th>
<th>Charge State Fraction (%)</th>
<th>Qm</th>
<th>dm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50</td>
<td>51</td>
<td>52</td>
</tr>
<tr>
<td>170</td>
<td>2.49</td>
<td>5.94</td>
<td>12.14</td>
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<tr>
<td>251</td>
<td>2.47</td>
<td>5.89</td>
<td>11.84</td>
</tr>
</tbody>
</table>

Table 7: Charge state distribution measurements ²⁰⁸Pb²⁺⁺, W_j = 4.575 MeV/amu