

**Proposal for an Experiment at GSI, Darmstadt**Submit to **EA32**Title of Proposal: **Beta-decay of very neutron-rich Rh, Pd, Ag nuclei including the r-process waiting point 128Pd** New Proposal       Continuation of Previous Experiment with Exp. No.:Spokesperson: **Montes, Fernando, Dr.****f.montes@gsi.de****GSI****Planckstr. 1, 64291 Darmstadt, Germany**Participants: **Montes, F., GSI Darmstadt Germany, f.montes@gsi.de****Davinson, T., The University of Edinburgh UK, td@ph.ed.ac.uk****Faestermann, T., Technische Universität München Germany, Thomas.Faest...****Geissel, H., GSI Darmstadt Germany, h.geissel@gsi.de**

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GSI Contact Person: **Montes, Fernando**UNILAC: SIS: ESR: Phelix Laser: 

Requested Beam Properties and Experimental Equipment:

- |   |   |
|---|---|
| a) Ion Species (Charge State):          | <b>238U</b>                               |
| b) Intensity (Particle nA):             | <b>2 10<sup>9</sup> ions/spill</b>        |
| c) Energy (MeV/u):                      | <b>1 GeV</b>                              |
| d) Target Station:                      | <b>FRS</b>                                |
| Target Station Phelix Laser:            |   |
| e) Special Requests on Beam Properties: | <b>Extraction length 6 seconds</b>        |
| f) Special Target Requirements:         | <b>5 g/cm<sup>2</sup> Be target at S2</b> |

Requested Beam Time (in Shifts of 8 Hours each)

Primary: **30**Secondary: **6**Phelix Laser: **0**Number of Runs: **1**

Detailed description of the Proposal: Please attach an experiment description (max. 10 pages including figures) which should summarize the scientific justification and relevant technical details for the proposed experiment. For a continuation request, a brief status report of the previous as well as an outline of the future experiments should be given.

Attachment (PDF file): **betadecay.pdf**

**SUPPLEMENTARY FORM FOR SAFETY ASPECTS OF A PROPOSAL**

Title: **Beta-decay of very neutron-rich Rh, Pd, Ag nuclei including the r-process waiting point 128Pd**

Spokesperson: **Montes, Fernando, Dr.**  
**GSI, 64291 Darmstadt, Germany**

GSI-Contact Person: **Montes, Fernando**

1. General Safety

- a. Do you use combustible or hazardous gases within your experiment Yes  No   
(e.g. gas target, gas detectors)?  
What sort of gases?  
Which quantities or flow rates?
- b. Do you use other dangerous (e.g. toxic, inflammable, biologically hazardous etc.) materials within your experiment? Yes  No   
What sort of materials?  
Which quantities?
- c. Is your vacuum set-up equipped with fragile parts like thin glass or foil windows etc. (danger of implosion)? Yes  No   
Brief description of the construction: **Standard FRS vacuum window at S4**
- d. Is it intended to move heavy parts for setting-up your experiment or during the experiment? Yes  No   
Brief description of the equipment and working procedure:

2. Radiation Safety

- a. Do you use radioactive sources or materials on-site? Yes  No   
What sources? **Standard n,e,alpha calibration sources**  
Which activities? **Standard**
- b. Is it intended to direct the beam through air or other gases? Yes  No   
Beam sort, energy, intensity: **Mixed beam ~750 Mev/u, 10<sup>3</sup> pps**  
Distance through air or gas: **About 2 m at the final focal plane of the FRS**

3. Electrical/Laser Safety

- a. Do you use electrical instruments on-site? Yes  No   
Max. Voltage/max. current: **3kV HV supply (standard FRS equipment)**
- b. Do you use high-intensity radio frequency (RF) sources on-site? Yes  No   
Frequency region/power:
- c. Do you use lasers in your experiment? Yes  No   
Laser-type, max. power:

4. Is there any other special safety aspect to be considered in connection with your proposal? Yes  No

Mar 09, 2006

## $\beta$ -decay of very neutron-rich Rh, Pd, Ag nuclei including the r-process waiting point $^{128}\text{Pd}$

F. Montes<sup>1</sup>, T. Davinson<sup>2</sup>, T. Faestermann<sup>3</sup>, H. Geissel<sup>1</sup>, R. Gernhäuser<sup>3</sup>, M. Gorska<sup>1</sup>, K.-L. Kratz<sup>4</sup>,  
Y. Litvinov<sup>1</sup>, G. Lorusso<sup>5</sup>, A. Musumarra<sup>6</sup>, C. Nociforo<sup>1</sup>, J. Pereira<sup>5</sup>, B. Pfeiffer<sup>4</sup>, H. Schatz<sup>5</sup>,  
C. Scheidenberger<sup>1</sup>, K. Sümmerer<sup>1</sup>, H. Weick<sup>1</sup>, P. Woods<sup>2</sup>, M. Winkler<sup>1</sup>.

<sup>1</sup> GSI, Darmstadt, Germany

<sup>2</sup> The University of Edinburgh, UK

<sup>3</sup> Technische Universität München, Germany

<sup>4</sup> Institut für Kernchemie, Universität Mainz, Germany

<sup>5</sup> NSCL, Michigan State University, USA

<sup>6</sup> Laboratori Nazionali del Sud, INFN Catania, Italy

### Motivation

The astrophysical origin of about half of the elements heavier than iron existing in the universe has been attributed to the rapid (r-) neutron capture process. In addition to astronomic observation studies of the r-process abundance pattern in the solar system and in metal-poor r-process enriched stars, the r-process has motivated not only experimental but also theoretical studies of neutron-rich nuclei.

To correctly link astronomical observations with theoretical models, reliable nuclear physics are needed. To date, about 50 nuclei along or near the r-process path have limited experimental information. Because the proposed path of the r-process in the nuclei chart runs far away from stability most of the relevant nuclear physics is experimentally unknown and cannot be predicted theoretically with sufficient accuracy. Furthermore, the origin of the r-process is still a matter of debate and no astrophysical scenario has been identified with certainty.

The region around the  $N = 82$  shell closure is particularly important in r-process studies because it is responsible for the observed  $A = 130$  peak in the solar system r-process abundance distribution. The region  $A = 113 - 124$  is also very sensitive to nuclear structure properties as shell quenching effects are believed to explain the underabundance observed when comparing r-process calculations with the solar r-process abundance in this region[2]. In addition, neutrino spallation reactions may also affect abundances in this region[3] and there are also indications that a second r-process is needed to explain the solar abundances of some nuclei in the  $A = 90 - 130$  mass region based on observations of the abundance pattern in r-process-enhanced extremely metal-poor stars [4, 5]. In order to disentangle the various neutron capture processes potentially contributing to the origin of the  $A = 90 - 130$  nuclei in nature, reliable nuclear data are required.

The most important nuclear data inputs necessary to successfully model the r-process are  $\beta$ -decay half-lives ( $T_{1/2}$ ) of the participating nuclei,  $\beta$ -delayed neutron emission branchings ( $P_n$ ) and nuclear masses. Because of the relatively long half-lives of nuclei participating in the r-process path when it reaches the  $N = 82$  shell closure, these isotopes serve as bottlenecks where material accumulates. While the neutron separation energies determine the location of the bottlenecks, the  $\beta$ -decay half-lives determine how much material accumulates on them during the process. When the neutron flux is exhausted,  $P_n$  values change the final abundance composition while the material finally decays back towards stability.

Te (52)	Te122	Te123	Te124	Te125	Te126	Te127	Te128	Te129	Te130	Te131	Te132	Te133	Te134	Te135
						>99		>99		>99	>99	>99	>99	19.000
Sb (51)	Sb121	Sb122	Sb123	Sb124	Sb125	Sb126	Sb127	Sb128	Sb129	Sb130	Sb131	Sb132	Sb133	Sb134
						>99	>99	>99	>99	>99	>99	>99	>99	0.780
Sn (50)	Sn120	Sn121	Sn122	Sn123	Sn124	Sn125	Sn126	Sn127	Sn128	Sn129	Sn130	Sn131	Sn132	Sn133
						>99	>99	>99	>99	>99	>99	56.000	39.700	1.450
In (49)	In119	In120	In121	In122	In123	In124	In125	In126	In127	In128	In129	In130	In131	In132
	>99	3.080	23.100	1.500	5.980	3.110	2.360	1.600	1.090	0.840	0.610	0.320	0.280	0.201
Cd (48)	Cd118	Cd119	Cd120	Cd121	Cd122	Cd123	Cd124	Cd125	Cd126	Cd127	Cd128	Cd129	Cd130	Cd131
	>99	>99	50.800	13.500	5.240	2.100	1.250	0.650	0.506	0.370	0.340	0.270	0.200	0.180
Ag (47)	Ag117	Ag118	Ag119	Ag120	Ag121	Ag122	Ag123	Ag124	Ag125	Ag126	Ag127	Ag128	Ag129	Ag130
	72.800	3.760	2.100	1.230	0.780	0.520	0.293	0.172	0.166	0.107	0.079	0.058	0.046	
Pd (46)	Pd116	Pd117	Pd118	Pd119	Pd120	Pd121	Pd122	Pd123	Pd124	Pd125	Pd126	Pd127	Pd128	Pd129
	11.800	4.300	1.900	0.920	0.492	0.285	0.175	0.174	0.038					
Rh (45)	Rh115	Rh116	Rh117	Rh118	Rh119	Rh120	Rh121	Rh122	Rh123	Rh124	Rh125	Rh126	Rh127	Rh128
	0.990	0.688	0.394	0.266	0.171	0.136	0.151							
Ru (44)	Ru114	Ru115	Ru116	Ru117	Ru118	Ru119	Ru120	Ru121	Ru122	Ru123	Ru124	Ru125	Ru126	Ru127
	0.510	0.405	0.204	0.142	0.123									
Tc (43)	Tc113	Tc114	Tc115	Tc116	Tc117	Tc118	Tc119	Tc120	Tc121	Tc122	Tc123	Tc124	Tc125	Tc126
	0.170	0.091	0.073											
Mo (42)	Mo112	Mo113	Mo114	Mo115	Mo116	Mo117	Mo118	Mo119	Mo120	Mo121	Mo122	Mo123	Mo124	Mo125
	70	71	72	73	74	75	76	77	78	79	80	81	82	83

Figure 1:  $^{112}\text{Mo}$  to  $^{135}\text{Te}$  mass region showing the region of interest. The isotopes for which we propose to study the  $\beta$  decay half-lives are colored in orange and yellow.  $P_n$  values in the proposed experiment can be measured for the isotopes colored in orange. The r-process waiting points predicted with the ETFSI-Q mass model are framed with black thick lines. Stable isotopes are shaded with gray. Experimental half-lives are given in seconds below the names of the isotopes.

Figure 1 shows the proposed r-process path along the nuclear chart and the current limit of known  $T_{1/2}$  in this region. Only the half-lives of  $^{130}\text{Cd}$  and  $^{129}\text{Ag}$  are known experimentally in the r-process path at or “bellow” the N=82 shell closure. The known  $P_n$  values are still too small or too far away (with the exception of  $^{120}\text{Rh}$ ) to have a direct impact on r-process calculations and no  $P_n$  value is known experimentally at the shell closure.

Properties of nuclei along the r-process path and the astrophysical conditions used in the modeling are reflected in the calculated abundance pattern. Because the calculated abundances directly reproduce the observed r-process abundances, reliable nuclear input is a requisite to obtain astrophysical conditions independent from astrophysical models. Bottleneck abundances for different neutron densities at the N=82 shell closure are shown in Fig. 2. In one of the most promising r-process scenarios, the neutrino-heated wind in core-collapse supernovae, the neutron density starts around  $10^{28-30}\text{ cm}^{-3}$  and eventually drops to around  $10^{22}\text{ cm}^{-3}$  when freezeout occurs. Fig. 2 can thus be seen as a progenitor abundance distribution before freezeout occurs with the time axis going from left to right. Of the progenitor bottleneck isotopes involved, only  $^{128}\text{Pd}$  does not have any experimental information available. Moreover, because  $^{128}\text{Pd}$  is a bottleneck of the r-process, its decay has implications in the predictions of the Th, U cosmochronometers in ultra-metal poor stars.

We therefore propose the measurement of  $\beta$ -decay half-lives and  $P_n$  values for the very neutron-rich Rh-Pd-Ag isotopes shown in Fig.1. While the half-lives of  $^{125-128}\text{Pd}$  and  $^{122-125}\text{Rh}$  will be measured for the first time, the statistical uncertainty of the known  $^{121}\text{Rh}$  and  $^{124}\text{Pd}$  half-lives will be greatly reduced. All the proposed  $P_n$  values are currently unknown. Expected half-lives range from milliseconds to seconds while

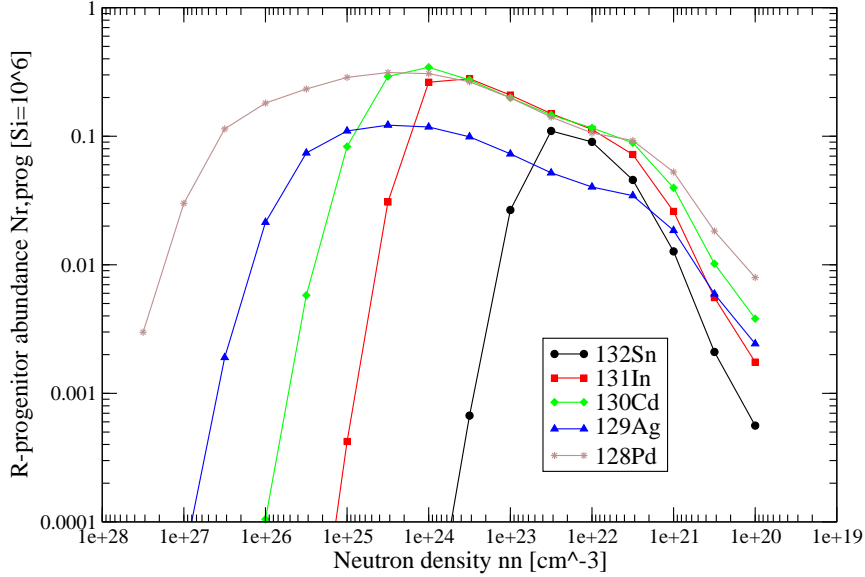


Figure 2: Calculated r-process abundances of the N=82 bottleneck isotopes as a function of neutron density. Taken from [6].

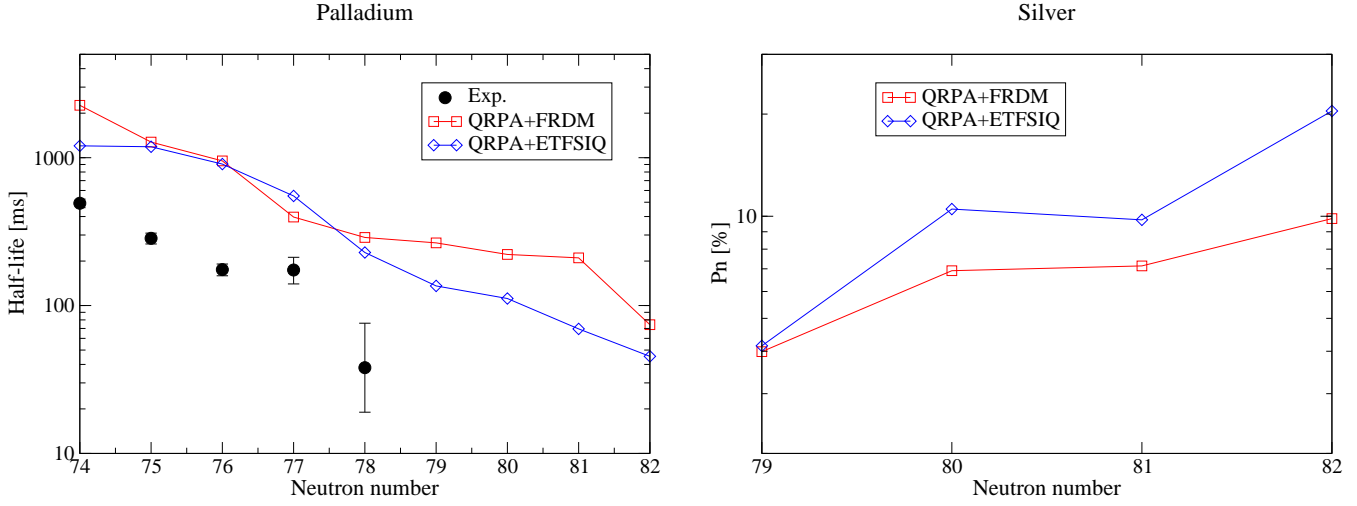
expected  $P_n$  values are expected from 2 to 25%. Besides the direct influence of the  $P_n$  values and the  $^{128}\text{Pd}$  half-life in r-process calculations, the remaining half-lives can be used as gross estimates of nuclear structure. Comparison of theoretical predictions with measured half-lives and  $P_n$  values will give indication of the strength of the shell closure at N=82. Furthermore, the new measurements will provide a better test ground from which more reliable extrapolations can be made to more exotic nuclei.

Fig. 3(a) and Fig. 3(b) show existing experimental information along with theoretical estimates of the desired isotopes. Theoretical predictions are based on the quasi-particle random-phase approximation (QRPA)[7] coupled with the FRDM[8] and ETFSIQ[9] mass models. These measurements will provide direct input in r-process models and will solve discrepancies between theoretical models crucial to our understanding of the abundance pattern in this mass region. The proposed experiment is expected to begin a series of measurements of beta decay properties of nuclei with astrophysical interest that together with mass and lifetime measurements at the ESR[10] will improve the reliability of nuclear physics input in astrophysical calculations.

## Experimental details

In the proposed experiment neutron rich nuclei are produced in two steps. First, a beam of  $^{132}\text{Sn}$  is produced by fission of  $^{238}\text{U}$  accelerated to 1 A GeV impinging onto a 2400 mg/cm<sup>2</sup> Pb target and then transmitted to the intermediate image plane (F2) of the FRS. Secondly, the specific neutron-rich isotopes are produced by fragmentation of the  $^{132}\text{Sn}$  beam in a 5500 Be mg/cm<sup>2</sup> target located in F2. The reaction products after fragmentation are separated according to mass and charge in the second part of the FRS and unambiguously identified. Magnetic rigidity, time-of-flight, energy loss and position of each fragment is measured event-by-event using the standard set of detectors at the F2 and F4 planes at the FRS.

A similar two-step reaction scheme has been discussed before in [11] and it is predicted to give the highest rates for the particles of interest than by pure fragmentation or fission reactions. Cross sections for the fission



(a) Beta decay half-lives for Pd neutron-rich isotopes.

(b) Beta delayed neutron emission probabilities for Ag neutron-rich isotopes.

Figure 3: Experimental data is shown when available. Theoretical predictions are based on the quasi-particle random-phase approximation (QRPA)[7] coupled with the FRDM[8] and ETFSIQ[9] mass models.

process were taken from the results of a previous GSI experiment[12]. Theoretical fragmentation cross sections using EPAX[13] and ABRABLA/COFRA[14] differ, and because COFRA rates are believed to be more accurate, estimates based on COFRA were used in the calculations. Accepted experiment E294[15] plans to measure fragmentation cross sections of neutron-rich nuclei and in particular the ones of interest.

Once the neutron-rich nuclei are transmitted to F4, they are slowed down in a variable degrader and stopped in an implantation detector at F4. An overview of the proposed setup is shown in Fig. 4. The implantation detector consists of a stack of segmented silicon detectors where each implantation is detected and recorded along with its position and time.  $\beta$  particles are detected in Si detectors and spatially correlated with implantations.  $\beta$  decay half-lives will be determined by detecting the time difference between implantation and decay. In addition, a neutron detector will be used to measure neutrons emitted in coincidence with a  $\beta$  decay.  $P_n$  values are extracted using a ratio between  $\beta - n$  coincidences and  $\beta$  decays for a specific isotope. The neutron detector consists of 3 concentric rings of  $^3\text{He}$  proportional gas counters embedded in a polyethylene moderator matrix. Expected neutron energies are in the range of hundreds of keV where the neutron detector efficiency is roughly 30%. A similar setup was used in a previous GSI experiment to study the  $\beta$ -decay of neutron-rich Te isotopes[16].

## Beam time request

Table 2 shows expected implantation rates, total number of detected  $\beta$  particles and total number of detected  $\beta$ -neutron coincidence events. These numbers are based on an incident  $^{238}\text{U}$  beam intensity of  $2 \times 10^9$  ions/spill and a lead target of  $2400 \text{ mg/cm}^2$ . Particle identification of the secondary beam  $^{132}\text{Sn}$  and optimization of the transmission to F2 will be done at the beginning of the experiment and we expect a rate of around  $10^4$   $^{132}\text{Sn}$  ions at F2 assuming a transmission of 8% calculated with the program MOCADI. Two different settings centered at  $^{125}\text{Pd}$  and  $^{128}\text{Pd}$  in the second part of the FRS will be used.

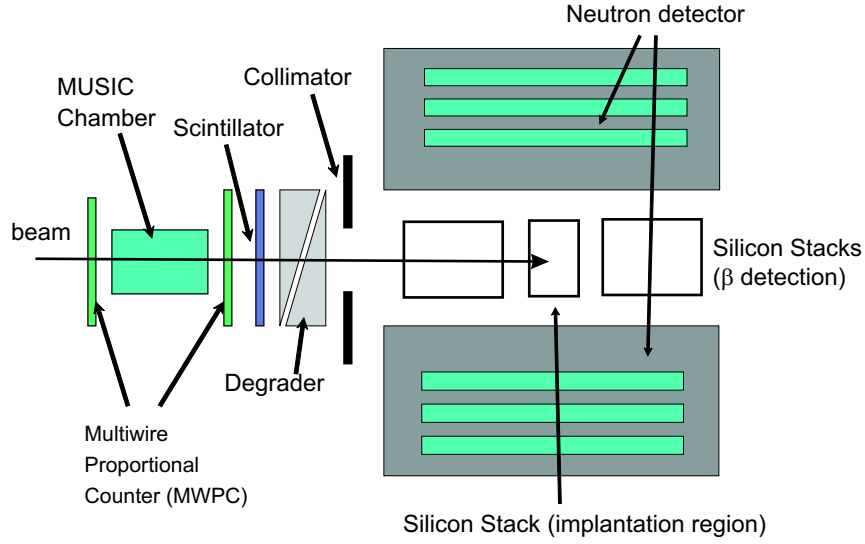


Figure 4: Schematic Diagram of the experimental setup at the FRS focal plane F4.

Table 1: Calculated implantation rates, detected  $\beta$  particles, and detected  $\beta$ -neutron coincidence events ( $\beta$ -n events) for the nuclei of interest for the different FRS fragment settings. Predicted  $P_n$  values are taken from the QRPA calculations in Ref. [2] and Ref. [17].

Isotope	Rate ( $10^{-3} \text{ s}^{-1}$ )	Detected $\beta$ particles	Detected $\beta$ -n events	$P_n$ (%)
Central Fragment: $^{128}\text{Pd}$		12 shifts		
$^{129}\text{Ag}$	2.7	282	17	13.1
$^{128}\text{Ag}$	1.4	145	4	4.9
$^{128}\text{Pd}$	0.4	34	2	7.6
$^{127}\text{Pd}$	0.8	86	2	3.9
$^{126}\text{Pd}$	1.2	122	2	1.5
$^{125}\text{Pd}$	0.8	75	1	1.5
$^{126}\text{Rh}$	0.1	7	1	29.4
$^{125}\text{Rh}$	0.3	25	2	16.9
$^{124}\text{Rh}$	0.5	55	3	11.2
$^{123}\text{Rh}$	0.8	74	5	12.5
$^{122}\text{Rh}$	0.5	46	3	10.5
Central Fragment: $^{125}\text{Pd}$		15 shifts		
$^{129}\text{Ag}$	3.5	394	24	13.1
$^{128}\text{Ag}$	9.0	1166	26	4.9
$^{127}\text{Ag}$	16.1	2084	44	4.6
$^{126}\text{Ag}$	15.5	2011	39	4.3
$^{127}\text{Pd}$	0.3	36	1	3.9
$^{126}\text{Pd}$	1.4	177	3	2.9
$^{125}\text{Pd}$	4.1	529	4	1.5
$^{124}\text{Pd}$	6.7	861	2	0.4
$^{124}\text{Rh}$	0.2	27	2	11.2
$^{123}\text{Rh}$	0.9	114	7	12.5
$^{122}\text{Rh}$	2.4	304	15	10.5
$^{121}\text{Rh}$	3.4	435	13	6.6

Because F4 will effectively work as a dispersive plane for the reaction fragments, transmission and implantation efficiencies for different isotopes vary widely. Total implantation rates are calculated to be less than 10 ions/s to prevent multiple implantations in the same pixel of the Si detector before the  $\beta$ -decay takes place and to avoid background from accumulated activity in the detector. The accuracy of the measurements depends on statistics and for the case of half-lives, it will range from 10% to 45%. For  $P_n$  values, the accuracy will vary from 15% to 35%.

Based on the intensity estimates we request 27 shifts of beam time and 6 shifts of parasitic  $^{136}\text{Xe}$  beam to calibrate the FRS and detectors before the main beam time.

Table 2: Beam time request

<b>Parasitic beam time</b>			
projectile	beam time		
$^{136}\text{Xe}$ (1 A GeV)	2 days		
<b>Main beam time</b>			
projectile	1 <sup>st</sup> FRS section	2 <sup>nd</sup> FRS section	beam time
$^{238}\text{U}$ (1 A GeV)	FRS calibrations		1 day
$^{238}\text{U}$ (1 A GeV)	$^{132}\text{Sn}$	$^{125}\text{Pd}$	5 days
$^{238}\text{U}$ (1 A GeV)	$^{132}\text{Sn}$	$^{128}\text{Pd}$	4 days
<b>Total requested beam time</b>			
main beam time $^{238}\text{U}$	10 days		
parasitic beam time $^{136}\text{Xe}$	2 days		

## References

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