

## HNPS Advances in Nuclear Physics

Vol 32 (2026)

HNPS2025

HNPS Advances in Nuclear Physics

Hellenic Nuclear Physics Society

**HNPS  
Advances in  
Nuclear  
Physics**

Editors:  
T.J. Mertzimekis  
P. Koseoglou

Proceedings of the  
33rd Hellenic  
Symposium  
on Nuclear Physics  
and Applications  
**HNPS2025**  
National and  
Kapodistrian  
University  
of Athens  
5 & 6 June 2025

33rd Symposium of the Hellenic Nuclear Physics Society

### Progress in Modeling Proton Reactions on Natural Silicon Targets

*Nikolaos Nicolis*

doi: [10.12681/hnpsanp.8982](https://doi.org/10.12681/hnpsanp.8982)

Copyright © 2026, Nikolaos Nicolis



This work is licensed under a [Creative Commons Attribution-NonCommercial-NoDerivatives 4.0](https://creativecommons.org/licenses/by-nc-nd/4.0/).

#### To cite this article:

Nicolis, N. (2026). Progress in Modeling Proton Reactions on Natural Silicon Targets. *HNPS Advances in Nuclear Physics*, 32, 132–135. <https://doi.org/10.12681/hnpsanp.8982>



ARTICLE

# Progress in Modeling Proton Reactions on Natural Silicon Targets

Nikolaos G. Nicolis\*

Laboratory for Nuclear Physics and Applications, National Technical University of Athens

\*Corresponding author: nnicolis@uoi.gr

(Received: 24 Nov 2025; Accepted: 12 Jan 2026; Published: 13 Jan 2026)

## Abstract

We investigate proton-induced reactions on natural silicon, which are of importance to assess radiation damage in semiconductor electronic devices. Excitation functions for isotopes  $^{28}\text{Mg}$ ,  $^{26}\text{Al}$ ,  $^{24}\text{Na}$ ,  $^{22}\text{Na}$ ,  $^{18}\text{F}$ ,  $^{10}\text{Be}$ ,  $^7\text{Be}$  were analyzed at beam energies of 20–150 MeV using EXFOR cross-section data and TALYS-2.0 predictions. Six level density models were tested, with two showing superior accuracy for heavy residue formation. Production of intermediate mass fragments  $^{10}\text{Be}$  and  $^7\text{Be}$  was negligible, consistent with TALYS limitations on fragment emission. Preliminary calculations with the ISABEL intranuclear cascade coupled with the MECO sequential binary decay code are presented, highlighting low-energy validity, limitations, and possible extensions for improved modeling.

**Keywords:** Proton-induced reactions; Nuclear reaction models; Intranuclear cascade; Isotope production; Intermediate mass fragments

## 1. Introduction

The study of nuclear reactions involving protons and natural silicon is essential for understanding radiation damage in semiconductor devices. Silicon-based detectors employed in particle physics and space exploration are exposed to high radiation levels and cosmic rays. High-energy charged particles passing through condensed matter cause disturbances because of the ionization they produce. Ionization is also produced from Silicon recoils in elastic scattering. The resulting errors are recoverable and classified as soft errors. If nuclear reactions occur, both light and heavy products ionize the medium. More important are the modifications of the medium properties due to the production of new nuclear species. The corresponding hard errors result in radiation damage in electronics, such as those employed in space missions and nuclear reactors.

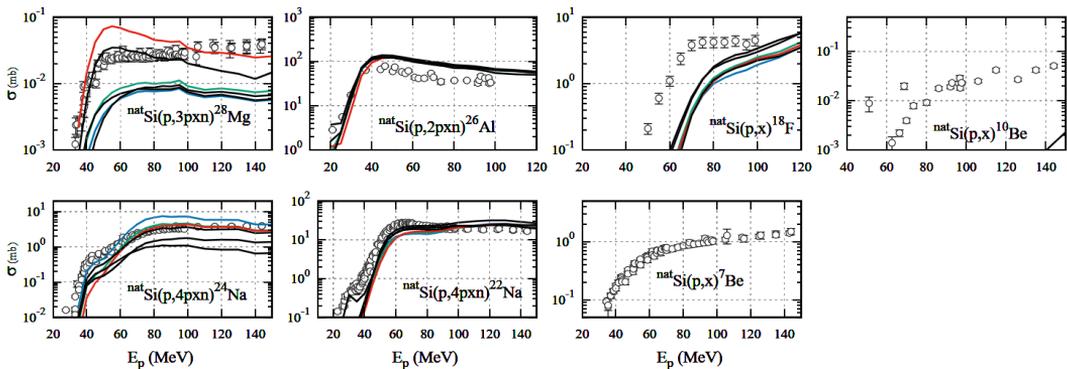
Therefore, it becomes a necessity to obtain a deep understanding of nuclear reactions induced by different projectiles on Silicon [1]. The present work concerns proton-induced reactions. We consider experimental data from the EXFOR library [2] and compare them with theory using two different

approaches. In the following two Sections we describe briefly the models we employed and compare their results with the experimental data. Our findings are summarized in the last Section.

## 2. Calculations with the code TALYS

In the first one, we employ the most recent Version 2.0 of the nuclear reaction code TALYS, which has been widely used in modeling of nuclear reactions [3]. TALYS is designed to simulate nuclear reactions at projectile energies up to about 200 MeV. It incorporates state-of-the-art nuclear structure and reaction models, including optical models, level densities, direct reactions, compound nucleus formation, pre-equilibrium processes, and fission. The code can handle reactions induced by neutrons, photons, protons, deuterons, tritons, helium-3, and alpha particles. The same kind of particles are used as ejectiles. In our case, TALYS is used to calculate cross sections of the residual nuclei as a function of the bombarding energy, below 150 MeV. TALYS 2.0 enables to compare our experimental data with 6 level density models, namely, the composite level density (constant T plus Fermi gas) model, the backshifted Fermi gas model, the Generalized superfluid model plus 3 additional microscopic models.

Symbols in Fig. 1 show the experimental data and the solid lines show the results of our calculations. Four of the models give similar results for the excitation functions of the heavy residues. Two of them, namely the Generalized superfluid model (GSM) and the Skyrme-Hartree-Fock-Bogolyubov (SHFB) combinatorial level densities model from numerical tables produce a much better description of the  $^{28}\text{Mg}$  excitation function as shown by the red and black solid lines, respectively. The GSM describes the excitation function well at the threshold but overestimates between 40 and 100 MeV. The SHFB describes well the cross sections below 100 MeV and underestimates above 100 MeV. All models describe well the  $^{24}\text{Na}$  data. The predictions of all models are similar and underestimate  $^{18}\text{F}$  which is produced as a residue after particle emission. Common characteristic of all is the inability to predict the  $^{7,10}\text{Be}$  cross sections. This was expected since Be fragments are not included in TALYS as ejectiles. These findings are similar to the ones obtained with the earlier and more limited in level density options version of TALYS 1.95.



**Figure 1.** Experimental excitation functions producing  $^{28}\text{Mg}$ ,  $^{26}\text{Al}$ ,  $^{24}\text{Na}$ ,  $^{22}\text{Na}$ ,  $^{18}\text{F}$ ,  $^{10}\text{Be}$ , and  $^7\text{Be}$  in  $p + \text{natSi}$  reactions are shown with symbols. Lines show the results of calculations described in the text.

## 3. Calculations with the codes ISABEL and MECO

In an alternative approach we employ a two-stage model in which the preequilibrium stage is simulated by an internuclear cascade (INC) followed by an equilibrium statistical decay model (SM). The intranuclear cascade may be considered as classical analogue of the preequilibrium models. For the

INC stage the Monte-Carlo code ISABEL [4, 5] was used. Its applicability was tested by comparing (i) the reduced de Broglie wavelength ( $\lambda/2\pi$ ) of the incident proton in the bombarding energy range of the present study, (ii) the internucleon distance ( $d$ ), (iii) the mean-free-path ( $\Lambda$ ) between nucleon collisions and (iv) the radius ( $R$ ) of the target nucleus. The condition for the applicability of the INC model  $\lambda/2\pi \ll d < \Lambda < R$  was found to hold. Fig. 2 shows these quantities plotted as a function of the bombarding energy in the range of the present study.

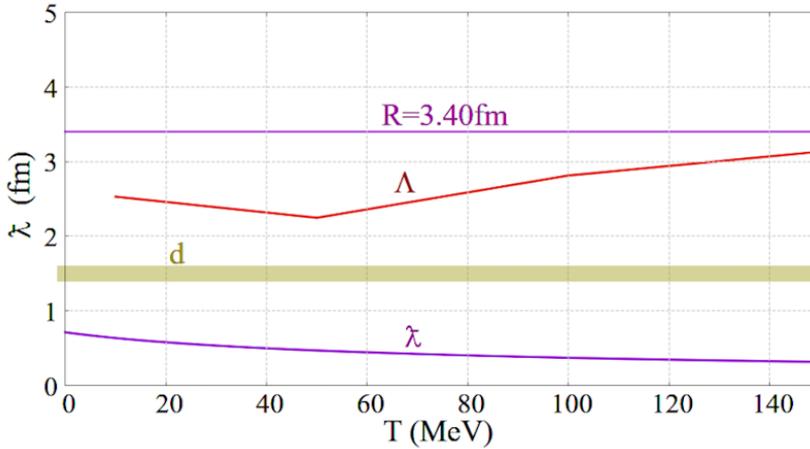


Figure 2. Plot of the quantities  $\lambda/2\pi$ ,  $d$ ,  $\Lambda$ ,  $R$  in the bombarding energy range of the present study.

For the equilibrium decay of the excited heavy remnants of the collision, we employed the Monte-Carlo sequential binary decay code MECO [6]. The code employed 16 decay channels involving gammas, neutrons, protons, deuterons, tritons,  ${}^3,4\text{He}$ ,  ${}^{6,7,8}\text{Li}$ ,  ${}^{7,9,10}\text{Be}$ ,  ${}^{8,9,10}\text{B}$ . All fragments were assumed to be emitted in their ground states.

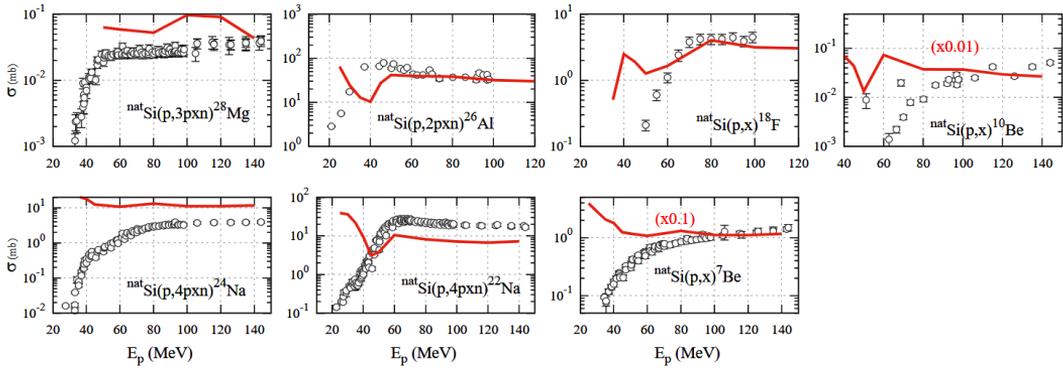
Fig. 3 shows the outcome of this calculation. Cross sections are predicted for all decay channels. Above 50 MeV there is a reasonable agreement with the cross sections of the channels involving heavy residues, namely,  ${}^{28}\text{Mg}$ ,  ${}^{26}\text{Al}$ ,  ${}^{22,24}\text{Na}$  and  ${}^{18}\text{F}$ . However, the magnitude of the calculated excitation functions for  ${}^7\text{Be}$  and  ${}^{10}\text{Be}$  is overestimated by a factor of 100 and 10, respectively. The magnitude of these cross sections depends on the relevant level density parameters and the population of excited prefragment states in the INC stage of the reaction. Below 50 MeV, all excitation functions are overestimated. This is because the INC model as it stands does not consider the distortion of the proton's trajectories due to Coulomb repulsion.

#### 4. Summary

We presented results of model calculations to describe experimental cross sections in  $p + {}^{nat}\text{Si}$  reactions.

The TALYS code reproduces the cross sections leading to the heaviest residues, but it is unable to calculate the cross sections of emitted fragments, such as  ${}^{7,10}\text{Be}$ . Inclusion of additional decay modes in TALYS would be desirable.

The INC+evaporation procedure provides a consistent method towards a complete description. However, improvements are needed in the INC code such as the introduction of Coulomb trajectories in the entrance channel. Furthermore, a fine tuning of the level density parameters or introduction of



**Figure 3.** Experimental excitation functions producing  $^{28}\text{Mg}$ ,  $^{26}\text{Al}$ ,  $^{24}\text{Na}$ ,  $^{22}\text{Na}$ ,  $^{18}\text{F}$ ,  $^{10}\text{Be}$ , and  $^7\text{Be}$  in  $p + \text{natSi}$  reactions are shown with symbols. The results of ISABEL-MECO calculations are shown with solid lines. They are valid above  $E_p \sim 50\text{MeV}$

a new level density option in the evaporation stage may diminish the calculated yield of emitted  $^{7,10}\text{Be}$ , thus improving the model description of this reaction.

## Acknowledgements

The author is indebted to Prof. M. Kokkoris, School of Applied Mathematics and Physical Sciences and Prof. M. Anagnostakis, Department of Mechanical Engineering, of the National Technical University of Athens, for providing him with the version of the ISABEL code employed in the present work.

## References

- [1] N. G. Nicolis and G. Zafeiri. "A study of proton-induced reactions on natural Silicon targets". In: *HNPS Adv. Nucl. Phys.* 29 (2023), 204–207. doi: 10.12681/hnpsanp.5086.
- [2] N. Otuka et al. "Towards a More Complete and Accurate Experimental Nuclear Reaction Data Library (EXFOR): International Collaboration Between Nuclear Reaction Data Centres (NRDC)". In: *Nuclear Data Sheets* 120 (2014), pp. 272–276. ISSN: 0090-3752. doi: 10.1016/j.nds.2014.07.065.
- [3] A. Koning, S. Hilaire, and S. Goriely. "TALYS: modeling of nuclear reactions". en. In: *Eur. Phys. J. A* 59.6 (2023), p. 131. ISSN: 1434-601X. doi: 10.1140/epja/s10050-023-01034-3.
- [4] Y. Yariv and Z. Fraenkel. "Intranuclear cascade calculation of high-energy heavy-ion interactions". In: *Phys. Rev. C* 20 (6 1979), pp. 2227–2243. doi: 10.1103/PhysRevC.20.2227.
- [5] Y. Yariv and Z. Fraenkel. "Intranuclear cascade calculation of high energy heavy ion collisions: Effect of interactions between cascade particles". In: *Phys. Rev. C* 24 (2 1981), pp. 488–494. doi: 10.1103/PhysRevC.24.488.
- [6] N. G. Nicolis. "Sequential binary decay of highly excited nuclei". In: *Int. J. Mod. Phys. E* 17.08 (2008), pp. 1541–1556. doi: 10.1142/S0218301308010556.