Summer School Report [Nov-Dec 2019]

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Abstract

This summer school report includes the main astrophysical processes to produce elements in the cosmos. In particular, the connection of nuclear physics data to astrophysical relevant cross sections, including hands-on exercise with the state-of-the-art TALYS reaction code, to deepen the understanding of the interplay of nuclear physics and astrophysics.

I Introduction and Short description of the topics covered in the School

The summer school broadly describe the astrophysical process to produce element in the cosmos. The ideas about the connection of nuclear physics data to the astrophysical relevant cross section was covered with the description of different processes like the s-process, the r-process and the p-process. The broad ideas on nuclear reactions models such as the Hauser-Feshbach relevant to the nuclear astrophysics was presented. The school gave the detailed knowledge on the heavy element nucleosynthesis and the needed nuclear physics quantities to understand it with the introduction of the topics like nuclear level density and the gamma-ray strength function (more on heavy element nucleosynthesis process), with the experimental methods to measure level densities and the gamma-ray strength function. The short description of the Nuclear reaction for the isotopes production was also presented. Similarly, the nuclear reactions happening in the Sun, the process that makes the Sun shines, the process of conversion of hydrogen to helium in the Sun, and the overall pp chain with estimated energy that is released in the process was discussed in detail.

II The formation of the heavy element in the astrophysical Environment

Nearly all elements heavier than Iron are produced by neutron capture reactions. While the basic concepts of their production are understood, the origin of the heavy elements remains one of the most important outstanding problems. About half of the heavy elements are produced in the slow neutron capture process (s-process) by a sequence of neutron captures and β-decays close to the stability valley. Current models suggest this process happens during quiescent burning phases in intermediate mass stars (1-5 solar masses) and in massive stars which later explode as core collapse supernovae. A key ingredient to determine abundances produced in this process are neutron capture cross-sections. "The heavy element nucleosynthesis broadly describes the three main processes; the s-process, the r-process and the p-process. The s-process deals with nuclei close to the valley of stability; astrophysical sites: Asymptotic Giant Branch (AGB) stars and massive stars (8 times the mass of the sun). The p-process is a secondary process; seed nuclei from the s and r-processes; likely takes place in SN Ia and SN II (O-Ne shell)."[1] The r-process, or the rapid neutron-capture process, of stellar nucleosynthesis is called for to explain the production of the stable (and some long-lived radioactive) neutron-rich nuclides heavier than iron that are observed in stars of various metallicities, as well as in the solar system. [1]

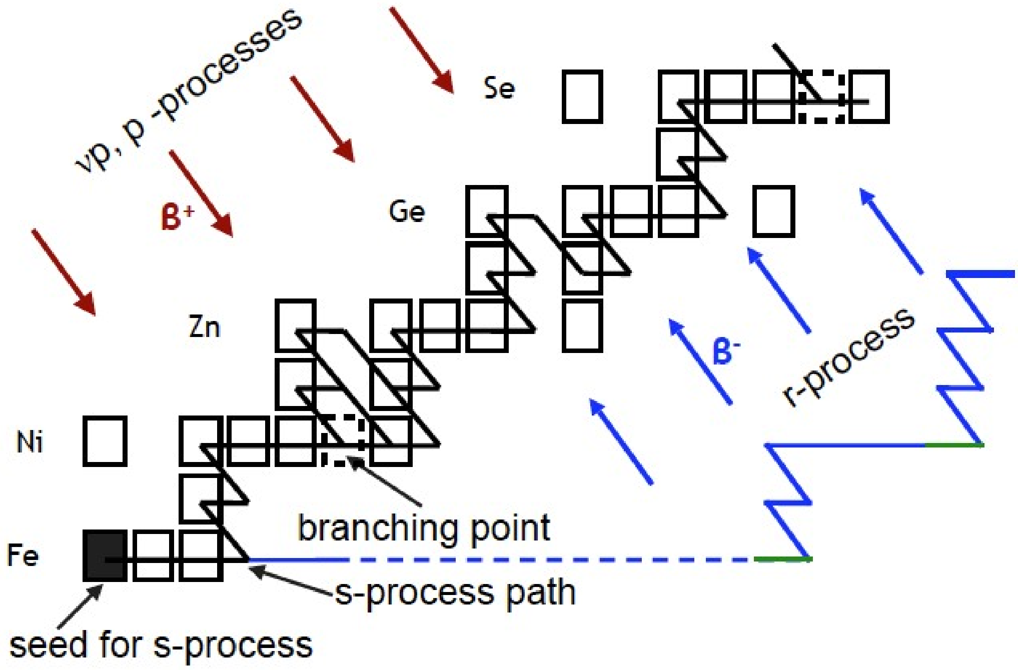

Figure 1. *The main processes contributing to heavy element synthesis through neutron captures and beta decays (s- and r-process). Proton-rich p-nuclei, beyond Fe may be formed via charged particle or photon-induced reactions (gammap- and p-processes).* [2]

III Experimental method for measuring Nuclear Level Density and Gamma strength Function

The nuclear level density and the γ-ray strength function give a measure of the gross properties of the nucleus. These average quantities are indispensable in practical applications of nuclear physics, such as calculations of nuclear reaction rates in astrophysical processes, the design and operation of fission reactors, and transmutation of nuclear waste. The summer school describe many methods to calculate the NLD and the γ-strength func-

[1] Presentation Slides of Ann-Cecilie Larsen,Lecture-2, Summer School INTPART FYS4525

tion. Photo-nuclear reactions (above Sn), Primary transitions following n-capture (around Sn), (γ, γ'), (e,e'), (p,p'), ... (below Sn), Spectrum fitting: Two-step cascade spectra following n/e capture (below Sn), Primary g spectra (Oslo method, below Sn) are some of the technique to measure gamma-ray strength function. Similarly, IAEA Reference Database of Photon Strength Function (2019) mentioned the following experimental information on Photon Strength Function[3].

- Photo data in the GDR region (10-20MeV): E1 for 159 nuclei,
- ARC/DRC data: e.g. 5-8MeV; E1 and M1 for 88 nuclei,
- Oslo data: e.g.<Sn; E1+M1 for 72 nuclei,
- NRF data: e.g.<Sn; E1+M1 for 23 nuclei,
- SB(M1) scattering data: e.g. 2-4MeV for 47 nuclei,
- (p, γ) data: E1+M1 at e.g. 5-10MeV for 22 nuclei ($A = 46 - 90$),
- (p,p') data for 96Mo, 120Sn, 208Pb: E1 and M1 at e.g. 5-20MeV.

Standard Lorentzian, Lorentzian with E-dependent width and Generalized Lorentzian with T- and E-dependent width (e.g Kopecky and Uhl 1990) are the models of gamma ray strength function. Nevertheless, different recent models are being employed to calculate the gamma-ray strength function.

III.1 The Nuclear Level Density

The nuclear level density plays a significant role in statistical model calculations in various nuclear fields in nuclear astrophysics, reactor physics, spallation neutron physics, and intermediate-energy heavy-ion collision investigations. It can be obtained from experimental data on neutron and proton-resonances, from cross section fluctuation analysis and from the slope of the particle spectra in nuclear reactions. Many experimental methods are used in calculating the nuclear level densities, like neutron resonance spectroscopy, the Oslo method for study of continuum gamma rays.For the description of the level densities the Fermi-gas and constant temperature models are used frequently with parameters obtained from fitting some experimental data. The recent progress in the measurements highlighting various aspect of the nuclear level density was briefly discussed in Summer school.

IV The nuclear Reactions Models

The variety and complexity or nuclear reactions make this fascinating area of the research quite apart from the practical value of understanding fusion and fission. From the studies of such properties as relative amount of information of various competing products, the variation of the yield of these with bombarding energy, the directional characteristics and kinetic energies of the product etc. we may formulate models of nuclear reaction mechanism. The different models of nuclear reaction such as the optical model, the liquid drop model, the life time of compound nucleus, direct interaction model and the mean field model were discussed in the school with its applications. Experimental nuclear structure information exists for a limited number of nuclei.If not experimentally known, be critical about the accuracy and reliability of the theoretical model. This is fundamental for nuclear structure properties, i.e. masses, deformation, spin/parities, matter densities. These are the building blocks for the prediction of ingredients of relevance in the determination of nuclear reaction cross-sections, β-decay rates, ... such as nuclear level densities, γ-ray strengths, optical potentials, fission probabilities and yields etc.

V Talys Code

TALYS is a extensively used software for nuclear data analysis. It has been used in different publications since its initial release in 2004. Mainly, TALYS is a nuclear physics tools that can be used for the analysis of nuclear reaction experiments. The interplay between the experiment and theory gives us the insight in the fundamental interaction between particles and nuclei, and the precise measurements enables us to constrain our model with desired outputs.

Its main objective is to provide a complete and accurate simulation of nuclear reactions in the 1 keV-200 MeV energy range, through an optimal combination of reliable nuclear models, flexibility and user-friendliness. TALYS can be used for the analysis of basic scientific experiments or to generate nuclear data for applications. "It is constructed to simulate the nuclear reactions that involve neutrons, photons, protons, deuterons, tritons, 3 He- and alpha-particles, in the 1 keV - 200 MeV energy range and for target nuclides of mass 12 and heavier."Koning etal.(2008)[4] To achieve this, TALYS implemented a suite of nuclear reaction models into a single code system. This enables us to evaluate nuclear reactions from the unresolved resonance range up to intermediate energies.

"With TALYS, a complete set of cross sections can already be obtained with minimal effort, through a four-line input file of the type for e.g." Koning etal.(2008)[4]

Projectile	n
Element	Pb
Mass	208
Energy	20

These four-keyboard projectiles, element, mass and the energy determines the fundamental parameters for any nuclear reaction induced by light particles.

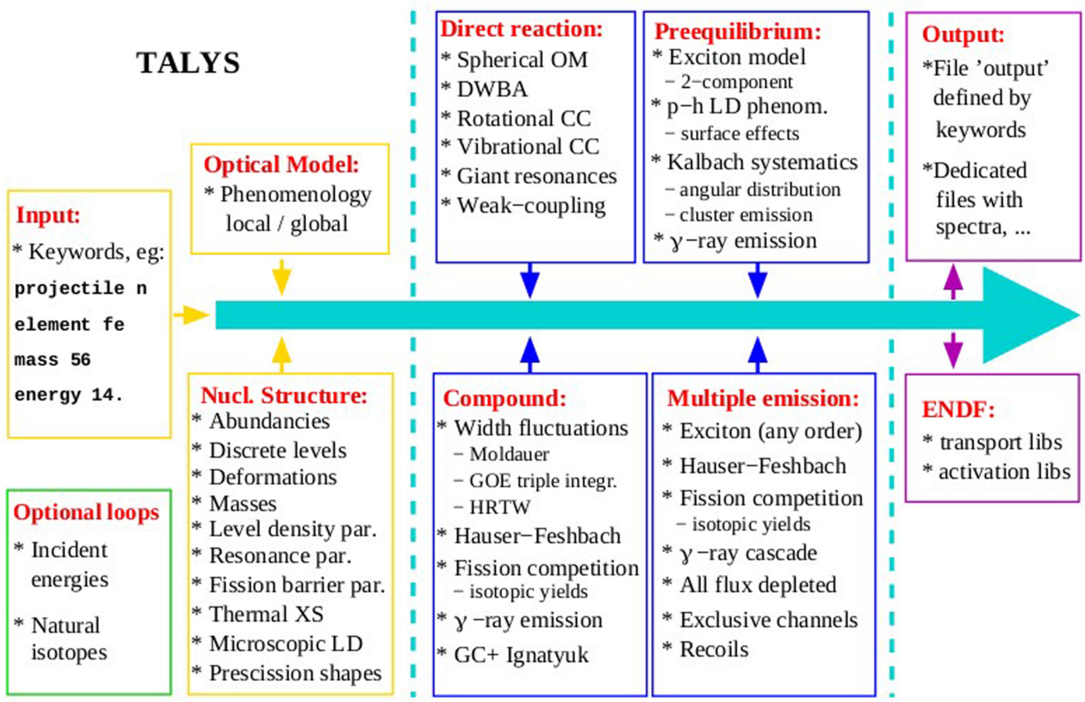

Figure 2. *Nuclear model in TALYS [4]*

VI TALYS Results

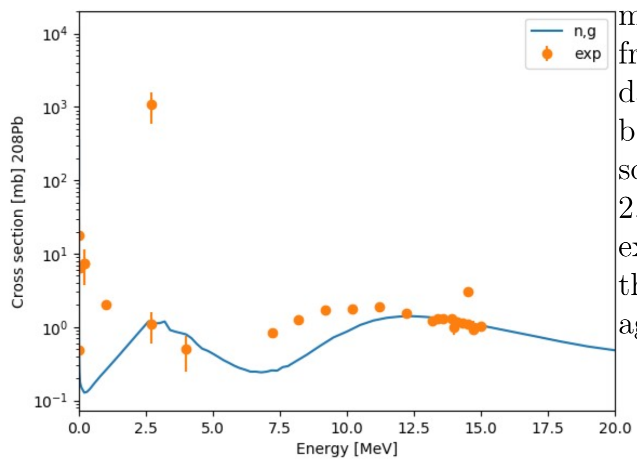

Figure 3. *(n, γ)208Pb cross-section vs experiment. The input is 208 Pb within the energy grid 0-20 MeV. [5] Mihailescu etal.(2008)*

The above plot shows (n,γ) cross-section of the ^{208}Pb with TALYS and experimental data. At low energies, especially up to about 3Mev the experimental and the TALYS data seems very unmatched. However, for higher energy level from about 8 MeV to 17 MeV both the data seems to be in same flow. It might be TALYS default value or there might be some discrepancy in experimental data. At 2.5 MeV energy level, cross-section for the experimental data is almost three fold more than the TALYS data which is not in good agreement with each other.

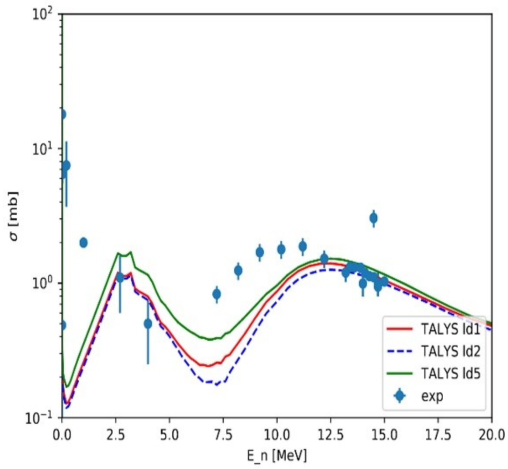

Figure 4. *208Pb (n,γ) for different LD models [5] Mihailescu etal.(2008)*

Plot [4] compares (n,γ) cross-section for different level density. TALYS LD1 is the default level density fot Constant Temperature(CD) and Fermi gas model(FG). The TALYS LD2 for the Back Shifted Fermi-Gas model (BSFG) and the TALYS LD5 for HF model. The three level density model from TALYS data are are plotted and compared with the experimental data as shown in above plot [4]. The three level density model follows mutual-energy cross-section relation with each other. There is a significant differences between the experimental data and the level density model at low energy. However, at higher energy level from 7.5 MeV, there are some similarities in the trend line.

VI.1 The Optical Model

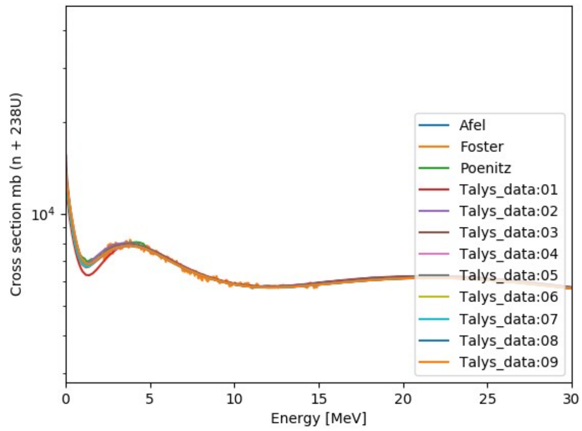

Figure 5. *Optical model n +238U Cross-section for energy up to 30MeV [6]Abfalterer etal.(1993) [7] Foster etal.(1971) [8]Poenitz etal.(1970)*

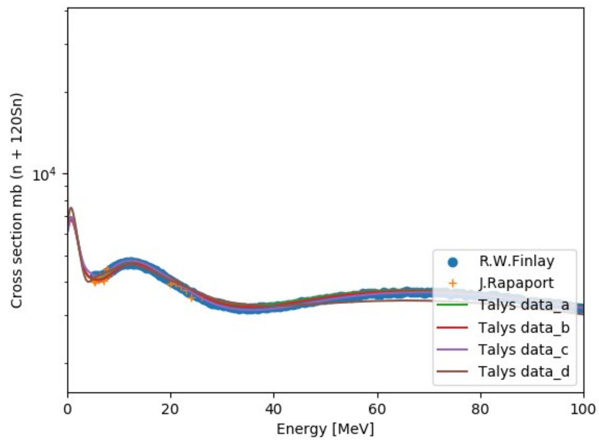

Figure 6. *Optical model ^{nat}Sn Cross-section for energy up to 100MeV [9] Rapaport etal.(1977)*

The optical models in TALYS are performed by ECIS 06 [10] an implemented subroutine method. They are first performed, and stored, for all possible outgoing particle channels and energies, so that the associated transmission coefficients can be used in pre-equilibrium and compound nucleus calculations.Thenafter, the energy calculation is done for the defined incident energy. In fig.[5] The data Afel, Foster and Poenitz are the data taken from EXFOR.

Similarly, in fig.[6] data a,b,c and d are the talys data. Here, in these two plots there is comparison between the energy difference between 30MeV upto 100 MeV with how well it works with the extension of energies. The plots shows that the data are almost matched with each other.

VI.2 The γ-strength Function

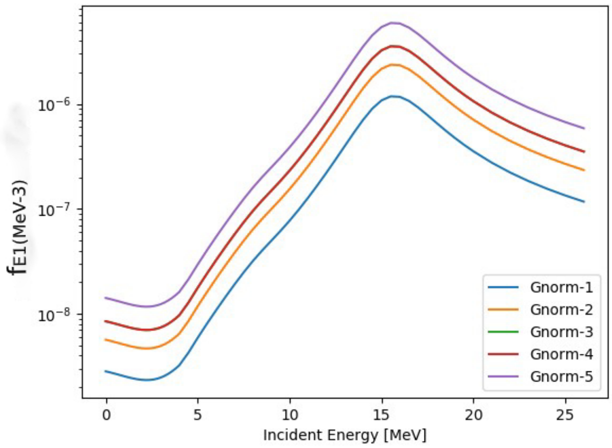

Figure 7. *Gamma strength function of ^{100}Mo with gnorm 1, 2, 3 and 4.with the energy range up to 30Mev.*

Fig.[7] describes the gamma strength function of ^{100}Mo with four different gnorm values compared in between the energy range 0-30MeV. Experimentally, this strength function follows a Lorentzian shape, whose parameterization can be somehow more complicated for E1, M1 transitions. The magnitude of the strength function rely on both E1 and M1 and the multi-polarity of the photon.Typically, E1 transitions are one to two orders of magnitude greater than M1, and more comprehensively, an increase in multi-polarity by one unit decrease by three orders of magnitude the corresponding strength. overall, in most cases, E1 and M1 transitions are enough to obtain a good elucidation of capture cross sections. From GLO gnorm 1 to GLO gnorm 5 we can see the photon strength multiplies 5 times.

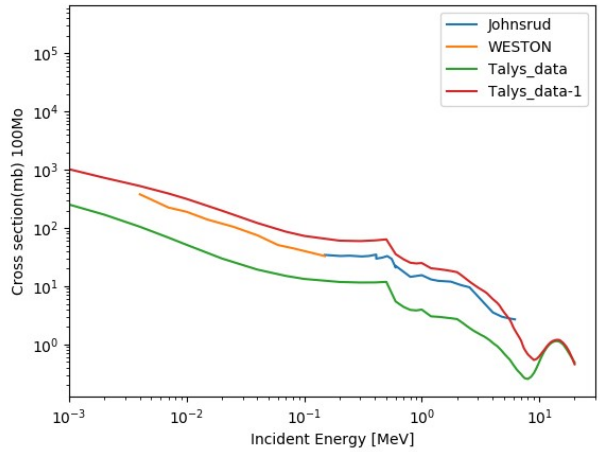

Figure 8. *Impact of $< \Gamma\gamma >$ re-normalization on radiative n-capture.[11] Johnsrud etal.(1959), [12] Weston etal.(1971)*

Plot [8] illustrate the impact of $<\Gamma\gamma>$ renormalization on the radiative neutron capture. At lower energies there is no any significant changes in the plot. But at higher energies there are some differences. The TALYS-data is the GLO gnorm 5 and TALYS-data-1 is QRPA gnorm1 in above case.

VI.3 The (n,γ) cross-sections of ^{237}Np on the level density and gamma-ray strength function.

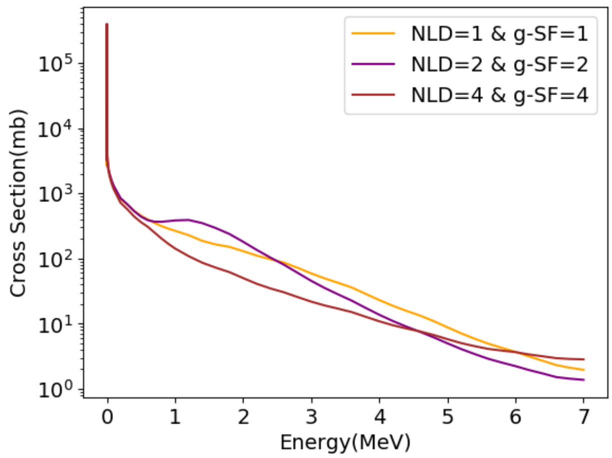

Figure 9. *The (n,γ) cross-sections of ^{237}Np on the level density and gamma-ray strength function.*

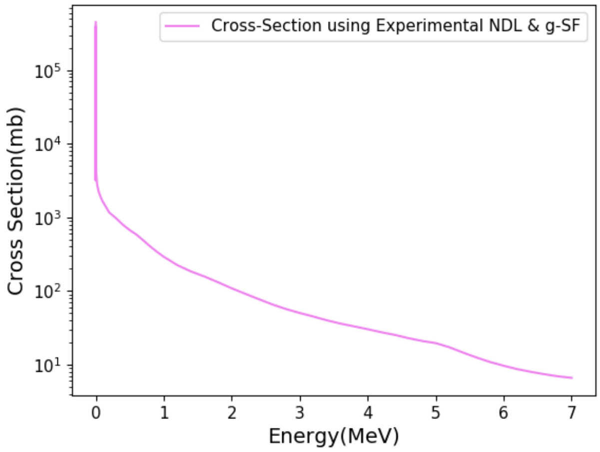

Figure 10. *The cross-section using the Experimental nuclear level density and the gamma-strength function.*

The Nuclear Level Density(NLD) and the gamma-Strength Function(γ-SF) describes the average properties of nuclei in compact quasi-continuum region.The quasi-continuum is the region where the number of level is too high to study the individual states and their transitions. These functions also plays a very important role in statistical Hauser-Feshbach reaction rate calculations. Fig [9] illustrates the outcome of cross-section calculation. The quantitative Talys data of various level densities and strength functions are analysed and the result is also similar to the experimental results as shown in fig [10]. Furthermore, if we made a qualitative analysis between these two plots we can see the very similarities between the Talys and the experimental fits. These two cross-section plots are also in good agreement with the result from [13] paper.

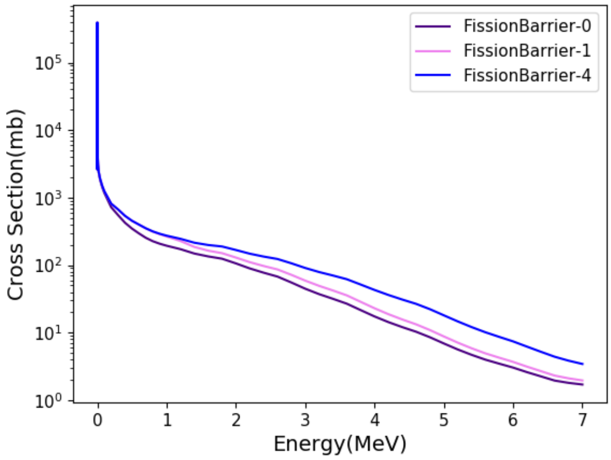

Figure 11. *The (n,γ) cross-sections of ^{237}Np with fission barrier adjustment[fisbaradjust 93 238 (0,1,4)]*

Fig[11] manifest the resulting cross-section with varying fission barrier. Though there is some significant changes in the plots[9] and [11], there not so much gratifying changes in cross sections between the two.

VII Conclusion

The summer school broadly describe the astrophysical process to produce element in the cosmos. The ideas about the connection of nuclear physics data to the astrophysical relevant cross section was covered with the description of different processes like the s-process, the r-process and the p-process. Running through the Talys software, most programs does run easily with a lot of default values. The large number of options of TALYS provides the opportunities to fine tune model parameters or model ingredients to perform in depth nuclear reaction analysis. Few examples are illustrates above. Overall the whole course and the school is fruitful with good results and loads of information on lectures.

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