Investigation of beam purity after in-trap decay and Coulomb excitation of ^{62}Mn-^{62}Fe.

J. Van de Walle,[1] V. Bildstein,[2] N. Bree,[3] J. Cederkäll,[1] E. Clément,[4] J. Diriken,[3] P. Delahaye,[1]
V.N. Fedosseev,[5] R. Gernhauser,[2] M. Huyse,[3] O. Ivanov,[3] T. Kröll,[2] R. Krücken,[2] N. Patronis,[3]
P. Van Duppen,[3] D. Voulot,[5] F. Wenander,[5] K. Wimmer,[2] and the MINIBALL collaboration.
[1]*PH department, ISOLDE, CERN, Geneva, Switzerland*
[2]*Physik Department E12, Technische Universität München, Garching, Germany*
[3]*Katholieke Universiteit Leuven, Leuven, Belgium*
[4]*GANIL, Caen, France*
[5]*AB department, CERN, Geneva, Switzerland*

The in-trap decay of short lived radioactive ions is not well understood. This poses a problem for Coulomb excitation experiments at MINIBALL, where the normalization of the experiment depends strongly on observed secondary target excitation, which in turn strongly depends on the knowledge of the beam composition. For pure ISOLDE beams of short lived isotopes, the in-trap decay becomes important since a large fraction of the beam is transformed in unwanted daughter isotopes. In this proposal we intend to quantify the production of these daughter products in the REXTRAP accurately by making use of the short lived isotopes ^{61,62}Mn and the newly installed Bragg ionization chamber at the end of the REX linear accelerator. Apart from the technical interest, the A=62 beam provides as well a good physics case, concerning the development of collectivity in neutron rich Fe isotopes. Coulomb excitation, utilizing the standard MINIBALL setup, is proposed on both A=62 Mn and Fe. The Fe beam would be the first post-accelerated beam of daugther isotopes following the in-trap decay of the radioactive mother isotope. If succesfull, this method could provide post-accelerated beams of isotopes which were before not accessible at REX-ISOLDE.

Spokesperson : J. Van de Walle
Contactperson : J. Van de Walle

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I. INTRODUCTION : TRAPPING AND DECAY LOSSES

At REX-ISOLDE, prior to post-acceleration, the radioactive isotopes are trapped in a Penning Trap (REXTRAP) in order to ensure an efficient transmission to the EBIS, where they are brought to high charge states. Both the trapping and the charge breeding happen on the same time scale, depending on the mass of the isotope, ranging from 20 to ~200 ms. The breeding and maximum trapping time shall be noted as "T" from now on. This limits the possibilities to accelerate short lived isotopes, with half lives similar to the trapping + breeding time, without considerable losses of the already weak radioactive ion beam. At the same time, the isobaric purity of the radioactive ion beam deteriorates. The knowledge of this isobaric contamination is *crucial* in Coulomb excitation experiments, performed at MINIBALL, since it affects the normalization procedure. On the other hand, the in-trap decay of the pure ISOLDE beam can provide a pure post-accelerated beam of the daughter isotope. Two such examples are the neutron rich beams of Manganese and Potassium, which are produced with high yields at ISOLDE, which decay to Iron and Calcium, respectively. Though, to date, it remains unclear how much of the daughter isotopes are lost during the in-trap decay, due to effects described below.

A straightforward analytical calculation of the daughter production can be performed, assuming a continuous injection in the REXTRAP, where the ions spend a time from 0 to T ms in the REXTRAP, and a constant charge breeding time of T ms. Additionally, a transmission function given by a*t+b is assumed, where a the transmission is 1 for t=T and 0.5 for t=0 (i.e. 50% of the ions is lost when they are NOT cooled at all). In this first approach this gives for the mother ($n_1(t)$) and daughter ($n_2(t)$) nuclei after an average trapping time from 0 to T ms :

$$\begin{aligned} n_1(T) &= \frac{1}{T}\int_0^T e^{-\lambda_1 t}(a.t+b)dt \\ &= \frac{a}{T\lambda_1^2}(1-e^{-\lambda_1 T}) - \frac{a}{\lambda_1}e^{-\lambda_1 T} - \frac{b}{\lambda_1 T}(e^{-\lambda_1 T}-1) \\ n_2(T) &= \frac{1}{T}\frac{\lambda_1}{\lambda_2-\lambda_1}\int_0^T (e^{-\lambda_1 t}-e^{-\lambda_2 t})(a.t+b)dt \end{aligned}$$

$$
\begin{aligned}
= & \frac{\lambda_1}{(\lambda_2-\lambda_1)T}(a(\frac{1}{\lambda_1^2}-\frac{1}{\lambda_2^2})+b(\frac{1}{\lambda_1}-\frac{1}{\lambda_2}) \\
& +(\frac{aT}{\lambda_2}+\frac{a}{\lambda_2^2}+\frac{b}{\lambda_2})e^{-\lambda_2 T}-(\frac{aT}{\lambda_1}+\frac{a}{\lambda_1^2}+\frac{b}{\lambda_1})e^{-\lambda_1 T})
\end{aligned}
$$

and for a constant charge breeding time of T ms :

$$
\begin{aligned}
n_1(2T) &= n_1(T)\cdot e^{-\lambda_1(T)} \\
n_2(2T) &= \frac{\lambda_1 n_1(T)}{\lambda_2-\lambda_1}\cdot\left(e^{-\lambda_1(T)}-e^{-\lambda_2(T)}\right)+n_2(T)e^{-\lambda_2 T}.
\end{aligned}
$$

Additinally, after the A/q selection prior to injection to the linear accelerator, the P_n branch of the mother isotope (P_n^1) should be taken into account : $n_2^{A/q}(2T)=(1-P_n^1)\cdot n_2(2T)$.

Two effects can change these numbers considerably :
1- When the daughter isotopes acquires a high recoil energy, it can escape the confinement potential of the REXTRAP.
2- Due to electron-shake off and Auger cascades, the daughter isotope ends up in a higher charge state and the charge state distribution of the daughter isotope might be affected. Thus, a different ratio of mother over daughter nuclei can be found at different A/q values.

The decay-loss effects, especially in the REXTRAP, are poorly studied and recent Monte Carlo simulations [1] suffer from insufficient experimental input. Since short lived isotopes are investigated at REX-ISOLDE and with the increased usage of traps in ISOLDE, the decay loss effects prior to post-acceleration must be investigated. This in order to establish the knowledge of the isobaric purity of the beam, in turn affecting the normalization of the experiment and the final physics result.

II. THE EXPERIMENT

We propose to use a ^{61}Mn and ^{62}Mn beam to investigate decay losses in the REXTRAP and EBIS. ^{61}Mn has a known half life of 670(40) ms and Q_{β^-}=7.2 MeV and is produced at ISOLDE with a yield of 1.7E6/μC. From a decay study of ^{62}Mn [2] and ^{62}Cr [3], two half life components of 671(5) ms and 92(13) ms are observed. The yield of ^{62}Mn is 7E5/μC and corresponds possibly to the longest lived component. The arguments for using these radioactive ion beams are :
- ^{62}Mn and ^{62}Fe have a strong nuclear structure interest ;
- ^{61}Mn is a pure beam with no (known) isomers ;
- Mn is a standard high quality ISOLDE beam ;
- Mn (Z=25) and Fe (Z=26) can be separated in the newly installed Bragg chamber after MINIBALL.

A. Production Method

The neutron rich Mn beams are produced with a UC$_x$ target and the RILIS laser ion source. The A=61 beam is expected to be pure and the main anticipated (marginal) contaminant for A=62 is ^{62}Ga. For comparison, the ^{63}Ga yield with a surface ionization ion source and the same UC$_x$ target is 2.1E3/μC, whereas the ^{62}Mn yield is 7E5/μC.

B. Technical Interest and Method

In this experiment, we would charge breed and trap the ions with three different time periods : 50 ms, 200 ms and 400 ms. In these three cases, a significant change in daughter content (Fe) should be observed in the post-accelerated radioactive ion beam. In Table I, the ^{62}Fe content is given as % of the total beam. The ^{62}Mn lifetime of 671(5) ms was utilized in this calculation. These percentages are roughly the same for ^{61}Fe, seen the similar half life of 670(40) ms. The Monte Carlo simulation of the in-trap decay of mother isotopes, incorporating preliminary assumptions on the loss of the decay products in the REXTRAP and EBIS (program and information from [1]), are included in the table, together with the analytical calculation. It is seen that for longer breeding times, larger decay losses are

T$_{Breeding}$= T$_{Trapping}$[ms]	% Fe Analytical	Simulation	Counts/Shift Fe (877 keV)	Ag (415 keV)
50	7%	6%	16	1634
200	26%	12%	56	1634
400	46%	29%	96	1634

TABLE I: Expected count rates for the Coulomb excitation of the daughter isotope ^{62}Fe ($2^+_1 \rightarrow 0^+_1$=877 keV) and the target nucleus ^{109}Ag, assuming a 2 μA proton beam, a ^{109}Ag target thickness of 4 mg/cm^2, a yield of 7E5 ^{62}Mn isotopes/μC, a B(E2) for ^{62}Fe of 574 e^{2}fm^4 (taken from [5]), a zero diagonal matrix element for ^{62}Fe ($Q_{2^+_1}$=0 eb), a beam energy of 2.9 MeV/u, no difference in target excitation cross section induced by Fe and Mn and the straightforward estimation of the Iron content in the beam, described in the introduction.

predicted by the simulation. The results for A=61 are similar. Three methods are available to quantify the changing composition of the post-accelerated beam :

1- With the newly installed Bragg ionization chamber at the end of the REX beamline (2007), the beam composition can be measured from the specific energy loss properties of the different ions. From a test experiment in 2007, the resolution of this detector was measured with a composite beam of ^{12}C, ^{16}O, ^{20}Ne and ^{40}Ar. Within 2σ, the Z resolution was measured to be 0.5 up to Z=18. For higher Z this will become worse, but it is expected that Fe and Mn can still be separated. The detector was operated with standard CF4 gas in 2007. The usage of P10 gas would increase the resolution, but currently this possibility does not exist in ISOLDE. From a test experiment in Munich with P10 gas, Nickel (Z=28) and Iron (Z=26) could nicely be resolved [4]. The presence of a small Ga contamination is in this case not severe, since it gives an additional calibration point for the Bragg chamber. This measurement gives a direct indication for the ratio of Fe over Mn isotopes in the beam.

2- Together with the Bragg chamber, a Ge detector monitors the gamma rays following the β-decay of the radioactive isotopes in the beamdump. Ex. ^{62}Fe can be monitored with the 100% intensity 506 keV gamma ray and ^{62}Mn with the 90(9)% intensity 877 keV line. These two intense β-decay lines provide a good monitor of the relative intensity of both isotopes. The relative intensity of β-decay gamma rays, observed for different breeding and trapping times, contain information on decay losses in the REXTRAP and EBIS. At the same time, a beam stopper can be placed in the beam in the center of MINIBALL. With the accurately known efficiency of the gamma spectrometer, this provides an additional tool to check the ratio of Fe and Mn.

3- In 2004, a ΔE-E (gas-Si) telescope was tested successfully on the REX zero degree beamline. By steering the REX beam in this telescope, an accurate measurement of Z and A could be achieved. With this telescope a Z resolution better then 1 could be achieved up to Z>28.

We ask for 4 shifts to perform these test measurements with different trapping and breeding times for ^{61}Mn (with known half life) and ^{62}Mn (with two half life components and a strong physics interest). If the in-trap decay of mother isotopes to produce a post-accelerated beam of daughter nuclei works, this could open new possibilities to produce post-accelerated beams at ISOLDE which were before not accessible (ex. K to Ca decay).

For the Bragg chamber measurements, no secondary target can be placed in the beam since this worsens the Z resolution of the detector. Depending on the result and the yield, the physics case for the A=62 beam described below, can be obtained with 200 ms trapping and breeding time in 4 shifts (aiming at a statistics of >200 counts in the Fe $2^+_1 \rightarrow 0^+_1$ peak and assuming the analytical result for the Iron content) and for 400 ms trapping and breeding time in 3 shifts. At the same time, the Coulex of ^{62}Mn (in all cases still expected to be the dominant beam component) provides information on the level structure of this nucleus, which is so far unknown. The proposed secondary target to induce Coulomb excitation is a 4 mg/cm^2 ^{109}Ag target. This nucleus has a large Coulex cross section and the two main target de-excitation lines are well below the 877 keV line of Fe, making the spectrum in this region particularly clean. Possible de-excitation lines from Mn might be blinded by these target lines, but this cannot be anticipated since no spectroscopic information is available on ^{62}Mn. Gamma rays following Coulomb excitation will be detected by the MINIBALL germanium array. Both Iron and Mangenese are kinematically separated from the recoiling target nucleus in the standard DSSSD used with MINIBALL.

In Table I, the expected count rates for the Coulomb excitation of ^{62}Fe and ^{109}Ag are given for different charge breeding and trapping times (T$_{Breeding}$=T$_{Trapping}$). The analytical result for the Fe content is used in this.

C. Nuclear Structure Interest

The apparent onset of deformation in neutron rich Fe isotopes was firstly recognized from the decreased E(2_1^+) in ^{64,66}Fe, probed in a β-decay experiment of neutron rich Mn isotopes at ISOLDE in 1998 [2]. A similar decrease of the $2+_1$ state has been observed in the same region around the neutron number N=40, for Z<28 in Cr and Fe and for Z>28 for Zn, Ge and others (see Fig. 1B). This decreased E(2_1^+) state is in most cases accompanied with and increased B(E2) values, as can be seen from Fig. 1A. This apparent onset to deformation around N=40 has been attributed to the presence of the $\nu g_{9/2}$ orbital, which is an intruder orbital in the pf-shell.

Large scale shell model calculations have difficulties in reproducing this gradual onset to collective behavior in this region of the nuclear chart. This can mainly be attributed to the large valence spaces needed for these nuclei (and the subsequent computational problems) and the residual interaction needed in truncated valence spaces. In Fig. 1A, large scale shell model calculation from Caurier *et al.* are shown for the Fe isotopes (data taken from [6]). These calculations crucially depend on the inclusion of the $g_{9/2}$ and $d_{5/2}$ orbital. The measurement of the B(E2) value in ^{62}Fe can thus be a valuable input to test and/or fit the currently available residual interactions.

Recently, a life time measurement at INFN, Legnaro has yielded a first preliminary B(E2,$0_1^+ \rightarrow 2_1^+$) value for ^{62}Fe of 0.057 e^2b^2 [5], included in Fig. 1A. It is clear that this result is not in agreement with the theoretical results from [6], also included in Fig. 1A. Currently, the preliminary lifetime value from Legnaro has an error bar of 21%. Provided we can give an accurate estimate of the beam composition, we can reduce this error bar to below 20% with 200 counts in the Fe Coulex peak.

The life time value from [5] can be used as a constraint when fitting the matrix element, related to the B(E2) value. In this way, an estimate can be given on the magnitude of the quadrupole moment. In case the quadrupole moment is >0.38 eb, the sign of the quadrupole moment can be determined with 200 counts in the $2_1^+ \rightarrow 0_1^+$ transition.

The latter is possible due to the two distinct center of mass (CM) ranges, given by the detected recoiling target and projectile nuclei, which are separated in the particle detector. Assuming a spherical ($Q_{2_1^+}$=0 eb) nucleus, an oblate ($Q_{2_1^+}$=0.38 eb) or prolate ($Q_{2_1^+}$=-0.38 eb) deformation, 55%, 61% or 49% (respectively) of the total number of counts is detected in coincidence with a scattered Fe ion. The determination of the quadrupole moment would give a strong indication on the deformation of ^{62}Fe. From the systematics in Fig. 1C it can be seen that the majority of nuclei in this region is prolate deformed. The three quadrupole moments known in ^{54,56,58}Fe (see Fig. 1C) were determined in 1981 [7] also by Coulomb excitation.

III. BEAM TIME REQUEST

We ask for **1 shift of setup time** (=testing of the Bragg chamber with stable beam and linac optimization), **4 shifts for the decay-loss investigation with different trapping and charge breeding times** and **4 shifts** to obtain a relevant physics result for A=62. In total we ask for **9 shifts** of REX beam time with a radioactive Mn beam.

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[1] F. Ohlsson, Ph.D. thesis, Chalmers University of Technology (2007).
[2] M. Hannawald *et al.*, Phys. Rev. Lett. **82**, 1391 (1999).
[3] O. Sorlin *et al.*, Nucl. Phys. A **669**, 351 (2000).
[4] W. Weinzierl, Ph.D. thesis, Technische Universitat Munchen (2006).
[5] A. Gadea *et al.*, Presentation at the Zakopane Conference on Trends in Nuclear Physics, Poland (2006).
[6] E. Caurier *et al.*, Eur. Phys. J. A **15**, 145 (2002).
[7] M. LeVine *et al.*, Phys. Rev. C **23**, 224 (1981).

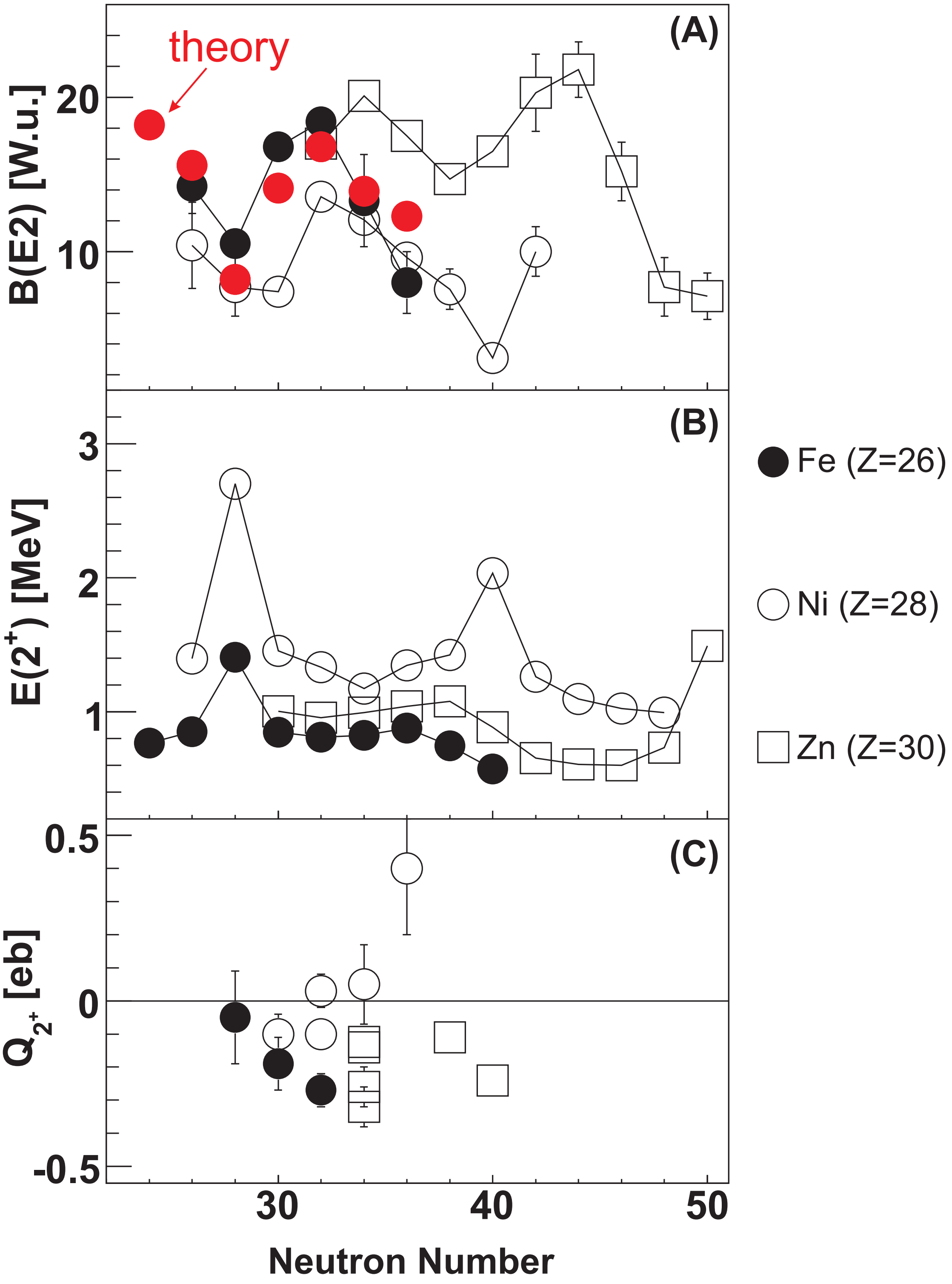

FIG. 1: (A) B(E2) values in W.u. for even-even isotopes of Iron (Z=26), Nickel (Z=28) and Zinc (Z=30). (B) $E(2_2^+)$ values and (C) $Q_{2_1^+}$ values for the same isotopes. Theoretical values from [6] are given in (A) for Fe isotopes.