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Nuclear two-photon decay of ^{72}Ge

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Abstract

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Abstrakt

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Introduction

From a general blah blah to a more specific, recopilling also the results of all previous experiments

1.1 Mass and lifetime measurements

1.2 Storage ring mass spectrometry

1.2.1 Nuclear isomer studies

1.2.2 Nuclear two-photon decay

Chapter 2

Theoretical framework

2.1 Nuclear structure topics

Nuclear structure topics, focused on deformation and polarizabilities General info about the theoretical models used to reproduced the previous properties

2.1.1 Two-photon decay as a second order perturbation theory

2.2 Ion dynamics at storage rings

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Chapter 4

Results of E143

4.1 Nuclear two-photon decay at a heavy-ion storage ring

4.1.1 Methodology

Cooled IMS?

When we cool the ions by any means, all of them share the same velocity after a certain time. Due to this, it can occur intra-beam scattering due to the Coulomb repulsion between ions of the same specie. Therefore, this sets a limit on how reduced the momentum spread can be reached since where the Coulomb repulsion and the cooling force are in equilibrium. However, in IMS the ions do not share the same orbit, so in principle this limit is removed and theoretically speaking the IMS have more potential for mass spectrometry. Now, if we try to cool the IMS, by definition we are forcing the ions to follow some specific orbit.

What is heavier an isomer or its ground state?

An isomer is heavier since it is a less bounded system, i.e. the binding energy of the system is lower since an isomer is an excited state of the nucleus. We know that the sum of the mass of the constituents is greater than the mass of the system itself. Practically, this means that an isomer will **ever** have a longer revolution time (lower revolution frequency) than its ground state.

For neutral atoms the excited 0^+ state is a rather short-lived isomeric state with a lifetime of the order of a few tens to hundreds of nanoseconds. However, at relativis-

tic energies most of the fragments produced are fully stripped of their atomic electrons when they pass through matter (stripper) [<https://lise.nsl.msui.edu/doc/charge-global.pdf>] and decay by ICE emission is hence not possible. If the state of interest is located below the pair creation threshold the IPC process is not possible either and the lifetime increases considerably [reference]. Consequently, bare nuclei can be trapped in a long-lived isomeric state, which can only decay by 2γ emission to the ground state or by particle emission (alpha or beta decay) for unstable isotopes. Therefore, the experiment was conducted at the accelerator facility GSI, since it is the only facility able to create the ideal conditions for the study of the non-competitive 2γ decay. In this experiment, we studied the stable mid-shell nucleus ^{72}Ge where the excited 0^+ state is located at an excitation energy of 691 keV and hence interpreted as a shape isomer.

The fully stripped ions were produced by in-flight fragmentation from a relativistic (441 MeV/u) ^{78}Kr primary beam against a 1 mm thick Be plate since few-nucleon removal reactions at relativistic energies are known to produce low-lying isomeric states with rather high cross sections [references]. The fragments were separated in the direct connection (TE-)line from the synchrotron accelerator SIS18 to the experimental storage ring (ESR), bypassing the fragment separator (FRS) since we wanted to avoid losing decay events as much as possible. The produced fragments were stored at the ESR where high-precision mass measurements using time-resolved Schottky mass spectroscopy (SMS) [reference] are carried out. However, this method constraints the lifetimes of the isotopes to be at least of the order of seconds due to the needed cooling time. Therefore, in order to be able to study isotopes in the ms regime, we employed the isochronous ion optical setting of the ESR [reference] which was used routinely in the past.

$$\tilde{\Delta}f = -\alpha_p \tilde{\Delta} \left(\frac{m}{q} \right) + (1 - \alpha_p \gamma^2) \tilde{\Delta}v \quad (4.1)$$

The mass spectrometry relation at storage rings is shown in equation 4.1 where we have defined the relative distances as $\tilde{\Delta}x = \Delta x / x(^{72}\text{Ge}^{32+})$. This relation tells us that the distance in frequency of an isotope with respect to a reference particle is linearly proportional to the ion-optical momentum compaction factor times the relative difference of the mass to charge ratio of the studied and reference isotope up to a second term which depends on the relative velocity distance and the Lorentz factor of the reference isotope. This second term is the responsible of the frequency spread, i.e. it is the factor that determines our mass resolving power. In isochronous mass spectrometry we tune the kinetic energy of our reference particle to coincide with $(\alpha_p)^{-1}$, which is known as the transition energy of the ion optical setting.

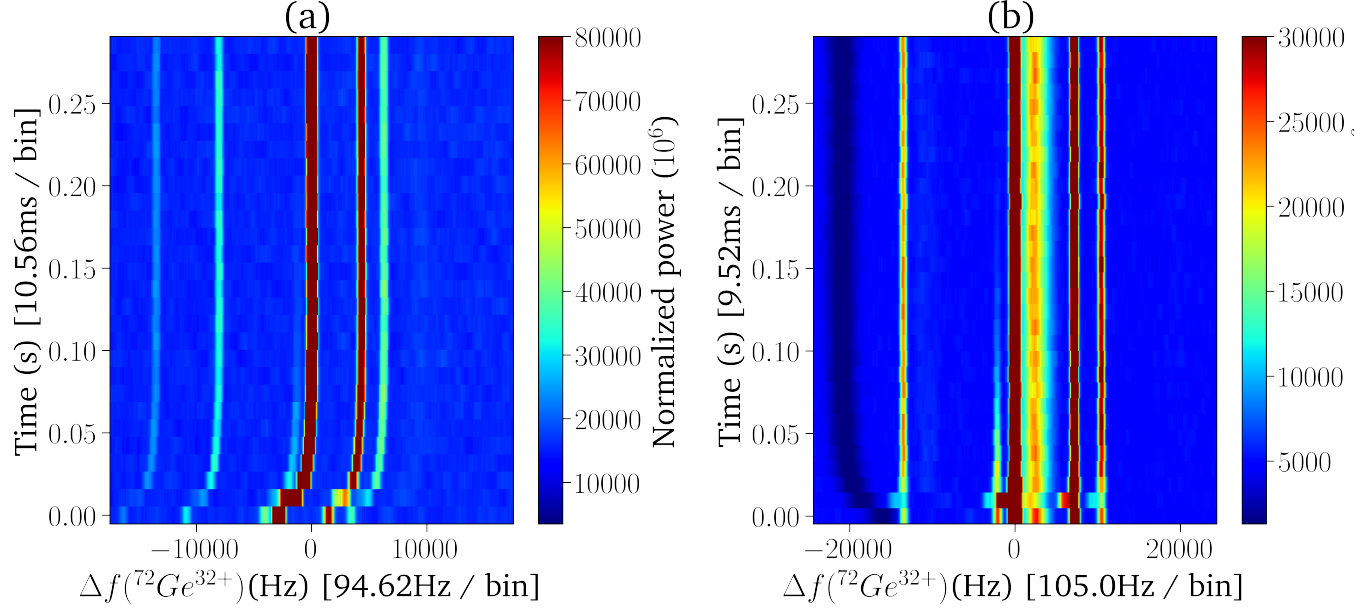


Figure 4.1. (a) Schottky spectrum showing the time evolution of the power for each frequency bin with its corresponding time and frequency resolution in the resonant Schottky cavity working at 245 MHz. (b) Frequency corrected spectrum of the 410 MHz cavity.

As a pioneering feature, instead of using time-of-flight detectors to determine the revolution frequency of the stored highly charged ions as it was used in the past at ESR [reference] and currently at CSRe in Lanzhou [reference], we used two-independent newly developed highly-sensitive non-destructive resonant Schottky detectors [references]. Such cavity-based detectors enabled us to monitor the frequencies and intensities of all secondary ions stored in the ESR with unprecedented resolution and without perturbing the state of the highly charged ions, paramount in the study of exotic isotopes. Each of the Schottkies works at different resonant frequencies, facilitating the identification of the isotopes and offering more statistics for the same physical phenomena.

The experiment on ^{72}Ge consisted of 3 days of preparation to get the correct ion optical settings and 1 more day to achieve a high resolution setting in which by using scrappers, there were cutted in the phase space the isotopes around ^{72}Ge in order to reduce the contamination with other isotopes and being able to resolve the isomeric state. This high resolution setting is one of the subsets of data used for the analysis, containing 102 injections (32 min of data). After the ^{72}Ge measurement we changed the setting to search for new possible low-lying 0^+ states in ^{70}Se (for 1 day). After those measurements, we came again to ^{72}Ge , however we couldn't achieve the exact same setting, and we ended up with another high resolution setting in which we cutted

more ^{72}Ge particles, cutting therefore the number of produced ground and isomeric states, and in different proportion (we cut more ground states than isomers in relation with the previous setting). This different high resolution setting took place for about 9 hours, with a total of 2459 injections. Each of these two subsets has been labeled as $i = [1, 2]$ respectively in the tables and figures. In figure 4.1 it is shown an example of the spectrums generated by the measured data after performing a discrete Fourier Transform by the application of the FFT algorithm to the recorded IQ data.

A new analysis methodology based on the superposition of the Schottky-noise power has been developed. By superimposing injections belonging to the same data set, we reduce considerably the quantity of data to be further analysed while maintaining the exact same spectral features (half-life and masses). Before applying the superposition, each individual injection was frequency corrected to the power center of gravity of ^{72}Ge . In such a way, even if we modify the frequency information of the individual spectrograms, their frequency distances are preserved. Doing so we obtain spectrograms such as the one in figure 4.1 (b). Therefore, the following measurements have been realised by superimposing the data of each of the subsets in each detector.

The data of the 245 MHz cavity was recorded continuously in time in a frequency range of 18 MHz around 243 MHz with the New Time CAPture data acquisition system (NTCAP) with a sampling frequency of 20 MSamples/s and, in addition, it was recorded temporally with a real-time spectrum analyser (RSA) in a frequency span of 20 kHz around the injections for a few seconds with a sampling rate of 50 kSamples/s. The data of the newly developed 410 MHz Schottky resonant cavity ([1]) was just recorded with another RSA with the same recording characteristics than for the 245 MHz cavity but centered in 407 MHz.

The NTCAP measures continuously in time, therefore in order to analyse the data we must identify univocally the time in which new isotopes are injected. For that, we could analyse the scalar data or we could directly search for injections features within our data. We observed that we loose 30 ms before each injection most of the isotopes present into the ring, and then we observe an increase of power. Hence, by identifying this deloading-loading cycle, we can identify the injections. At figure 4.2 we can observe the time between consecutive injections. As we can observe the injection time is periodic around 14.547 s up to 9.2 ms. That standard deviation is an accelerator timing issue (not my analysis), since I have proved my method with the analyser data (all injections happens at the same relative time) with precisions of 100 microseconds. Once, that we have identified the injections we apply the frequency correction.

The most notable feature in figure 4.1 is an exponential temporal frequency shift in

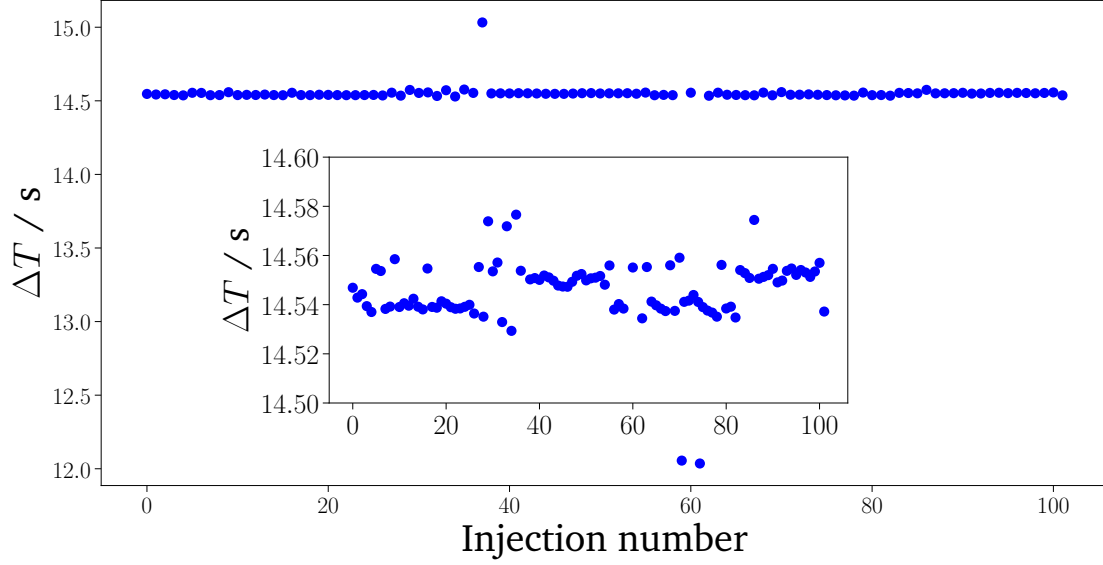


Figure 4.2. Time step between consecutive injections.

the ms regime. This feature was unnoticed in the past since the standard working time regimes in SMS are greater than seconds and in IMS of microseconds. The causes of this phenomena are still unknown and are under investigation, however we were able to characterize the phenomena by time-resolved Schottky analysis. We have been able to determine within $100\mu s$ the starting and ending times of the frequency shift. Due to the frequency shift with time, and since we have binned data, for a few time frames the spectrum looks frequency distorted. Specially, the time frame in which starts the frequency shift, since due to its exponential behaviour that time frame contains biggest frequency variation. We choose the best frequency and time binning in such a way that we start a new injection with a new bin, are short enough to avoid in the first frame the frequency shift (since it starts at 10 ms after the injection) but long enough to still been able to resolve in frequency the isomeric state from the ground state. This frequency shift was corrected by software in order to facilitate the analysis. However, the frame containing is the beggining of the shift is unresolved, therefore in the following analysis it has always been excluded.

4.1.2 Isochronicity

In order to characterize the ring conditions of our setting we studied how the relative frequency standard deviations evolve in the frequency domain, since the relative frequency spread depends on the second term of equation ???. This relation is derived from equation ??? for the case in which the studied and reference isotopes are the of the same specie where the first term of that equation is cancelled out, obtaining equation

4.2. Thus, by calculating this relative frequency spread for each of the identified isotopes, we can obtain information about the isochronicity condition and ring settings. The relative frequency spread for each isotope has been obtained by analysing their frequency centroids and standard deviations discretely once they were identified in the data recorded by the NTCAP. One question arises:

What is the effect of a modification of the Lorentz factor?

Indeed, as we know this term just depends on the longitudinal velocity of the ions, therefore if you produce your ions with slightly higher velocities you would observe a shift of your whole frequency pattern towards lower frequencies, therefore its effect can be misinterpreted as a standard deviation when you take into account the superposition of different injections for the same magnetic settings. The velocity of the produced fragments depends mainly on the energy acquired by the primary beam at the acceleration stage, which has some deviations from injection to injection.

Thus, in order to solve this issue we determine the frequency power centroid of the whole summed spectrums of the isochronous isotope, hence determining the average Lorentz factor of the reference isotope. Once that we know this value ($243.097276274e6$), we shift the whole individual spectrums in such a way that the power centroid of the reference isotope falls on the average frequency channel (we have look for the power centroid in 200 Hz of range). Therefore, we can fix the value of $\gamma = 1.3957335$ to that one. Then, for each setting I sum up all the different injections (the same time window after the injection time with the same FFT parameters) and I determine the mean frequency of $^{72}\text{Ge}^{32+}$ ground state. Once that I know that value I go injection by injection, move the average maximum of ^{72}Ge to the mean value and sum all the others injections.

This is shown in figure 4.3, where it was analysed the average noise power per frequency channel of 53 seconds (3 different injections) of the NTCAP data. From figure 4.3 we can infer that the isochronicity condition was set on $^{72}\text{Ge}^{32+}$ since it is the isotope in the global minimum of the curve, indicating that this ion specie is the one that experience less path correction in their kinetic energy distribution, hence having less frequency spread.

$$\frac{\sigma_f}{f} = (1 - \alpha_p \gamma^2) \frac{\delta v}{v} \quad (4.2)$$

The isochronicity curve shows an approximately constant (10^{-6}) region around $^{72}\text{Ge}^{32+}$. Therefore, we can neglect in that region the second term of equation ?? and

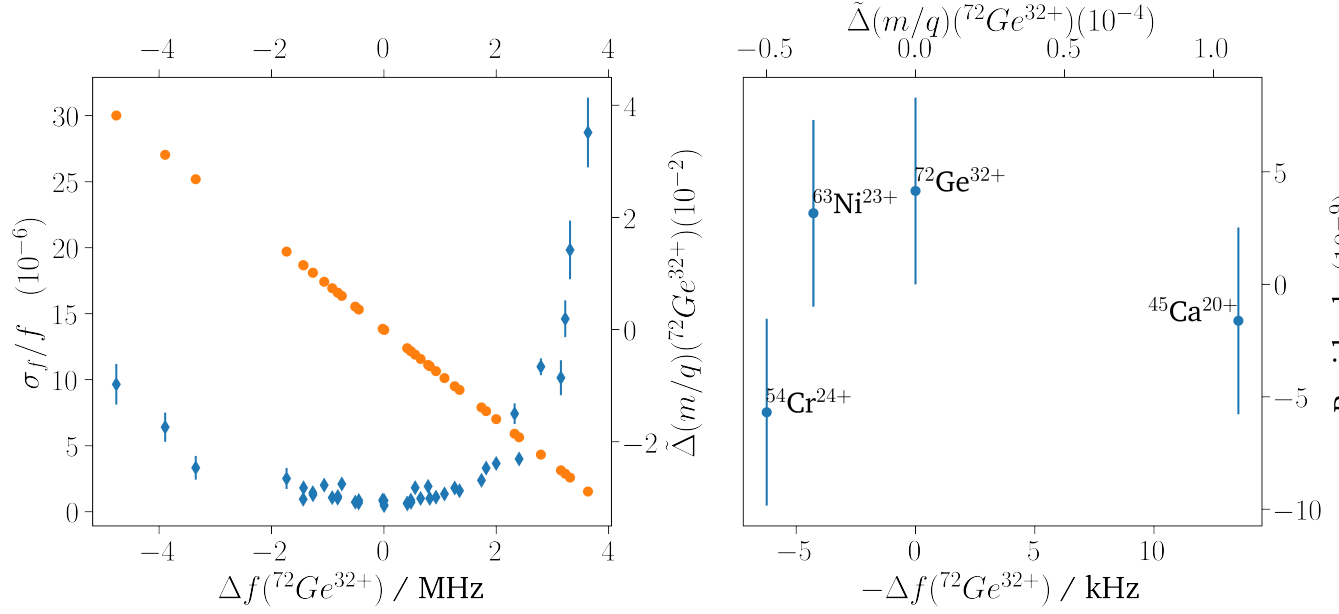


Figure 4.3. (a) (Blue) Relative frequency spread of each of the 62 identified isotopes in the NTCAP data and (orange) mass acceptance as a function of the frequency difference with respect to the ground state of $^{72}\text{Ge}^{32+}$. (b) Residuals of the linear fit performed in order to determine the local momentum compaction factor in a 20 kHz range around the ground state of $^{72}\text{Ge}^{32+}$.

perform a linear fit, relating the relative frequency distances and the relative mass to charge ratio of the identified isotopes, being the slope of the fit the local momentum compaction factor in the fitted region.

Since all the identified isotopes in figure 4.3 have a precise mass measurement (relative mass uncertainties of the order of $10^{-7} - 10^{-9}$ [reference]), we can use them in order to perform the linear fit and to obtain the local momentum compaction factor that will be used in the determination of the isomer's energy and half-life.

The linear fit gives a momentum compaction factor of $\alpha_p = 0.5138$ and with a constant $c = -4 \cdot 10^{-9}$. We have not include the standard deviation of α_p since the limiting value is not the precision in α_p but the product $\alpha_p \gamma^2$ and due to the lack of a measurement connecting the kinetic energy of the reference isotope with its velocity and path (frequency), we cannot determine the Lorentz factor γ for $^{72}\text{Ge}^{32+}$ that appears in equation ???. However, the isochronicity curve and the linear fit allows us to constraint its value to $\gamma = 1.395 \pm 0.001$.

Detector	i	Δf / Hz	ω / eV
RSC_{410}	1	2162 ± 309	693 ± 99
	2	2139 ± 314	685 ± 100
RSC_{245}	1	1304 ± 226	700 ± 121
	2	1296 ± 201	695 ± 108

Table 4.1. Excitation energy ω of the isomer and frequency distance Δf between isomer and ground state for the different data subsets (i) in each resonant Schottky cavity.

4.2 Results

4.2.1 Energy measurement

The excitation energy of an isomer (eq. 4.3) can be derived from equation ?? neglecting the second term and taking into account that the mass to charge ratio difference between isomer and ground state is exactly the same but by the excitation energy. The relative frequency distance has been determined by calculating the discrete centroids and standard deviations of both, isomer and ground state, after averaging in time the power per frequency channel 150 ms after injection. The results for each Schottky and subset of data are compiled in table 4.1 and an example of the obtained spectrums is shown in figure 4.9. Taking the average of all measurements we determine that $\omega = 693 \pm 107$ keV indicating a relative mass uncertainty of $\delta m/m = 1.6 \cdot 10^{-6}$.

$$\omega = \left| \frac{\Delta f}{f_{gs}} m_{gs} (-\alpha_p)^{-1} \right| \quad (4.3)$$

Half-life measurement

4.3 Discussion

4.4 Electron conversion factor measurements

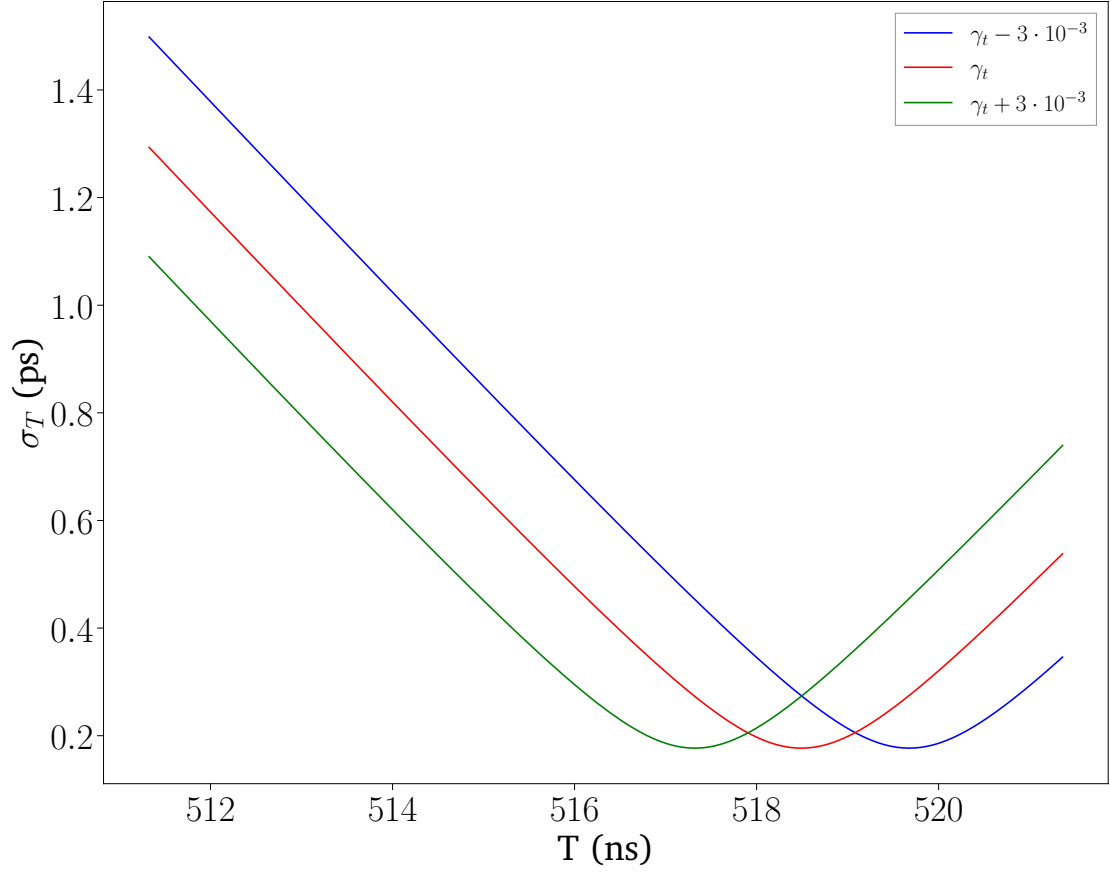


Figure 4.4. By changing the transition energy of the ring we "move" the isochronicity curve to other m/q regions. This would be equivalent to changing the gammas of the isotopes, this would result in an overall shift of the whole revolution time spectrum meanwhile maintaining γ_{mat} fixed (i.e the minimum of the curve) since the minimum of the curve corresponds to one specific energy, this is one specific orbit/revolution time in the ring. For the same difficulty of changing the ring settings or the primary beam ones, it would be a better approach changing the gammas since the revolution frequency of the isochronous particle would be "fixed" (minima), therefore when using Schottky resonant cavities, the resonant frequency does not need to be changed, although it could be done (unless it is bloqued, which can and has occurred.)

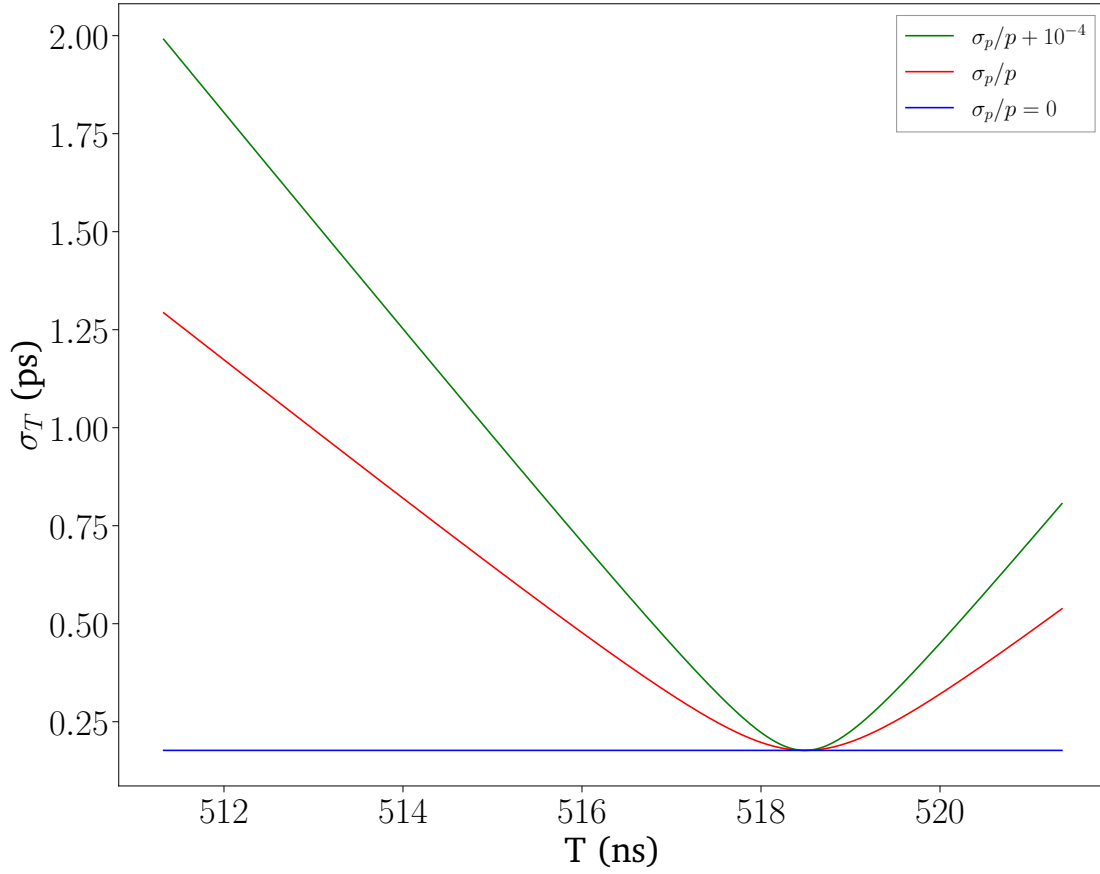
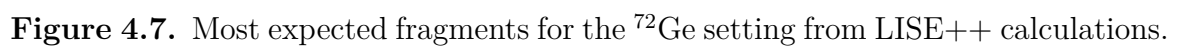
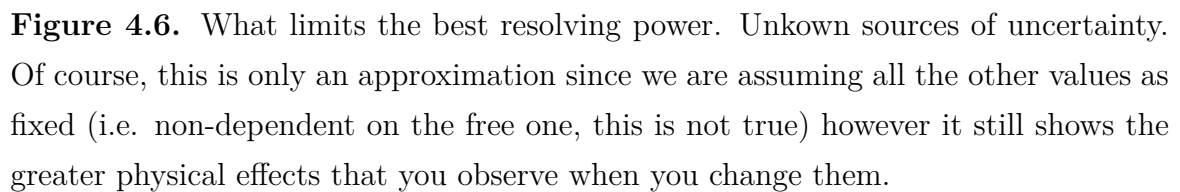


Figure 4.5. By changing the relative momentum spread of the particles we can improve the overall mass resolving power (making the curve more flat) however not the maximum value (i.e. not the resolution in the isochronicity window). This is not completely true, the minima should also change a bit, although the main difference is the curvature.



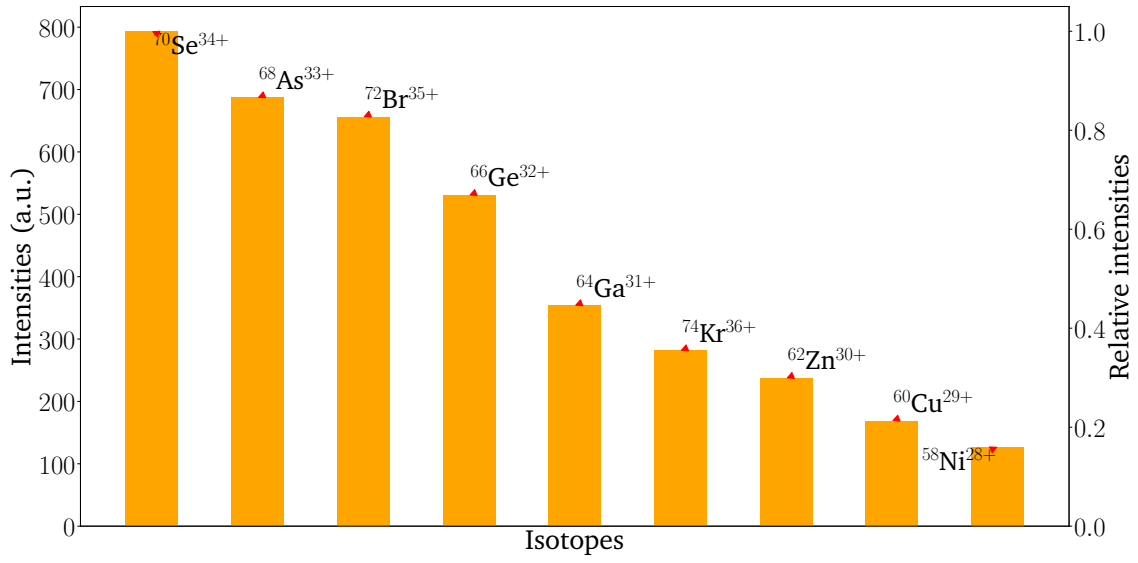


Figure 4.8. Most expected produced fragments for the ^{70}Se setting from LISE++ calculations.

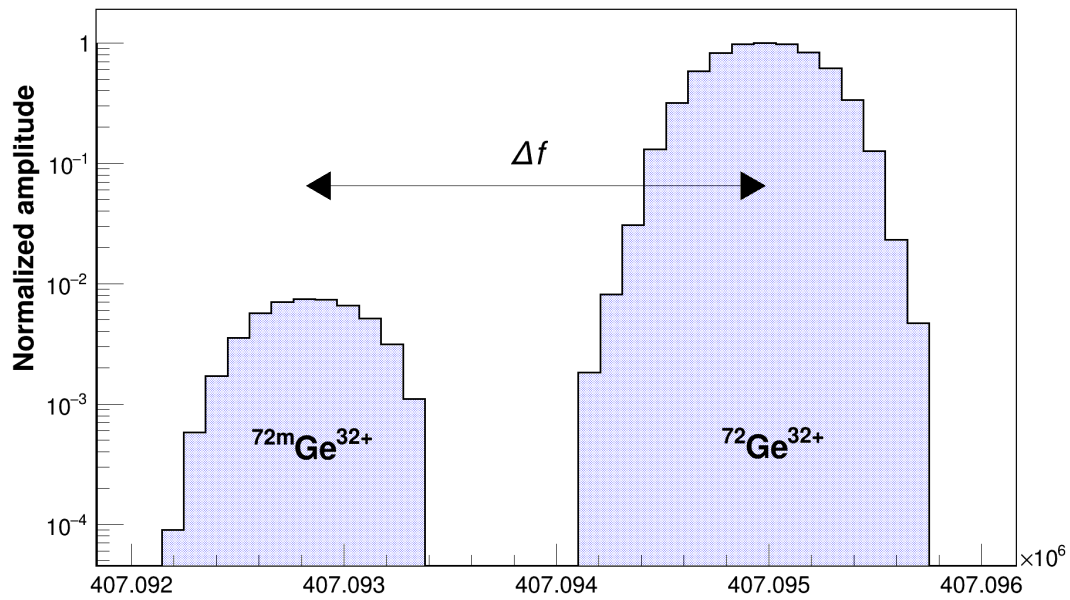


Figure 4.9. Normalized 1-dimensional noise-power spectrum of the time (150 ms) averaged superposition without background for subset 1 in the 410 MHz cavity in which it is completely resolved the isomeric and ground state of $^{72}\text{Ge}^{32+}$.

Chapter 5

Conclusions and overlook

Conclusions

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