First results from IS468 and further investigation of in-trap decay of ^{62}Mn.

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With the experiment IS468, the issue of in-trap decay of short lived radioactive isotopes in the REXTRAP-EBIS combination at REX-ISOLDE was addressed. The main technical question is how efficient the recoiling decay daughters remain trapped in REXTRAP and EBIS. The choice for ^{61}Mn and ^{62}Mn was made due to the absence of isobaric contaminants from the ISOLDE primary target, their relatively high yield and their short half life. From physics point of view, the in-trap decay of manganese isotopes produces iron isotopes which are not available from thick ISOL targets. ^{61}Fe and ^{62}Fe were post-accelerated successfully for the first time, providing the proof of principle of this production method. It was found that the EBIS is an efficient trap for recoiling daughter products, whereas unidentified losses occur in REXTRAP. With this addendum we propose to further investigate this issue with the ideally suited ^{62}Mn beam and to optimize the ^{62}Fe production to be able to measure the B(E2,$2_1^+ \rightarrow 0_1^+$) strength in this nucleus.

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I. FIRST RESULTS FROM IS468

A. Overview of shifts in 2008

The experiment IS468 was performed at the end of June 2008. The emphasis was put on the investigation of beam purity after in-trap decay of short lived ^{61}Mn isotopes in the REXTRAP-EBIS combination, prior to post-acceleration. A first attempt was made to investigate the purity of ^{62}Mn, but there was no time to investigate this in more detail. The beam intensities delivered were as expected : 3.5E6 ^{61}Mn atoms/μC and 6.7E5 ^{62}Mn atoms/μC (measured yields prior to the experiment). An average proton beam current of 1.3 μA was delivered throughout the experiment. The post-accelerated ^{61}Mn beam intensity was 1.3E5 ^{61}Mn atoms/s in the "standard" REX operation (see below for the definition of "standard"), which yields an overall REX+ISOLDE efficiency of $\approx$3%. In the following a short overview is given how the 9 attributed shifts were used.

In total 2 shift had to be spent on the setting up of the MINIBALL experiment, including the debugging of beam diagnostic detectors. Included in these two shifts is as well the modification of the trigger system for both REXTRAP and the MINIBALL experiment. The latter was needed since for the first time, REXTRAP and MINIBALL were operated synchronously with the proton impact.

1 shift was used for tests with the REXTRAP and EBIS controls (including mass resolving tests with REXTRAP, the application of a Time-of-Flight gate between REXTRAP and EBIS, changes of the high voltage barriers in the EBIS). The mass resolving tests are part of an ongoing project which deals with this matter in a broader perspective. The Time-of-Flight between REXTRAP and EBIS is potentially another option to obtain a pure Fe beam. Due to the potential 2^+ charge state of the Fe decay daughter during the injection into the EBIS, these isotopes arrive first at the EBIS and can be gated. Though, it remains unclear how fast the recombination time is for Fe^{2+} after the decay in the buffer gas environment. The Time-of-Flight spectrum that was obtained during the IS468 beamtime in June 2008 is shown in Fig. 1. It remains uncertain if the small peak is indeed ^{61}Fe^{2+}, since this peak

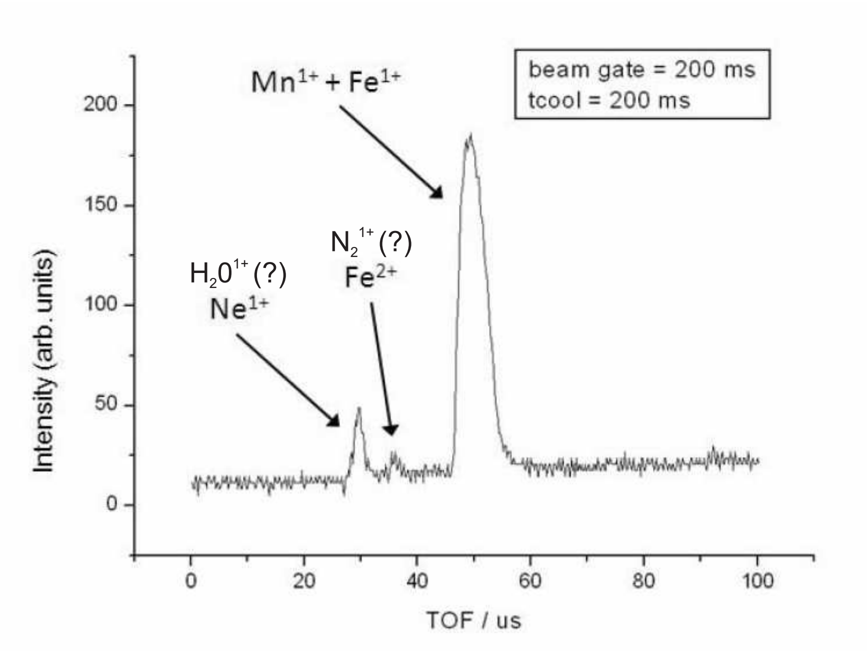

FIG. 1: Time-of-Flight spectrum of the A=61 beam between REXTRAP and EBIS, recorded on a MCP. The identification remains uncertain.

did not in- or decrease with the application of the cyclotron cooling frequency for ^{61}Fe^{2+}, nor did it change with in- or decreasing the trapping times. This topic is taken up as one of the issues we plan to investigate further in this addendum. The increase and/or change of the shape of the EBIS potential barriers had little or no effect on the final beam composition. Though, since there were stringent problems with the beam diagnostics after REX (see further), no definite conclusion can be given here.

Since the beam diagnostics after REX-ISOLDE didn't provide the necessary resolving power, Coulomb excitation was the most reliable way to deduce the beam composition. In total 5 shifts were spent on Coulomb excitation of the delivered ^{61}Mn(+^{61}Fe) beam on a 4 mg/cm^2 ^{109}Ag target.

The remaining shift was spent on a first trial to post-accelerate ^{62}Mn and ^{62}Fe with extended charge breeding times.

B. Remarks and problems

During the 2008 experiment, the ΔE-E$_{res}$ detector, which would serve as the highest resolution beam diagnostics detector suffered from a leak in the new gas system. This remained undetected during the beamtime, thus making this detector useless. The Bragg detector, which is the second beam diagnostics detector performed as expected, but no indication was found in this detector for two beam components (Fe and Mn). This might be due to the too poor resolution of this detector at REX-ISOLDE. A more systematic check of the evolution of the beam composition with varying cooling times in REXTRAP definitely needs a high resolution beam diagnostics detector. This will now be the emphasis in the first part of this addendum and is taken up as one of the priorities in paragraph II C.

The ΔE-E$_{res}$ detector was debugged during the summer campaign and was successfully tested during beam developments. Two example spectra are shown in Fig. 2. The first was obtained with a stable Kr beam from the EBIS (natural abundant Kr gas) and the second was obtained with a A=27 beam from the HRS. Both spectra were obtained at the 20 degrees beamline after the REX linear accelerator.

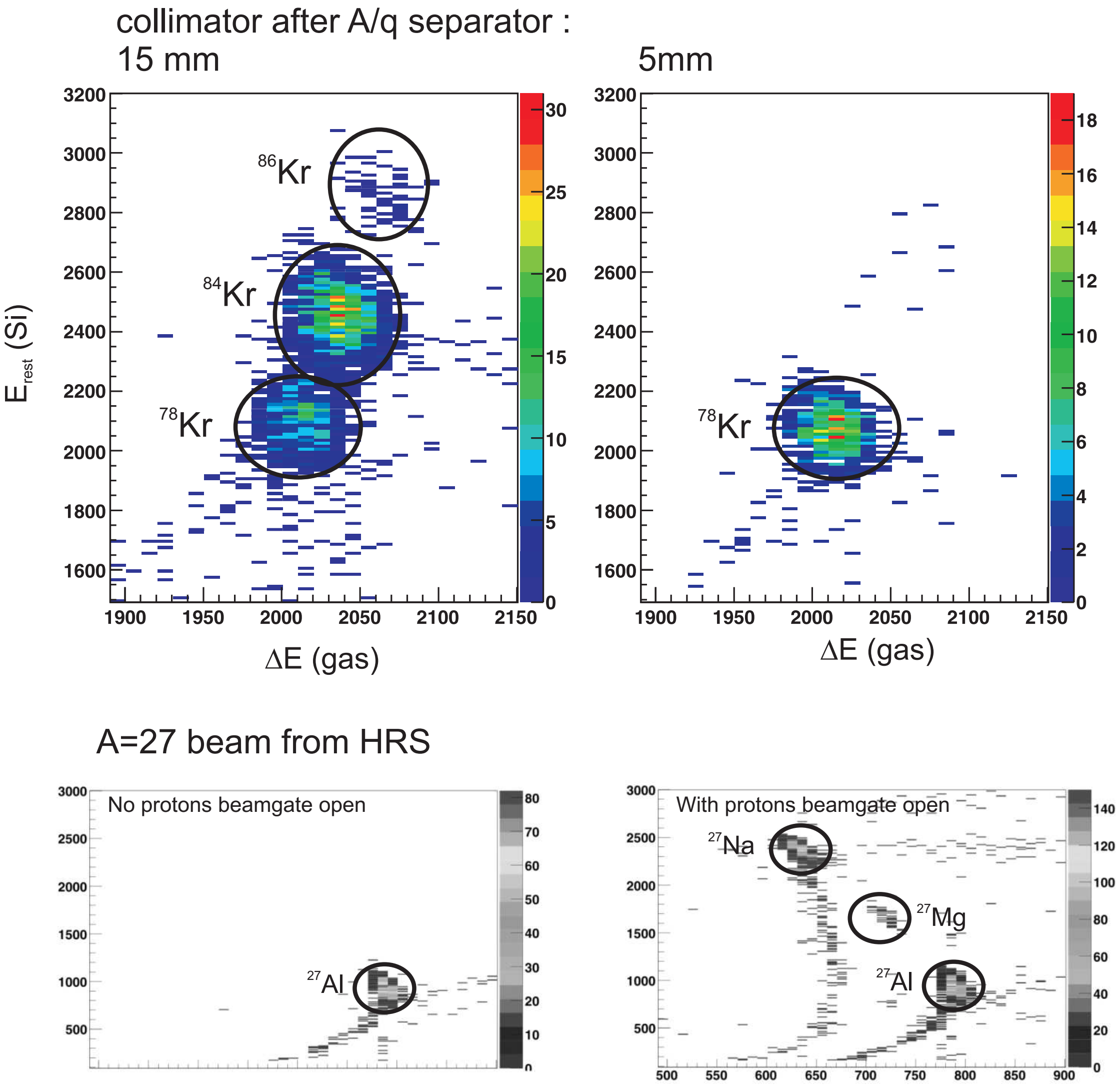

FIG. 2: Top : E$_{res}$(Si) versus ΔE(gas) spectrum obtained with a stable cocktail beam of Kr isotopes from the EBIS. Bottom : spectrum obtained with a A=27 beam from the HRS target, with and without protons.

C. Results from the Coulomb excitation

The final results of the Coulomb excitation experiments are summarized in four main parts :

1 "Standard" Coulomb excitation of the ^{61}Mn beam (1 shift);

2 Coulomb excitation of the A=61 beam with 29 ms breeding time and varying trapping times (2 shifts);

3 Coulomb excitation of the A=61 beam with 298 ms breeding time and varying trapping times (2 shifts);

4 Coulomb excitation of the A=62 beam with 298 ms breeding time and varying trapping times (1 shift);

During the "standard" Coulomb excitation experiment, the ^{61}Mn isotopes were continuously injected into REXTRAP, where they were trapped for 30 ms and subsequently charge bred for 28 ms in the EBIS. The REXTRAP was not synchronized with the proton impacts at this point. Decay losses of ^{61}Mn during these trapping and charge breeding times are limited. With the considered trapping and charge

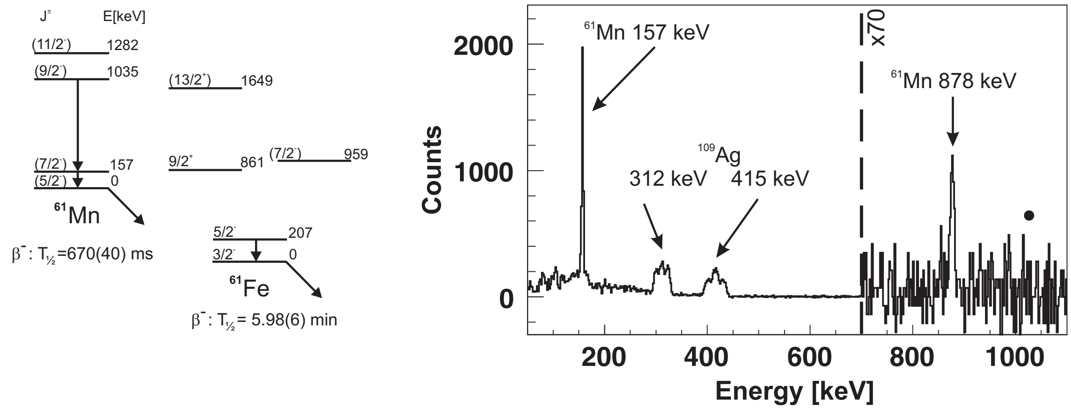

FIG. 3: Left : (partial) level scheme for ^{61}Mn and ^{61}Fe. Data are taken from [1] and [2] Right : the Coulomb excitation spectrum obtained with 28 ms charge breeding time and 30 ms trapping time. The spectrum is Doppler corrected for the detected projectile particle and random subtracted. The filled circle indicates the non-observed Doppler corrected $(9/2^-)\rightarrow(5/2^-_{g.s})$ transition at 1035 keV.

breeding times and assuming a straightforward exponential decay ≈96% of the post-accelerated beam should consist of ^{61}Mn isotopes. The total post-accelerated beam intensity was 1.3E5 isotopes/s, yielding a total REX efficiency of ≈3%. The resulting Coulomb excitation spectrum, background subtracted and Doppler corrected for the detected beam particle is shown in Fig. 3. In this spectrum the known de-excitation lines from the ^{109}Ag target are observed (312 keV and 415 keV), together with two γ transitions in ^{61}Mn at 157 keV and 878 keV. These two transitions could be placed in a recently published level scheme of ^{61}Mn [1]. Transition rates in ^{61}Mn could be deduced. At the same time, the ratio of Mn and target de-excitation lines provides a good normalization to identify any in- or decrease of the Mn content in the following.

A first attempt to increase the ^{61}Fe content in the post-accelerated beam was made by trapping the ^{61}Mn^{1+} ions over longer time periods in REXTRAP, ranging from 200 to 1100 ms. The breeding time in the EBIS was fixed to 28 ms. At this point, REXTRAP was synchronized with the proton beam impact and a beamgate of 200 ms was applied to the incoming isotopes, reducing the post accelerated beam intensity to 5.0E3 isotopes/s. This synchronization implies that all produced ^{61}Mn isotopes which are released up to 200 ms after the proton impact are trapped and charge bred for the same amount of time, resulting in a constant Fe/Mn ratio in the post-accelerated beam pulse from the EBIS. The resulting Coulomb excitation spectrum, which is the sum of all spectra acquired with different trapping times, is shown in Fig. 4(A).
No evidence is found for a Doppler corrected 207 keV γ-ray, which is expected from the known level scheme of ^{61}Fe (see Fig.1). From the observed amount of 157 keV γ-rays and the ratio of this γ-ray intensity with the 312 keV γ ray from the target found in the "standard" Coulomb excitation experiment (with a "pure" Mn beam), 68(10) counts are expected in the 312 keV transition. Experimentally, a total of 76(10) γ-rays are observed. Thus, no evidence is found for a strong ^{61}Fe component in the post-accelerated beam. A straightforward calculation, using the exponential decay of ^{61}Mn during the trapping and charge breeding times (a time-weighted average of the trapping times was taken), results in a total of 61% of ^{61}Mn in the beam.
From the ratio of Mn and Ag de-excitation lines observed during individual runs with a constant cooling time in REXTRAP, no definite conclusion can be drawn on the presence of decay daughters in the final beam due to lacking statistics. Though, within the error bar, one can conclude that there was no convincing evidence for a strong iron component, which one might assume since the combined cooling and charge breeding times are $> 2T_{1/2}$. Overall, the beam intensity dropped considerable for the long cooling times, hinting important losses.

In a second trial to increase the ^{61}Fe content, the trapping times were varied from 300 to 900 ms and the breeding time was increased and fixed to 298 ms. Because of this longer charge breeding time, the A/q separator after the EBIS was set to 2.9 (^{61}Mn^{21+}). The REXTRAP was synchronized again with the

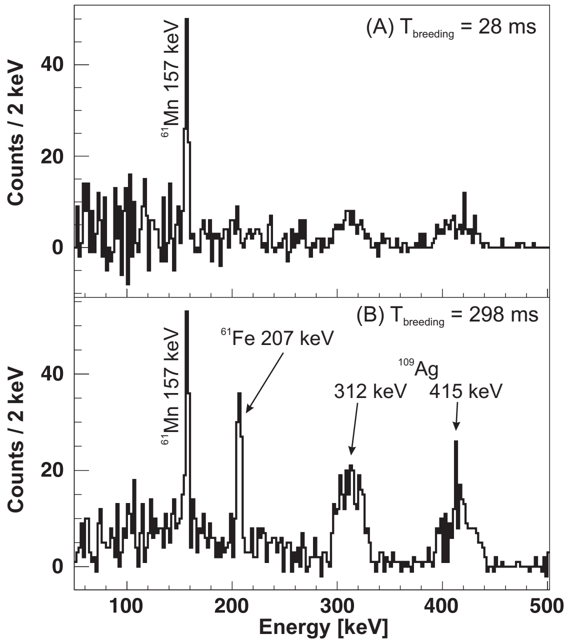

FIG. 4: The sum of all Coulomb excitation spectra obtained with 28 ms (A) and 298 ms (B) charge breeding time and with variable trapping times, ranging from 200 up to 1100 ms (A) and from 300 up to 900 ms (B). The spectrum is Doppler corrected for the detected projectile particle and random subtracted.

proton beam and a beamgate of 300 ms was applied to the extracted ^{61}Mn^{1+} ions, effectively reducing the post-accelerated beam intensity to 1.0E4 isotopes/s. The resulting Coulomb excitation spectrum, which is the sum off all different trapping times, is shown in Fig. 4(B). In this case, a de-excitation γ-ray is observed at 207 keV, which is the $5/2^{-}\rightarrow 3/2^{-}_{g.s.}$ transition in ^{61}Fe. From the observed amount of 157 keV γ rays, the amount of target excitation induced by Mn can be deduced, yielding the amount of target excitation induced by ^{61}Fe. From the known cross section for target excitation, a total manganese content of 39(6)% is deduced. A total of 49% manganese content is expected using the exponential decay, described above.

The reason for the large discrepancy between the calculated manganese content and the experimental observation in the first experiment (charge breeding time = 28 ms and long trapping times) is not well understood. Neither is it understood why in the second experiment, a rather good agreement is found. It is clear that a straightforward exponential decay inside REXTRAP and EBIS neglects possible losses of ^{61}Fe after the β-decay of ^{61}Mn, due to the recoil energy and/or the n^{+} (n$\geq$2) charge state of ^{61}Fe. These possible losses might be induced by the insufficient cooling of ^{61}Fe^{n+} in REXTRAP and thus the poor injection into the EBIS, poorly known recombination times for ^{61}Fe^{n+}, the possible difference in charge state distributions of Fe and Mn after charge breeding, charge exchange with the buffer gas atoms, collisions of the recoiling ^{61}Fe with the walls and electrodes inside the trap, and so on. One could conclude from this that the EBIS is a better option for trapping the isotopes over longer times then the REXTRAP, where undefined losses occur.

The latter procedure (298 ms breeding time and varying trapping times) was applied to the A=62 beam as well during 1 shift. The resulting Coulomb excitation spectrum is shown in Fig. 5. From the observed target excitation, an average incoming beam intensity of 1.6E3 atoms/s is estimated. This is consistent with a factor of ≈10 loss in primary target yield due to the 300 ms beamgate and an overall transmission efficiency of 2%. 10 counts are observed in the Doppler corrected spectrum at 877 keV, which is the $2^{+}_{1}\rightarrow 0^{+}_{1}$ transition in ^{62}Fe. This result was obtained without optimization of the combination of charge breeding and cooling times. From a straightforward exponential decay calculation and time averaged over the different trapping times, a total of 55% ^{62}Fe is expected in the beam. From the preliminary lifetime measurement of the 2^{+}_{1} state in ^{62}Fe and the observed 10 counts, a total Fe content of ≈30% can be deduced. The worse agreement with the calculation, compared to the A=61 case might be due to the

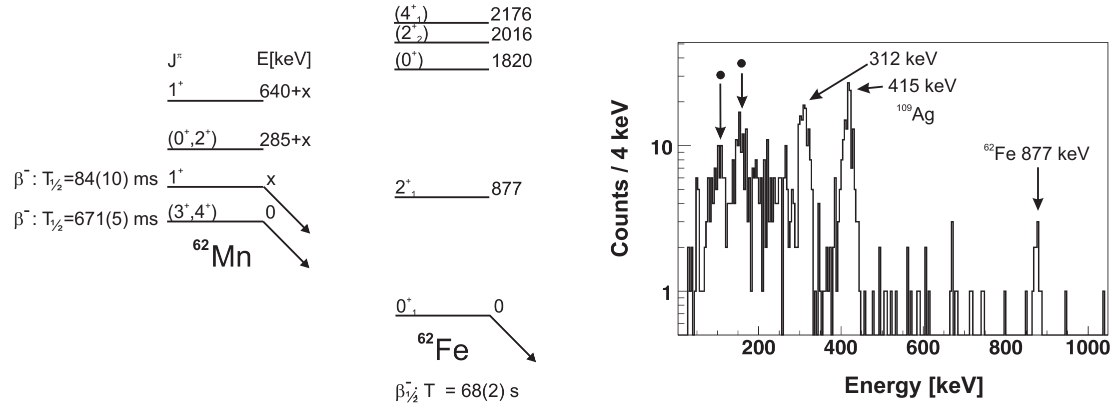

FIG. 5: The sum of all Coulomb excitation spectra obtained with 298 ms charge breeding time and variable trapping times, ranging from 300 up to 900 ms, for the A=62 beam. The spectrum is Doppler corrected for the detected projectile particle and random subtracted.

higher recoil energy of ^{62}Fe. This topic will be the emphasis in the current addendum to this experiment.

From these Coulomb excitation experiments important conclusions can be drawn concerning the in-trap decay :

1 A post-accelerated beam of in-trap produced decay products can be produced when the trapping happens predominantly in the EBIS;

2 The ^{61,62}Mn beams are particularly useful due to the absence of any isobaric contamination, the short life times of these isotopes and the good yields;

3 The extended trapping times in REXTRAP need more systematic investigation with a direct measurement in the ΔE-E$_{res}$ detector;

II. FURTHER INVESTIGATIONS

A. Technical interest

From the spectrum shown in Fig. 5 it is clear that the post-acceleration of ^{62}Fe is possible with long charge breeding times, as was the case for the A=61 beam. The main difference between the ^{61}Mn and ^{62}Mn beams is the recoil energy distribution of the decay product (Fe). The maximum recoil energy is 475 eV for ^{61}Fe and 1020 eV for ^{62}Fe. The effect of the high recoil energy of these isotopes within the trapping potentials is not very well understood and is the highest priority to investigate.
One of the ideas to explain the apparent higher efficiency in trapping the ions in the EBIS is that the trapping barriers for REXTRAP are too low to confine the isotopes (typically $\approx$ 200 V) compared to the EBIS (typically 500 V). Though, the recoiling ions are isotropically emitted and the trapping potentials are relevant for isotopes moving on the axis.
A more systematic check with the ΔE-E$_{res}$ detector is proposed. In this way the effect of changing the high voltage barriers, the buffer gas pressure, the cooling times, etc ... can be addressed (see paragraph II C for an overview of the proposed ideas).
The need to investigate the beam composition after cooling and charge breeding is relevant as well for all other experiments at REX-ISOLDE that deal with short lived isotopes, but where the physics interest is in the mother isotopes rather than in the daughter isotope. The beam composition is a crucial parameter in all Coulomb excitation experiments.

B. Physics case

The physics case for ^{62}Fe remains unchanged, compared to the original proposal. Recently, there was a second successful life time measurement on ^{62}Fe, performed at GANIL [3]. Results are expected shortly and will be a good check of the recent unpublished result from Legnaro. As emphasized in the original proposal, an additional low energy Coulomb excitation experiment on ^{62}Fe is a complementary result, since the Coulomb excitation cross section depends on both the B(E2) value to the 2_1^+ state as on the quadrupole moment of the 2_1^+ state. With a lifetime value, one parameter can be constraint (the B(E2) value) and the second parameter (the quadrupole moment) can be fitted.
The "standard" Coulomb excitation of ^{62}Mn can give insight in the level structures which are build on the ground state and on the isomeric state (see Fig. 5). γ rays are known from a β-decay study of ^{62}Cr. These γ-rays are associated with levels decaying to the isomeric state [4]. Five γ-rays were observed in a multi nucleon transfer reaction performed at Legnaro at 109, 155, 196, 225 and 541 keV. These γ-rays, which were not observed in the β-decay experiment, are assumed to decay to the ground state. No level scheme was constructed. In Fig. 5, some hint is already present for the observation of the 109 and 155 keV γ-rays. A low energy Coulomb excitation experiment can place these γ-rays in a level scheme. At the same time, the "standard" Coulomb excitation gives a good normalization point for the Coulomb excitation which is synchronized with the proton pulses.

C. Feasibility and planning

The proposed planning and ideas for a follow up of the IS468 experiment is separated in two parts. The first part focusses on the investigation of the REXTRAP and EBIS trapping properties. The proposed ideas are the following :

1 Check the reproducibility of the A=62 result with the ΔE-E$_{res}$ detector, i.e. : comparing the beam composition with the combination of trapping and charge breeding times T$_{Trapping}$=300 ms-T$_{Breeding}$=29 ms and T$_{Trapping}$=300 ms-T$_{Breeding}$=298 ms.

2 Apply a second cooling frequency for the Fe^{2+} isotopes in REXTRAP.

3 Try different beamgates (from 100 to 300 ms), thus changing the total amount of ions trapped, to investigate space charge effects.

4 Investigate further the Time-of-Flight between REXTRAP and EBIS and try to identify the observed peaks. This can be done by applying different cooling frequencies for the assumed candidates or removal by dipolar excitation.

5 Changing the buffer gas pressure in REXTRAP to investigate if this affects the recombination time.

6 Fixing the breeding time and changing the trapping time from 200 up to 1100 ms, similar to what was done in 2008. Now with the A=62 beam and the ΔE-E$_{res}$ detector for a more systematic and direct check.

7 Scan the A/q spectrum after the EBIS for different charge breeding times.

It must be emphasized that some of these tests can be done off-line with stable beam. Some of these tests have been done already (point 3, 4, 5). Though, the obtained results have to be checked with radioactive beam to investigate the effects related to the recoiling daughter isotopes. For example, buffer gas atoms will ionize only by collision with the recoiling decay daughter and thus appear in the time of flight spectrum, clearly an effect which can only be investigated with radioactive beam.
For these tests with radioactive beam we ask 4 shifts.

The second part involves the MINIBALL setup for Coulomb excitation of the delivered beam. The feasibility of the Coulomb excitation of ^{62}Fe and ^{62}Mn depends strongly on the results of the first part of this experiment. Though, with the numbers from the 2008 experiment and assuming slighter higher transport efficiencies, the following estimate can be made

- A primary target yield of 6.7E5 ^{62}Mn atoms/μC ;
- A proton beam current of 2μA ;

- A slightly higher overall REX efficiency of 5% ;
- A cross section of $\approx$ 400 mbarn for ^{62}Fe on 4 mg/cm^2 ^{109}Ag target and MINIBALL efficiency of 8.9% ;
- A beamgate of 300 ms is applied (thus reducing the beam intensity a factor 10) ;
- 60% of the beam is ^{62}Fe.

With these assumptions, 80 counts are expected in the $2^+_1 \rightarrow 0^+_1$ transition at 877 keV in 1 shift. A "standard" Coulomb excitation experiment on a pure ^{62}Mn beam is proposed as well to obtain more information on the level structure build on the ground state and on the isomeric state, which would still be present at low cooling and charge breeding times. The normalization of the experiment is governed by both the Mn Coulomb excitation as the results from the ΔE-E$_{res}$ detector in the first part. In total we ask for **4 shifts of Coulomb excitation**.

III. BEAM TIME REQUEST

In total we would like to ask for **9 shifts**. **1 shift** for initial setup time, **4 shifts** for the tests described in section II C and **4 shifts** to obtain a relevant physics result for A=62. This experiment is run with a standard UC$_x$ target and RILIS.

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