Novel results on experimental studies of the ^{46}Mn β^+ decay channel and its connection to CCSN

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^{44}Ti nucleosynthesis

- ^{44}Ti and its eventual decay chain are produced in type II supernovae (CCSN). The photons emitted during the decay chain (67.9, 78.4, 1157 keV) are observed by satellite telescopes for gamma-astronomy (i.e., INTEGRAL), making ^{44}Ti a good tracer for SN events.

- ^{44}Ti abundance is quite sensitive to the ^{45}V(p,γ)^{46}Cr reaction rate: the higher the reaction rate [1-3].

- **Main objective:** Obtain the energy of new resonant contribution(s) to the ^{45}V(p,γ)^{46}Cr reaction due to currently unknown excited state(s) of ^{46}Cr.

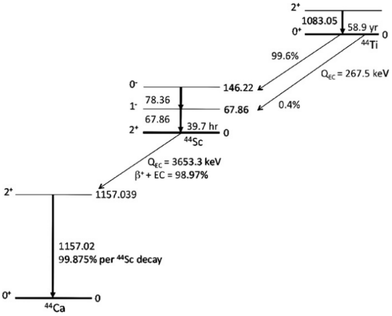


Figura: ^{44}Ti decay scheme taken from [1].

[1] L.-S. The, et al., ApJ **504**, 500-515 (1998);
[2] G. Magkotsios, et al., ApJS **191**, 66-95 (2010);
[3] K. Hermansen, et al., ApJ **901**, 77:90 (2020)

β-delayed proton emission

β-delayed proton emission of ^{46}Mn allows us to seek excited states of the daughter nucleus ^{46}Cr and thus, is an indirect method for measuring resonant contributions to the reaction rate of ^{45}V(p,γ)^{46}Cr.

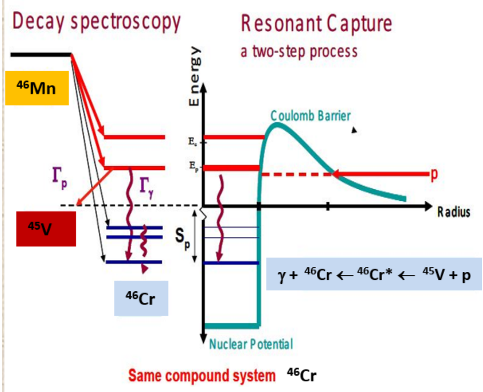
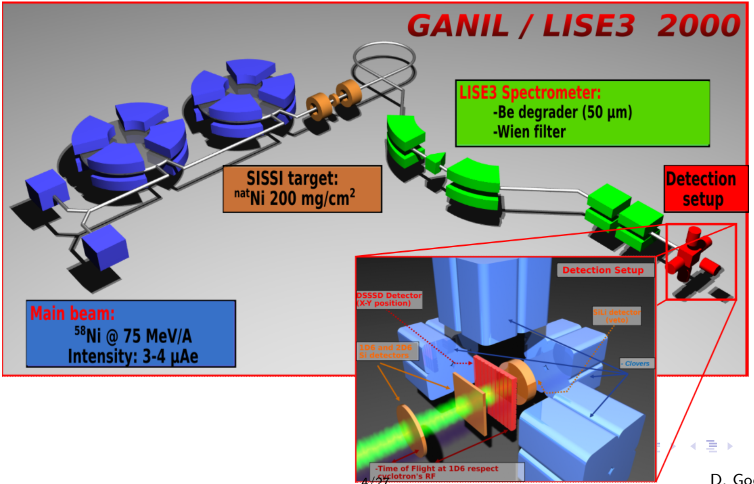


Figura: Adapted from L. Trache, et. al., AIP Conf. Proc 1409-1, 67-70 (2011).

Beam production at LISE@GANIL for E666 experiment

Data was taken from the experiment "Isospin mixing in pf-shell proton emitters" (Code: E666, Spokesperson: Bertram Blank, from CEN-BG, France) developed using the fragment separator LISE@GANIL (Caen, France).



Experimental analysis

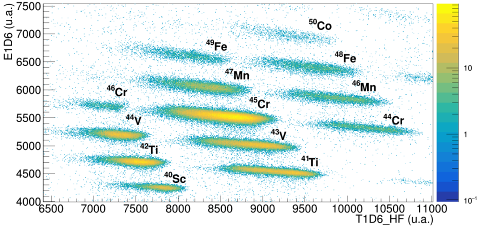
1. As a first step calibrations for the DSSSD X & Y strips, and for the HPGe clover sections were performed.
    1.1 For the DSSSD, a triple α-source (^{239}Pm, ^{241}Am, and ^{244}Cm), and proton emission of well-known nuclei (^{49}Fe, ^{45}Cr, ^{41}Ti, and ^{50}Co) were used.
    1.2 For the HPGe clovers, we use $^{56+60}$Co, ^{207}Bi, and ^{133}Ba+ ^{137}Cs sources.

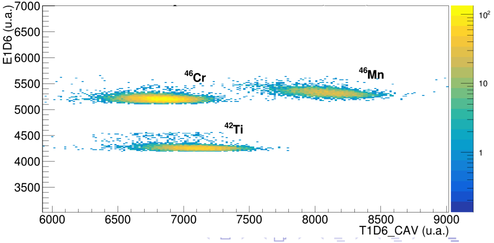
2. Later, the ions of interest were selected, ^{46}Mn, by means of energy loss vs time of flight (ToF) 2D histograms.

3. Finally, decay events corresponding to the ^{46}Mn were identified using spatial and time correlations between the implantation and the decay signals.

^{46}Mn identification

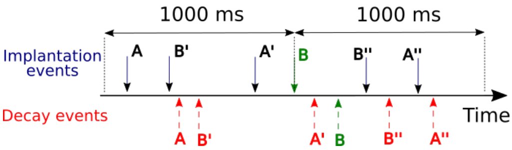
- We use the time of flight (ToF) in the silicon detector to identify the isotope of interest, ^{46}Mn, among others.
- These events were selected using graphical selection windows.
- More than 3.15×10^5 events of ^{46}Mn were selected during approximately 71.5 hrs of data acquisition.



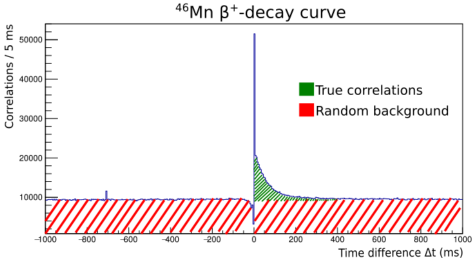


Time-correlated events

The time correlation between the ^{46}Mn implantation events and the decay ones were established in the following way:



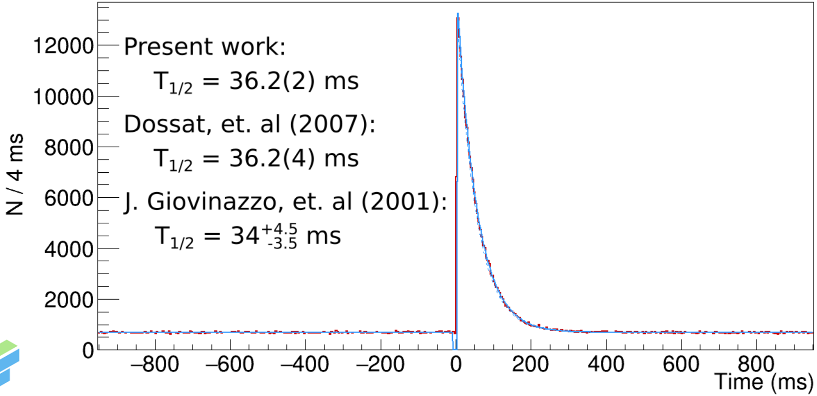
(a)



(b)

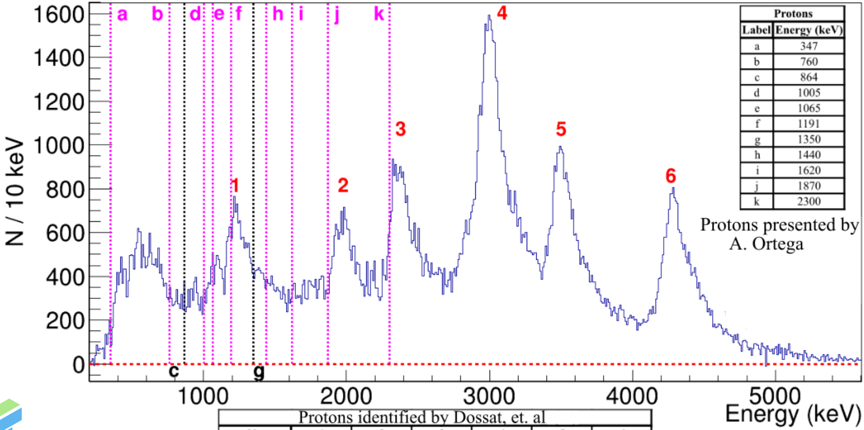
^{46}Mn β-decay curve

The half-life was obtained using a threshold $E_{\text{cut}} > 900$ keV, and the systematic error was set with $E_{\text{cut}} > 1000$ keV.



C. Dossat, et al., *Nuclear Physics A* **792**, 18-86 (2007).
J. Giovinazzo, et al., *Eur. Phys. J. A* **10**, 73-84 (2001).

β-delayed proton energy spectra



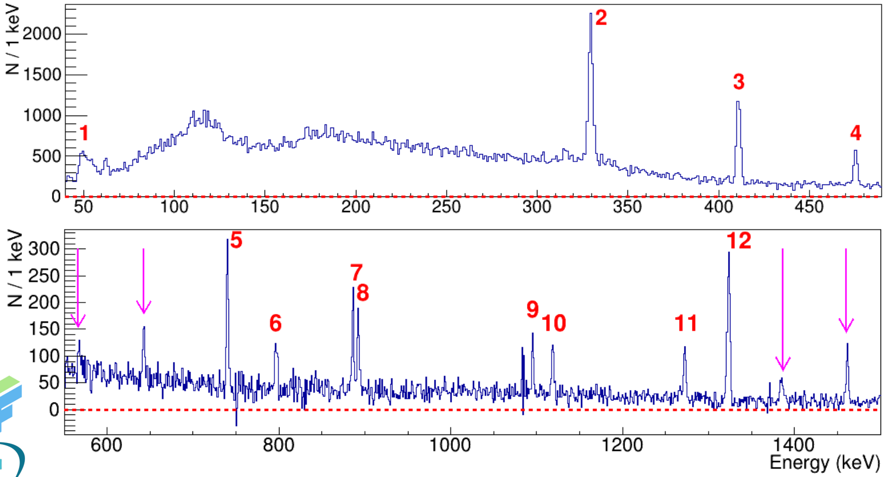
Protons	
Label	Energy (keV)
a	347
b	760
c	864
d	1005
e	1065
f	1191
g	1350
h	1440
i	1620
j	1870
k	2300

Protons identified by Dossat, et. al

No	1	2	3	4	5	6
Energy (keV)	1224	2090	2358	3003	3494	4254

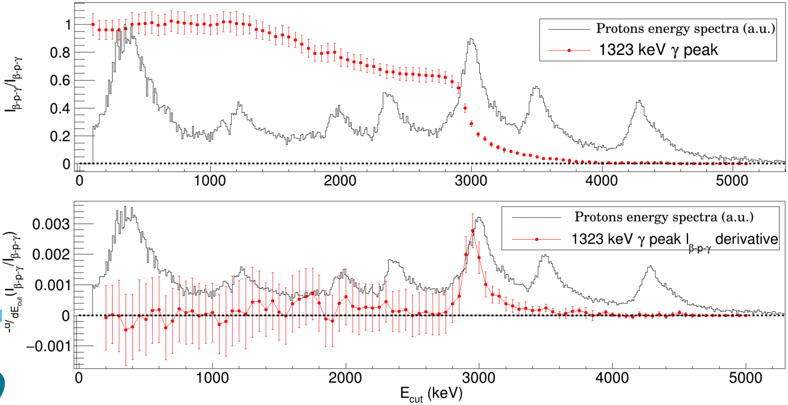
C. Dossat, et al., *Nuclear Physics A* **792**, 18-86 (2007).
A. Ortega, PHD dissertation, Université de Bordeaux (2023).

β-delayed γ energy spectra



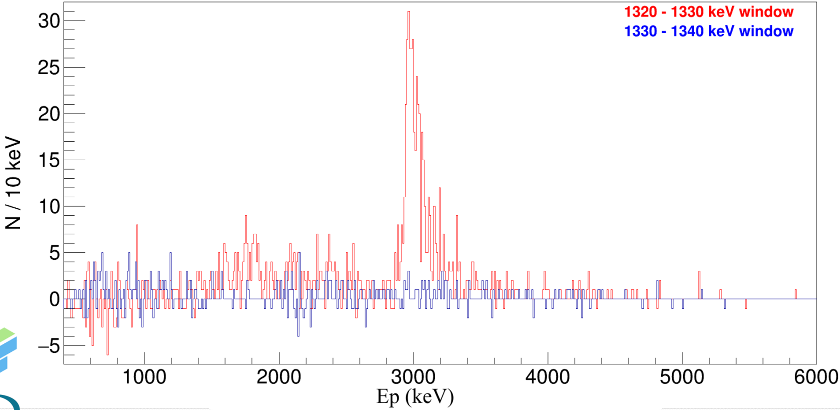
Study of p-γ coincidences for the γ 1323 keV with a novel data analysis methodology

We also studied the variation of the 1323 keV γ-peak intensity by applying energy thresholds (E_{cut}) to the charged particle energy spectra (top panel), and then calculating its numerical derivative (bottom panel):



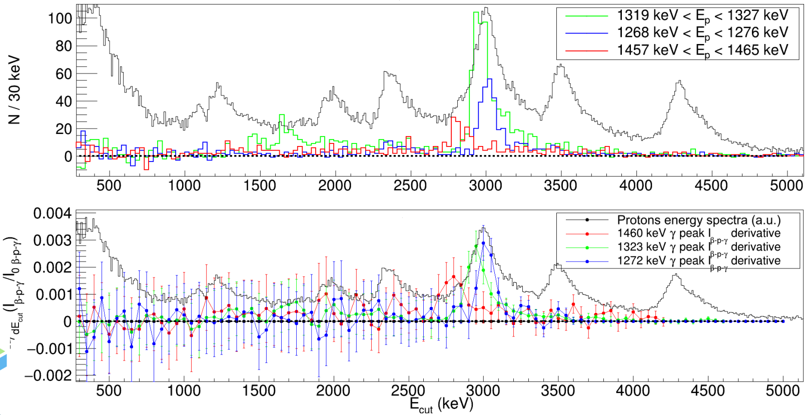
Study of p-γ coincidences using a traditional data analysis, gating in the 1323 keV γ

Charged particle spectra gating in the 1323 keV gamma.



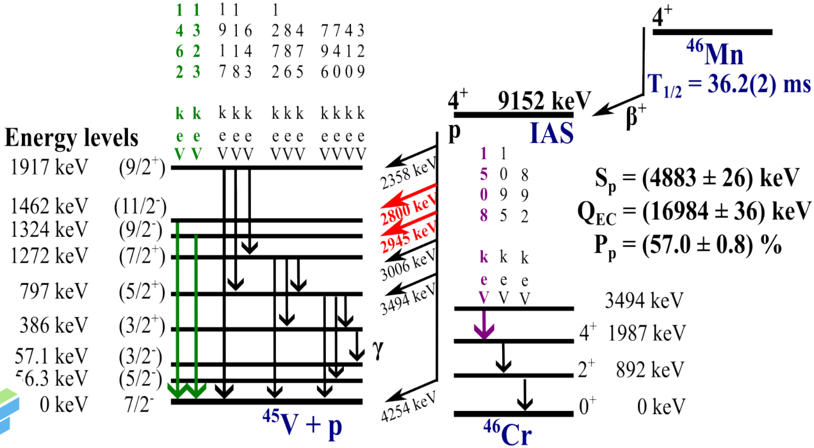
Study of p-γ coincidences for the 1323, 1272, and 1462 keV γs

Charged particle spectra gating in the 1323, 1272, and 1462 keV γs:



Results and interpretation

^{46}Mn decay with new insights



Conclusions and future work

- Energy spectra for charged particles (protons and betas) (200-5600 keV) and photons (40-500 keV and 550-1500 keV) related to the ^{46}Mn β-decay were obtained. Those spectra are compatible with J. Giovinazzo, et al. and Dossat, et al. results, **with greater statistics than previous experiments**.

- A novel experimental data analysis is presented, whose results are corroborated by a different method. Results allow us to identify 2 new proton emissions in the ^{46}Mn β-decay scheme.

- Next steps of the analysis:
  1. To identify relevant contributions, if any, to the ^{45}V(p,γ)^{46}Cr reaction rate due to narrow isolated resonances.
  2. To apply Shell Model, also looking into the mirror nuclei ^{46}Ti, to access to presently unknown excited states in ^{46}Cr.

Thanks for your attention!

- This work is partially supported by DGAPA-UNAM IG101423, CONACyT 314857, MICIU PID2023-147569NB-C21, and MICIU PID2023-147569NB-C22 projects.

- This work was supported by the European Union's Horizon 2020 Framework research and innovation programme 654002 (ENSAR2) and by the Conseil Régional d'Aquitaine, France.

- We thank the support from ASTRA-NUCAP, and the Centro de Estudios Avanzados en Física, Matemáticas y Computación of the University of Huelva, CEAFMC-UHU.

- Special thanks to **EuNPC 2025** organizers for making this talk possible.

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Efficiency evaluation for β and γ detection

γ detection efficiency of HPGe clovers

- The peaks of the γ-calibration sources were used: $^{56+60}$Co, ^{207}Bi, and ^{133}Ba+ ^{137}Cs.
- The efficiency in each peak was found using the equation:

$$\varepsilon_\gamma = \frac{N_\gamma * \text{Div}}{I_\gamma A T_{\text{run}}(1-\tau)}$$

- Then we fit the following fuction $f(E) = \exp a + b \ln E$ to get the γ efficiency detection at any energy value.

β detection efficiency of DSSSD strips

- We used the decay curves of the pure β emitters: ^{46}Cr and ^{42}Ti (within the cocktail beam).
- While doing the exponential fit, the total number of βs detected by the DSSSD strips N_β was counted.
- Then the β detection efficiency was obtained following the equation:

$$\varepsilon_\beta = \frac{N_\beta}{N_{\text{imp}}(1-\tau)}$$

Peak intensities

Measuring $\beta - \gamma$ intensities

- To measure the $\beta-\gamma$ intensities of the γ peaks we use the equation:

$$I_{\beta,\gamma} = \frac{\mathrm{N}_\gamma}{\varepsilon_\beta * \varepsilon_\gamma * \mathrm{N}_{\mathrm{imp}} * (1-\tau)},$$

- where N_γ stands for the number of γs detected, $\mathrm{N}_{\mathrm{imp}}$ for the number of implantation events, τ for the dead time, ε_β for the β detection efficiency, and ε_γ for the γ detection efficiency.

Measuring proton$-\gamma$ intensities

- In the case of the p-γ intensities, we use the equation:

$$I_{p,\gamma} = \frac{\mathrm{N}_\gamma}{\varepsilon_\gamma * \mathrm{N}_{\mathrm{imp}} * (1-\tau)},$$

- where ε_p, the proton detection efficiency, can be considered as 1 for protons with $E_p < 4$ MeV.

E. A. Orrigo, et al., *Physical Review C* **93**, 044336 (2016).

- Table obtained from L.-S. The, et. al., ApJ 504, 500-515 (1998).

TABLE 5

ORDER OF IMPORTANCE OF REACTIONS PRODUCING ^{44}Ti AT $\eta = 0$[a]

Reaction	Slope
^{44}Ti(α, p)^{47}V	−0.394
α(2α, γ)^{12}C	+0.386
^{45}V(p, γ)^{46}Cr	−0.361
^{40}Ca(α, γ)^{44}Ti	+0.137
^{57}Co(p, n)^{57}Ni	+0.102
^{36}Ar(α, p)^{39}K	+0.037
^{44}Ti(α, γ)^{48}Cr	−0.024
^{12}C(α, γ)^{16}O	−0.017
^{57}Ni(p, γ)^{58}Cu	+0.013
^{58}Cu(p, γ)^{59}Zn......	+0.011
^{36}Ar(α, γ)^{40}Ca	+0.008
^{44}Ti(p, γ)^{45}V	−0.005
^{57}Co(p, γ)^{58}Ni	+0.002
^{57}Ni(n, γ)^{58}Cu	+0.002
^{54}Fe(α, n)^{57}Ni	+0.002
^{40}Ca(α, p)^{43}Sc	−0.002

[a] Order of importance of reactions producing ^{44}Ti at $\eta = 0$ according to the slope of $X(^{44}\mathrm{Ti})$ near the standard reaction rates.

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Sensitivity of ^{44}Ti and ^{56}Ni Production in Core-collapse Supernova Shock-driven Nucleosynthesis to Nuclear Reaction Rate Variations

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Abstract

Recent observational advances have enabled high resolution mapping of ^{44}Ti in core-collapse supernova (CCSN) remnants. Comparisons between observations and models provide stringent constraints on the CCSN mechanism. However, past work has identified several uncertain nuclear reaction rates that influence ^{44}Ti and ^{56}Ni production in postprocessing model calculations. We evolved one-dimensional models of 15 $M_\odot$, 18 $M_\odot$, 22 $M_\odot$, and 25 $M_\odot$ stars from zero age main sequence through CCSN using Modules for Experiments in Stellar Astrophysics and investigated the previously identified reaction rate sensitivities of ^{44}Ti and ^{56}Ni production. We tested the robustness of our results by making various assumptions about the CCSN explosion energy and mass cut. We found a number of reactions that have a significant impact on the nucleosynthesis of ^{44}Ti and ^{56}Ni, particularly for lower progenitor masses. Notably, the reaction rates ^{13}N(α, p)^{16}O, ^{17}F(α, p)^{20}Ne, ^{52}Fe(α, p)^{55}Co, ^{56}Ni(α, p)^{59}Cu, ^{57}Ni(n, p)^{57}Co, ^{56}Co(p, n)^{56}Ni

- Not ^{45}V(p,γ)^{46}Cr, but ^{47}V(p,γ)^{48}Cr!

- ^{39}K(p,γ)^{40}Ca and ^{39}V(p,α)^{36}Ar also affect ^{44}Ti abundancy.

- ^{44}Ti is produced when a shock-wave after the core-collapse reaches the α-rich region in the cooling phase ($1 < T_9 < 5$).

- As $\vec{J} = \vec{\ell} + \vec{j_1} + \vec{j_2}$ and $\Pi = \pi_1\pi_2(1)^{-\ell}$, for ^{45}V+p $\rightarrow ^{46}$Cr* and only considering $\ell = 0, 1$ resonant capture then the candidates for resonances are:

$$J^\pi(^{45}\mathrm{V_{gs}}) = 7/2^-; \quad J^\pi(p) = 1/2^+ \Rightarrow J^\pi(^{45}\mathrm{V_{gs}}) = 2^+, 3^+, 4^+, 5^+, 3^-, 4^-$$

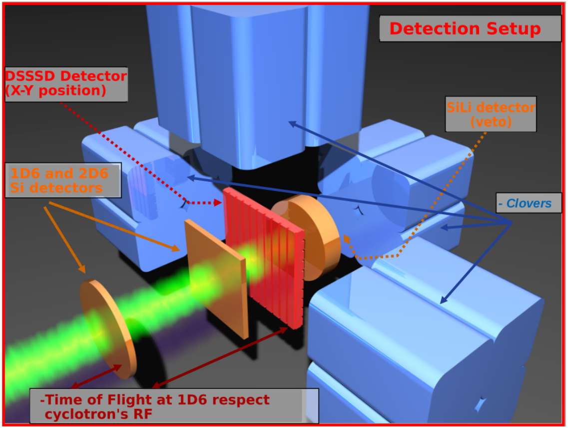
- On the other hand, allowed β-decay transitions follows:

$$\Delta J = 0; \quad \pi_i = \pi_f \quad \text{for Fermi}$$
$$\Delta J = 0, 1; \quad \pi_i = \pi_f \quad \text{for Gamow-Teller}$$

As $J^\pi(^{46}\mathrm{Mn_{gs}}) = 4^+$ and considering only allowed transitions:
$J^\pi(^{46}\mathrm{Cr}^*) = 3^+, 4^+, 5^+$ (2^+,3^- and 4^- could be sufficiently populated but they are strongly inhibited).

Detection setup

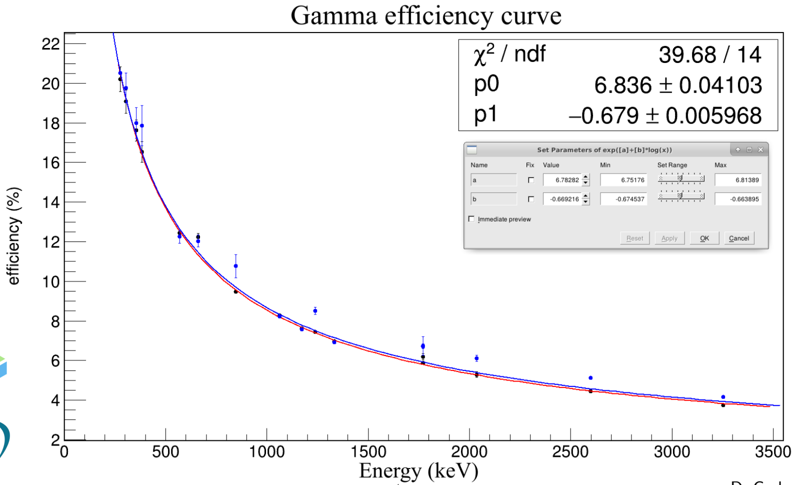
- The primary beam was a $^{58}Ni^{26+}$ at 74.5 MeV/u, which collided with a 230.6 mg/cm^2 thick ^{nat}Ni target.
- With the LISE separator elements, the isotopes to be implanted in the detectors array were selected.
- The detectors array used during the experiment is shown:



Gamma efficiency curve

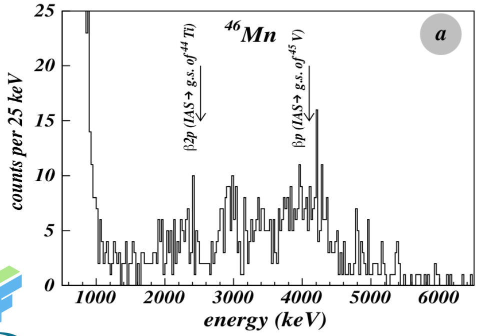
The gamma efficiency curve obtained for the analysis is shown in the next figure:

:

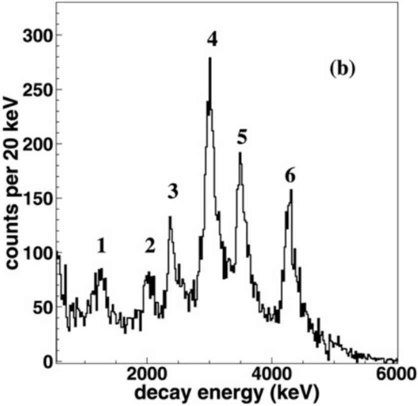


Charged particle espectra

The charged particle spectra obtained by Dossat and Giovinazzo are presented:

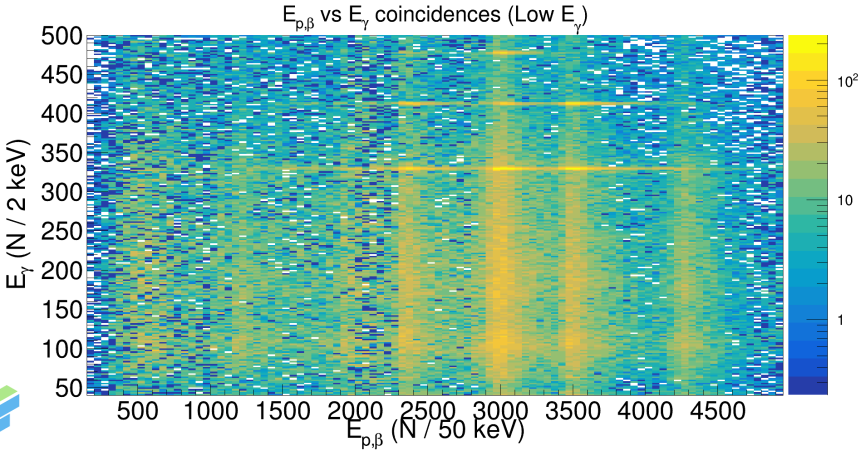


(c)

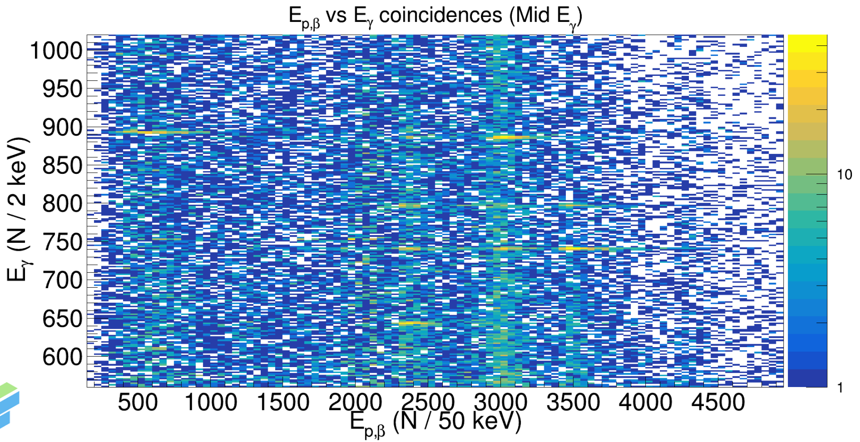


(d)

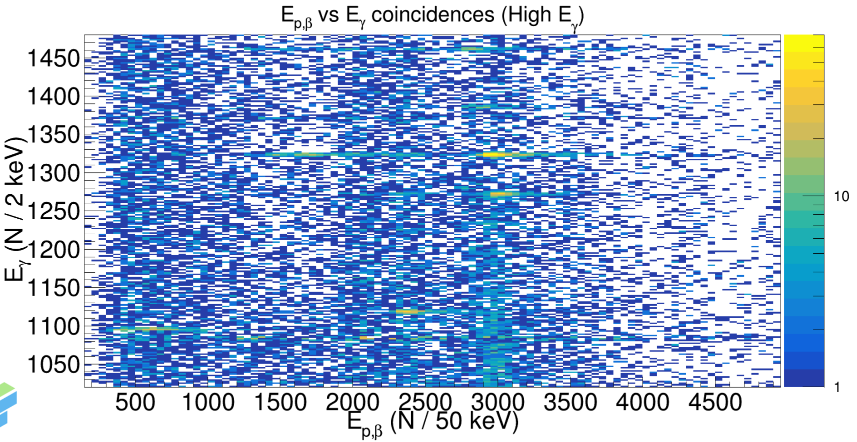
p-γ coincidences for 40-500 keV γ's



p-γ coincidences for 550-1020 keV γ's



p-γ coincidences for 1020-1480 keV γ's



p-γ coincidences for 1480-1940 keV γ's