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(alpha,n) Nuclear Data Evaluations and Data Needs

Summary Report of the Technical Meeting
27 November – 1 December 2023
(virtual event)

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September 2024

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ABSTRACT
The second IAEA Technical Meeting addressing (α,n) data needs for applications spanning reactor operation and safeguards, nonproliferation and spent fuel management, low-background experiments, and nuclear astrophysics was organized by the IAEA from 27 November to 1 December 2023. Fifty-six participants from thirteen Member States attended the virtual event. Participants reviewed the progress in (α,n) measurements, models, codes and evaluated libraries since the previous meeting of 2021. A summary of the presentations, technical discussions and recommendations is given in this report. The presentations are available from the meeting webpage: https://conferences.iaea.org/event/366/.

September 2024

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1. INTRODUCTION

(α,n) reactions are crucial for various applications. In nuclear fission reactors, energy-dependent neutron interactions with oxygen isotopes such as the $^{16}O(n,n)$ reaction are key, especially given the water-dominated core. Accurate nuclear data for these interactions require knowledge of inverse reactions, specifically, (α,n) reactions on ^{13}C. In nonproliferation, waste management, and homeland security, alpha particles from actinide decay in nuclear fuels interact with light elements like C, O, and F, producing neutrons used in non-destructive assays to determine fuel enrichment. In nuclear astrophysics, (α,n) reactions are important for the s and weak r process and nucleosynthesis in type 1A supernovae. Additionally, (α,n) reactions are significant neutron sources in geological repositories of spent fuel and contribute to background noise in underground studies of rare events, such as WIMPS or neutrinos, complicating the detection of true signals.

Alpha particles from decaying radioisotopes interact with light to medium-light nuclides at incident energies ranging from several keV to 9 MeV, forming an excited compound nucleus. These interactions are described by R-matrix theory at lower energies and by the statistical model as nuclide mass and energy increase. Accurate experimental data is critical for these calculations, but much of the available data is outdated, incomplete, or uncertain. Current evaluated libraries are also outdated or incomplete, highlighting the urgent need for updated nuclear data libraries for (α,n) and other charged-particle induced reactions. Lastly, improvements in nuclear reaction codes, such as R-matrix and statistical model calculations, and source codes for calculating neutron sources, are necessary.

These challenges can be effectively addressed through international cooperation among interdisciplinary groups active in (α,n) research. For this reason, the IAEA organized a virtual Technical Meeting on (α,n) evaluation needs and data needs from 8 to 12 November 2021. The meeting was attended by 60 participants from 15 member states who reviewed the status of (α,n) measurements, models, codes and evaluated libraries, identified the gaps, and proposed the necessary actions to fill the gaps with a view to producing reliable (α,n) data for applications. Presentations, summaries of the discussions, and recommendations from the meeting can be found in INDC(NDS)-0836 and at the meeting website (https://conferences.iaea.org/event/283/).

Building on the positive response to the 2021 meeting and in line with its recommendations, a second Technical Meeting was held from 27 November to 1 December 2023. The meeting aimed to review the most recent developments in the field and assess progress on the agreed-upon actions. The meeting was virtual and attended by 56 participants from 13 Member States. The Head of the Nuclear Data Section, Arjan Koning, welcomed participants and emphasized the importance of the topics and recommendations of the meeting, and Paraskevi (Vivian) Dimitriou, the Technical Officer, by way of introduction outlined the motivation and goals of the meeting. Subsequently, chairpersons and rapporteurs were elected for the five days of the meeting as follows:

Day 1: Roberto Santorelli (Chair), Vivian Dimitriou (Rapporteur)
Day 2: Ariel Tarifeno (Chair), Arnd Junghans (Rapporteur)
Day 3: Daniel Cano (Chair), S. Westerdale (Rapporteur)
Day 4: Valentina Lozza (Chair), Arnd Junghans (Rapporteur)
Day 5: Vivian Dimitriou (Chair and Rapporteur)

This summary report is organized as follows: Section 2 includes summaries of participants' presentations, Section 3 presents a summary of the technical discussions and recommendations. The conclusions are summarized in Section 4.

The timetable, participants' presentations and the list of participants are available at the meeting webpage: https://conferences.iaea.org/event/366/.

2. SUMMARIES OF PRESENTATIONS

2.1. Status of and perspectives for the study of (alpha,n) reactions at CNA HISPANOS by means of activation and time-of-flight, C. Guerrero (CNA)

For the MANY collaboration.

Neutrons emitted from (alpha,n) reactions play an important role in several fields such as nuclear technology, nuclear astrophysics or underground (low background) physics. However, the current knowledge of the neutron yields and neutron energy spectra from (alpha,n) reactions is neither complete nor accurate; which has triggered a renewed interest in studying such reactions.

In this context, several Spanish research groups have established the MANY Collaboration that aims at measuring (alpha,n) reactions by means of activation, neutron counting and time-of-flight at the CNA HISPANOS (Seville) and CMAM facilities (Madrid).

The preliminary results of the recent experiment carried out at CNA HISPANOS for the study of the ^{27}Al(alpha,n) reaction by means of activation (using LaBr3 detectors) and by time-of-flight (using a pulsed beam and a Ej301 liquid scintillator module from the MONSTER array) were presented. Then, the prospects for upgrades and future measurements were discussed.

Discussion:

- No systematic uncertainties were determined, only statistical uncertainties from the deconvolution procedure which consists of adjusting the weights of all the response functions to the measured data and normalizing by performing a least-squares fit. The absolute normalization is identical to the number of measured alpha-particles.
- In this measurement no contaminants are expected to be present in the high-purity Al target. However, the role of contaminants in rare-event measurements is a crucial issue since they can affect the measurements. This is why the target compound chemical composition is usually measured using chemical methods. At CNA it is possible to use the RBS method to measure the surface composition of the targets.
- The lowest energy of the alpha beam that can be measured is 1 MeV.

2.2. Innovative analysis technique of neutron time-of-flight spectra, validation, and first results in reaction studies, A. Pérez del Rada Fiol (CIEMAT)

An innovative methodology has been developed for the procurement of neutron energy distributions from neutron time-of-flight (TOF) measurements with neutron spectrometers. The methodology is based on the accurate determination of the response of the neutron spectrometer via Monte Carlo simulation and an iterative Bayesian unfolding technique for the analysis of the TOF data. The methodology has been validated first with the analysis of a virtual experiment and second with experimental data coming from the beta-delayed neutron measurement performed at the IGISOL facility of JYFL-ACCLAB with the MOdular Neutron time-of-flight SpectromeTER (MONSTER).

Several modules of MONSTER were shipped in 2023 to the Centro Nacional de Aceleradores (CNA) in Seville, Spain, and used in a test measurement of the reaction. The results from the analysis of the data were presented and plans for future measurements were discussed.

Discussion:

- The response function in this measurement is determined independently rather than being fitted as in CNA measurement.
- If all effects are considered, then the systematic uncertainties are approximately 5%.
- This method is not equivalent to using infinite shadow cones. Using infinite shadow cones would likely introduce a new (unknown) background. This method aims to reproduce the

background due to neutron interactions in surrounding materials directly instead of trying to measure and subtract it.
- The finer structure above 2 MeV in the previous measurement is due to its longer flight path (3 m vs 1 m) rather than statistics.
- The method has been validated in measurements of beta-delayed neutrons where the gamma emission rate is much lower, whereas, in these experiments the gamma emission rate could be comparable to the neutron emission rate. However, that is not an issue because there is a clear separation of neutron and gamma signals in the experiment.
- The fine structure in the Liskin ToF measurement is a result of the higher statistics. The poorer resolution in the Bayesian analysis experiment is due to the poor statistics used in resolving the inverse problem.
- The factor of 2 difference in the extracted yields of the CNA and CIEMAT analyses is probably due to the activation method used in one of them. Nevertheless, it is imperative that the two methods converge.
- Machine Learning was not used to reconstruct the energy spectrum from the response function.

2.3. Status and perspectives of thick target measurement of (alpha,n) reactions using the miniBELEN detector, A. Tarifeno-Saldivia (IFIC-Univ. Valencia)

The MANY (Measurement of Alpha Neutron Yields and Spectra) collaboration is a coordinated effort aiming to conduct measurements of (alpha,n) production yields, reaction cross-sections, and neutron energy spectra. MANY relies on the alpha beams generated by the accelerator facilities at CMAM (Madrid) [1] and CNA (Sevilla) [2]. The miniBELEN-10A neutron counter [3] is one of the detection systems available within MANY. This work reported on the commissioning experiment carried out at CMAM using natural aluminum targets. Specifically, we presented the results from measurements of the ^{27}Al(alpha,n)^{30}P thick target production yields using the miniBELEN-10A detector. Based on the commissioning results, the potential upgrade of miniBELEN was discussed. Finally, the future perspectives for measurements using this detector were outlined.

References:
[1] A. Redondo-Cubero, et al., Eur. Phys. J. Plus **136** (2021) 175.
[2] J. Gómez-Camacho, et al., Eur. Phys. J. Plus **136** (2021) 273.
[3] N. Mont-Geli, et al., EPJ Web of Conferences **284** (2023) 06004.

Discussion:
- The maximum counting rate of a single neutron counter is 100 K counts per second. This is constrained by the dead time and pileup of a single detector. The moderator effects are 2 orders of magnitude lower than the pileup.
- Although ^{27}Al is not a priority nuclide for low-background experiments, and most of the top priority nuclides have much lower yields, production yields are easy to measure with this setup. Background effects and counting times could be an issue, but as far as efficiency of the detector system is concerned, an array of detectors can be used to improve it. The geometry of the detectors can also be adapted to perform spectral measurements.

2.4. Preliminary results from thick target measurements of the ^{27}Al(alpha,n)^{30}P reaction cross-section using miniBELEN-10A, N. Mont i Geli (Universitat Politècnica de Catalunya)

The miniBELEN-10A detector is a modular and transportable moderated neutron counter with a nearly flat detection efficiency up to 8 MeV [1]. It is one of the detection systems available for the MANY collaboration (Measurement of Alpha Neutron Yields and Spectra), a Spanish project designed to conduct measurements of (alpha,n) production yields, reaction cross-sections, and neutron energy spectra. miniBELEN-10A has recently undergone commissioning by measuring ^{27}Al(alpha,n)^{30}P thick target production yields at various alpha energies. This work presented preliminary results from the first physics experiment using miniBELEN-10A. The cross-section of $^{27}Al(alpha,n)^{30}P$ was derived from thick target measurements for alpha energies near the reaction threshold up to 8 MeV. The experiment was introduced, and the status of the data analysis was discussed.

References:

[1] N. Mont-Geli, et al. EPJ Web of Conferences **284** (2020) 06004.

Discussion:

- Energy calibration is very difficult to perform for protons. The Flynn energy calibration may not be wrong after all.

2.5. Measurement of Al(α,nγ)P thick-target yields and total Al(α,n) yields by activation, L. Mario Fraile (Universidad Complutense de Madrid)

The Spanish efforts within the MANY collaboration, particularly with the GARY gamma array, have been focused on reaction yields and cross-section measurements. Key to these efforts is the CMAM facility in Madrid, where a 5 MV accelerator, installed in 2002, is employed for microanalysis of materials. The facility features a nuclear physics experimental area equipped with a Plasmatron ion source that can produce proton and alpha particle beams with energies of up to 15 MeV.

In 2013, an energy recalibration of the accelerator was performed, revealing a deviation of 0.3%. This prompted the recommissioning of the short beam line for nuclear physics research, despite the disadvantage of lacking focusing elements. Future upgrades planned for 2023 include the installation of a pulsed beam system with a chopper and buncher, aiming to enhance experimental precision.

For these experiments, an Aluminum target setup has been employed, utilizing a collimator and a Faraday cup with secondary electron suppression to accurately determine beam current. Neutron detection is managed by the MiniBELEN setup, which uses ^{3}He-moderated proportional counters.

There is significant interest in alpha-induced reactions, both for nuclear technology and nuclear astrophysics. Such reactions, particularly (alpha,n) processes, are crucial in understanding neutron sources for the s-process in stars and the weak r-process. Notably, the Debrecen group has studied the $^{100}Mo(alpha,n)^{103}Ru$ reaction via activation.

However, discrepancies between databases like TEND and JENDL-AN-2005 have been observed, motivating further studies, especially in the context of fusion research where alpha-loss diagnostics for ITER through activation is of interest. The $^{27}Al(alpha,n)$ reaction, in particular, is being investigated as a reference reaction for benchmarking purposes. This also serves as a test for the new CMAM beam line, where different measurement methods—neutrons, gammas, and activation—are cross-checked.

The threshold excitation function for this reaction was first measured in 1978 by Flynn, and now, the GARY LaBr3 detector array is being used to measure angular distributions of the emitted gamma-rays at 11 different forward and backward angles. This array, consisting of conical crystals coupled to fast PMTs, is well-calibrated and can handle high count rates. Monitoring is complemented by HPGe detectors for higher resolution and a neutron detector.

The production of ^{30}P, with a threshold of 3.0344 MeV, is also being studied via both online measurements and activation methods. The gamma-rays from reactions such as (alpha,n gamma), (alpha,p gamma), and (alpha, alpha’ gamma) have been identified, with activation results from the GARY data currently being analysed. The angular distribution of these gamma-rays is a work in progress, and the commissioning of the CMAM beam line is ongoing, with a focus on ensuring the stability and reproducibility of the beam focus position. The ^{27}Al(alpha,n) data, which is consistent across activation and decay methods, is largely analysed, with contributions from researchers like Odette Alonso-Sanudo.

Discussion:

- Only Pb shielding is used, not active Compton suppression. HPGe detector resolution is not as good as expected. The efficiency above 2 MeV is based on MC simulation and at lower energy it is adjusted with a ^{152}Eu calibration source.
- GARY 2022 and 2023 measured data are consistent with previous measurements of Brandenburg and with MiniBELEN.
- The positron range has been simulated and does not have a large effect on the measurement.

2.6. Direct measurement of the low-energy cross section of ^{22}Ne(alpha,n)^{25}Mg, A. Best (University of Naples Federico II / INFN)

The reaction plays a crucial role in the nucleosynthesis of heavy elements, in both the main and the weak s processes. In addition, its stellar reaction rate (and that of the competing channel ^{22}Ne(α,γ)^{26}Mg) determine the ratio of the Mg isotopes that can be directly observed in stellar atmospheres. To provide input for stellar and nucleosynthesis models, the cross section needs to be known between the neutron threshold at 565 keV and about 800 keV. Due to the very low experimental rates (counts/h) it has so far been impossible to measure directly besides at one resonance at E_α = 830 keV.

The ERC-funded project SHADES aims at measuring the reaction directly in the stellar energy range by exploiting the strong background suppression of the deep underground Gran Sasso national laboratory (LNGS) in Italy and a high-current beam from the new MV accelerator at the Bellotti Ion Beam facility. Neutron background from cosmic rays has been significantly suppressed by a factor of 1000 in the current experimental setup. This reduction in background noise is further enhanced using a gas target enriched with ^{22}Ne, which minimizes beam-induced background. As a result, the total background rate has been reduced to just 1 count per hour. Additionally, the stability of both current and energy has reached very high levels, as reported by Sen et al. in NIM B450 (2019).

To adapt to the low event rates encountered in these experiments, a hybrid detector array has been employed, combining ^{3}He counters and liquid scintillator EJ 309, known as the SHADES detector array. Plans are in place to determine the efficiency of the SHADES detector array through measurements of ^{13}C(α,n) reactions in an underground environment and ^{51}V(p,n) reactions on the surface. The characterization of this detector is being carried out at the FRANZ facility in Frankfurt, with ongoing analysis. Furthermore, the background levels of the detector have been thoroughly measured to ensure the accuracy and reliability of the data.

Discussion:

- The lowest alpha beam energy measurable is 300 – 350 keV.
- The liquid scintillator is the moderator and for a few hundreds of keV neutrons it is expected to reach 15-20% efficiency. This is for a low-energy measurement without coincidences between the liquid scintillator and ^{3}He.
- The efficiency will be measured with the two reactions mentioned for ground state emission.
- The current detection threshold is 140 keV neutrons with light yield of 60 keVee.
- The scintillator is an EJ 309 1.6 liter with a ETL 9390 PMT.

2.7. Neutron production yield in alpha induced reactions on CaF2 and ^{27}Al, D. Testov (Extreme Light Infrastructure - Nuclear Physics (ELI-NP))

Low energy (α,n) reactions are important for reactor applications and low background experiments. In both cases α-particles, typically of a few MeV, originated from actinides decay present either in reactor fuel and/or in surrounding materials due to the elemental natural abundance. The emitted α-particles can induce nuclear reactions on nuclei of a wide range of materials introduced in the given experimental environment such as ^{13}C, ^{19}F, ^{16}O, ^{18}O, ^{27}Al, ^{29}Si, ^{30}Si. Because of the considerable cross-sections in the indicated energy range, up to barns, the resulted neutron yield is significant and should be properly taken in the consideration.

Neutron detector systems based on proportional ^{3}He counters provide high efficiency and almost full angular coverage which makes it the ideal candidate for reaction cross-section measurements, including (α,n) reactions. The ELIGANT-TN array constructed at Extreme Light Infrastructure-Nuclear Physics (ELI-NP), Magurele, Romania was originally aimed at (γ, n) cross-section studies. It consists of 28 ^{3}He counters arranged in three rings in the high-density polyethylene matrix, shielded by a cadmium layer from background neutrons, in a way to reach a flat efficiency of ~37% up to ~5 MeV neutron energy. One more advantage of such a detector is the possibility to measure the average neutron energy by the ring ratio technique.

Lately, ELIGANT-TN was installed at the experimental hall of the 3 MV Tandetron facility of the Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH) Magurele, Romania. The accelerator provides intense low-energetic charged particles beams. In our first experiments, the cross-sections of F(α,n), C(a,n) and Al(α,n) in the 3–7 MeV energy range were investigated. Moreover, in November 2023, an experiment to measure the F(α,n) and C(α,n) cross-sections up to 17 MeV was undertaken. α-beam was delivered by the 9 MV Pelletron Tandem Accelerator (IFIN-HH).

The CaF2 target was characterized by ion beam analysis (RBS) and the reaction ^{19}F(alpha,n) was measured from 3000 to 7500 and at higher energy from 7000 to 10000 keV. Ring to ring ratios allow to deduce the neutron energy, but the results seem to indicate different neutron sources and energy.

To study the alpha loss in DT fusion the reaction ^{10}B(alpha,n)^{13}N is to be investigated in 2024 at low energies as well as ^{76}Ge(alpha,n)^{79m}Se for 3.9 min activity for plasma diagnostics with the 100 keV gamma-ray.

Discussion:

- Internal normalisation still needs to be done for the different runs. Publication is in preparation.
- ^{27}Al data at low energy below 3 MeV are influenced by a carbon 13C contamination. This will be corrected by calculating the yield.
- The new data agree with Flynn et al. although the alpha-particle energy was found to be shifted by 40.
- Can you measure below 3 MeV? It is possible but has not been done yet. The lower limit that can be achieved for 19F(alpha,n) is 500-600 keV beam energy. Measurements below 3 MeV would be valuable to help validate the Wrean and Kavanagh 2000 data.
- The shift of the ^{13}C resonance below 3 MeV is 50 keV relative to Williamson.

2.8. Global R-matrix analysis of the ^{19}F(α,n) reaction, E. Vagena (NCSR Demokritos)

In this work the progress in the R-matrix analysis of the ^{19}F(α,n)^{22}Na reaction at energies above the neutron threshold in the resolved resonance region, using the R-matrix code AZURE2, was reported. This reaction has been chosen for re-evaluation because of its importance in applications such as nonproliferation, nuclear astrophysics and low-background experiments.

At low energies the experimental data are influenced by carbon contamination (Balakrishnan et al) which is why the Wrean and Kavanagh 2000 is the adopted data set up to 3.1 MeV along with L. Van der Zwan, Cseh et al, Schier et al. 1976 data (alpha, elast, p_0, p_1 angular distributions).

The R-matrix analysis included alpha-^{19}F, n +^{22}Na g.s., p + ^{22}Ne g.s., a channel radius obtained from $1.4\cdot(A^{1/3} + A^{1/3})$ and up to L=4 angular momentum. No background poles were used.

The different channels were discussed. In the (alpha,p) channel, three J pi values were changed. The lower energy part of Wrean and Kavanagh is not fitted well yet, however, additional resonances from Kuperus et al. need to be added. Elastic scattering angular distributions have been normalized with factors 0.7 to 1.1. The (alpha,p) cross section shows a reasonable shape and scaling. Simultaneous fits are complicated as nuclear structure information is not complete.

The goal is to extend the R-matrix analysis to 9 MeV: the main challenges remain the quality of the data, breakup channels +^{15}N+2alpha, and lack of structure information.

Discussion:

- Trial and error were used for states with missing Jpi information. However, there are other alternative such as using a structure model or ML methods. Both will be investigated in the future.
- Total neutron cross section data on ^{22}Ne would be useful in this R-matrix analysis.
- The identified data needs could serve as a good motivation for getting new experiments approved at various facilities.

2.9. Overview of the (alpha,n) reaction measurements on light nuclei, H. Young Lee (Los Alamos National Laboratory)

An overview of the new project (five year funded project collaboration of LANL, Air Force Inst. Tech., ORNL, and Notre Dame Univ.) to measure the (α,n) reactions on light elements, such as ^{7}Li, ^{10,11}B, ^{13}C, and ^{19}F was presented. As an experimental campaign for the following 5 years, this study will provide partial, total reaction cross sections, neutron spectra, and gamma- and charged- particle yields. The experiment end station is composed of two different types of neutron detector arrays (deuterated liquid scintillators and stilbene scintillators), High Purity Ge detectors located at multiple angles, and two sets of silicon detector telescopes ($\Delta E1 - \Delta E2 - \Delta E3$) at forward and backward angles. The experiment will be performed at the Institute for Structure and Nuclear Astrophysics at the University of Notre Dame using the FN tandem and the 5U accelerators to cover the alpha energy from 2 to 9 MeV. Including the multi-channel R-matrix analysis on the data we obtain, we also plan to assess the impact of the updated (α,n) nuclear data relevant to nuclear applications.

Discussion:

- To deal with ^{13}C background, carbon backings will be made from enriched carbon 12 material. A cold trap will minimize carbon built up.
- A new chamber with movable charge particle detection will be built to improved charged-particle detection.

2.10. Improved evaluation of the ^{17}O system, Xu Han (China Academy of Engineering Physics)

We presented the results of the latest evaluation of the ^{17}O system. In the calculation of the RAC program, we have added several new sets of integral cross section data and differential cross section data for the ^{13}C(α,n)^{16}O reaction on the basis of the original data. The newly added data also include the latest measurements by the Peking University. The newly added data are shown below:

Integral cross section: 1. P.S. Prusachenko+ 2022, 2. G.F. Cian+ 2021, 3. B. Gao+ 2022.
Differential cross section: 1. M. Febbraro+ 2020, 2. E.M. Gazeeva+ 2020, 3. P.S. Prusachenko+ 2022.

Energy levels determined by fitting experimental data in an extended energy range from 0.233 to 11.67 MeV. The fits look good, however, for $^{13}C(a,n)$ there are some difficulties at larger angles whereas the fits seem better at smaller angles.

Discussion:

- The structure at higher energies is not reproduced well.
- ENDF-6 datafiles should be produced to allow validation of this evaluation against benchmark experiments.

2.11. Experimental study of thick target yield from the $^{13}C(\alpha,n0)^{16}O$ reaction, P. Prusachenko (Insitute for Physics and Power Engineering (IPPE))

The double differential thick target yields from $^{13}C(\alpha, n_0)^{16}O$ reaction were measured by the time-of-flight method over the incident energy range of 3.0 – 6.5 MeV and over the angle range of 0-150º. Two neutron detectors were used. The first one based on the p-terphenyl single crystal was used to measure neutron spectra over the angle range of 0-130º. The second one based on the stilbene crystal was permanently located at the angle of 150º. Both detectors were placed into special shielding collimators to decrease the influence of multiple scattering neutrons. The acquisition system was based on the waveform digitizer with a sampling rate of 500 MS/s.

The target used was the amorphous carbon pellet enriched in carbon-13 up to 94%. The precise analysis of target composition was made using ion beam analysis methods. In particular, the content of high-Z impurities (oxygen, silicon, iron) was determined by the elastic backscattering analysis (EBS) using the (α,α_0) reactions. Concentration of hydrogen in the target was measured by the elastic recoil detection analysis (ERDA) using the $^{1}H(\alpha,p)^{4}He$ reaction. The ratio between concentrations of carbon-12 and carbon-13 in the target was determined by the nuclear reaction analysis (NRA) using the $^{12,13}C(d,p_0)$, $^{13}C(d,\alpha_0)$ and $^{13}C(d,t_0)$ reactions.

The detectors efficiency was calculated by GEANT4 simulation. The simulated efficiency curve for the first detector was verified by three independent TOF experiments: relative to the differential cross-section of the $^{2}H(d, n)^{3}He$ reaction (the first experiment) as well as relative to the standard of the cross-section of the ^{235}U fission (two other experiments). The experimental efficiencies supported the simulated ones within uncertainties. The efficiency of the second detector was verified relative to the efficiency of the first one.

The multiple neutron scattering corrections were also obtained by GEANT4 simulation as the ratio of the number of counts calculated only for the detector material (all other excluded) and that for the full experimental geometry.

The neutron spectra measured in the work significantly differ from the experimental data previously reported by Jacobs in 1983 excepting the incident energy of 5.0 MeV. At the same time, spectra calculated based on the differential cross-section data on $^{13}C(\alpha, n0)^{16}O$ reaction available in the literature supports the results obtained in this work.

The total thick target yields (TTY) from this reaction were determined by integrating the measured neutron spectra both over the neutron energy range corresponding to the $^{13}C(\alpha, n_0)^{16}O$ reaction and over the entire solid angle. The stopping power dataset previously reported by Bobrovskiy (NIM B 543, 2023, 165094) were used to calculate the TTY from evaluated cross-sections for further comparison. The average difference between the TTY obtained in the work and ENDF-B/VIII.0 calculation is no more than 3.8% at the total systematic uncertainty of experimental TTY of 3.5% and calculated TTY of 3.0%. This result does not allow making the decision about renormalization for the ENDF-B/VIII.0 evaluation. The difference between our data and JENDL-5.0 evaluation reaches 15-20%.

Discussion:

- The simulated efficiency was used to calculate the double differential TTY.
- The shielding collimators were used to suppress the multiple scattered neutrons from the floor and walls of experimental hall. In our previous experiment, this was not such a problem due to the monoenergetic spectrum of neutrons.
- The experiment on the measurement of TTY from $^{13}C(\alpha, n_0)^{16}O$ reaction was performed to obtain the additional information for evaluations benchmarking.
- The flight paths were 223 cm for the first detector (p-terphenyl) and 100 cm for the second one.
- The results obtained support the ENDF-B/VIII.0 evaluation.
- There were no issues with anisotropic behaviour in stilbene.

2.12. Determination of the stopping power for alpha particles in carbon using resonant scattering, T. Bobrovskiy

It is important to have a correct stopping power of the charged particle in a target, because it directly affects experiments for thick target neutron yield measurements. The experimental stopping power for alpha particles in many substances can have discrepancies of up to 10% according to the database which was created by H. Paul [1]. These discrepancies can be significantly greater in the Bragg's peak region. The transmission method, which always is used to measure stopping power, has several limitations. These limitations are accuracy of target thickness measurement, the manufacturing of self-supporting films, and target uniformity. We used a different approach based on the resonant scattering of charged particles on target nuclei [2]. This method requires thick targets. Thus, it eliminates thickness inhomogeneity. In addition, the accurate value of the resonance energy is not important for this method. We obtained the stopping power for alpha particles in carbon to carry out a benchmark experiment to measure thick target neutron yield from $^{13}C(\alpha,n)^{16}O$ reaction [3].

References:

[1] C. Montanari, P. Dimitriou, The IAEA stopping power database, following the trends in stopping power of ions in matter, Nucl. Instrum. Methods B **408 (**2017) 50-55.

[2] T.L. Bobrovskiy, et al., Determination of stopping power for light ions using resonance backscattering, Nucl. Instrum. Methods B **543** (2023) 165094.

[3] P.S. Prusachenko, et al., Experimental study of thick target yield from the $^{13}C(\alpha,n)^{16}O$ reaction , Nucl. Sci. Eng. **198** (2024) 1062.

Discussion:

- Use different models to calculate beam straggling (no response as to which models were used).
- The new measured stopping data disagree with SRIM, ASTAR and other models at lower energies.

2.13. Uncertainty quantification in R-matrix analyses using Bayesian methods, D. Phillips (Ohio University)

Bayesian methods provide a unifying and powerful framework to quantify uncertainties. Their recent application to R-matrix calculations of nuclear reactions has lent a new level of rigor to R-matrix analyses, accessing new information about R-matrix parameters, and assessing the impact of experimental systematics on both estimates of those parameters and R-matrix predictions.

First a review of Bayesian methods within the specific R-matrix context was given. It was argued, using examples, that sampling of the full Bayesian posterior for the R-matrix parameter vector provides insights into the formulation of the R-matrix model that are difficult to obtain within a frequentist approach. It was then explained how, with that posterior in hand, it is straightforward to obtain predictions for as-yet-unmeasured reaction data.

Bayesian methods also permit straightforward modeling of experimental imperfections. I showed recent examples of Bayesian R-matrix analyses that treated experimental systematics such as acceptance effects at specific (lab.) angles [1], beam-energy shifts [2] and those which examined the impact of inflating the point-to-point uncertainties of different data sets [3].

I closed by touching on the treatment of theory imperfections within a Bayesian approach.

References:
[1] S.N. Paneru, et al., Phys. Rev. C **109** (2024) 015802.
[2] D. Odell, , et al., Front. Phys. **10** (2022) 88476.
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2.14. Refining the low energy R-matrix fit of ^{13}C(alpha,n)^{16}O, R. deBoer (University of Notre Dame),

Recent measurements of the differential cross section of the ^{13}C(alpha,n)^{16}O reaction have been made at the University of Notre Dame's Nuclear Science Laboratory over an incident laboratory alpha particle beam energy range from 0.7 to 6.5 MeV. For nuclear astrophysics application, the cross section was desired at ~150 keV and, while the present data was at higher energy, it has been shown previously that the differential data has a substantial impact on reducing the extrapolation uncertainty. However, there remain some issues with the fitting that need to be resolved, including a larger increased normalization factor for the simultaneously fit n+^{16}O total cross section data, energy calibration inconsistencies, and poorer agreement with the fits in regions of low cross section. Recent progress in resolving some of these issues was discussed, which has resulted in a significantly more consistent fitting across the different data sets.

Discussion:

- The original error bars on the data from Bair and Haas are likely incorrect by a factor of 2, possibly due to issues related to incomplete 4π coverage. Additionally, Cierjack's data appears to require both an energy shift and error rescaling. A notable dip around 4 MeV in the laboratory energy needs to be understood, as it may indicate a problem with the normalization of the entire cross-section. This issue requires further investigation.

2.15. (α,n) neutron yields for rare-event search experiments: a collaborative effort to understand the backgrounds, R. Santorelli (CIEMAT)

Accurate assessments of (α,n) neutron production rates, energy spectra, and associated gamma-rays play a crucial role in understanding the underlying backgrounds in experiments dedicated to rare-event searches. This presentation discussed the importance of the radiogenic neutrons within the context of low-background experiments, shedding light on the challenges presented by (α,n) neutrons in this specific field and presenting the methodology employed to calculate this articulated background. An integral aspect of our efforts involves the establishment of a new (α,n) Working Group, a collaborative initiative that brings together members from high particle (mainly dark matter and neutrino) and nuclear physics communities. This collective endeavour signifies a shared commitment to addressing the main challenges inherent in the study of (α,n) neutrons and their impact on experiments, aiming to tackle challenges collectively and advance in the understanding of backgrounds. We provided insights into the group's comprehensive plans for finalizing a white paper on this subject.

Discussion:

- Top priority measurements are (alpha,n) on Ar and chemical elements in resistors, PCB, Acrylic, Mechanical Parts, Sensors, Target) Al, N, B, + Si, Mg, C, N, O, Stainless Steel, Cu, Ti, Si, Ar, Xe, G. Argon will be measured. However, target preparation (gas) and required setup make this measurement particularly challenging.
- The assay experiments are performed for testing each material that is going to be used in the construction of the experimental components. It's difficult to assay everything that will be used and determine that it is the same material that will be used to build the experimental setup. A facility that could assay (alpha,n) reaction would be very useful but has not been established yet.
- The equilibrium in the Uranium-238 chain is broken by the long-lived radioisotopes in the chain, most likely due to their different chemical properties. Empirically it is found that the activity increases towards the end of the chain, probably from the different treatments in water and preparation methods.
- Teflon can be used in the experimental components. In fact, it has been used and found to produce very low residual radioactivity. The list of top priority measurements should focus on those where either no data or contradicting data exist.
- Priority lists and scoping studies focusing on relevant applications are very useful.

2.16. Neutron yield calculation for (α,n) reactions with SOURCES4, M. Parvu (Faculty of Physics, University of Bucharest)

The sensitivity of underground experiments searching for rare events such as dark matter, proton decay, neutrinoless double-beta decay, and low-energy neutrino physics is often limited by the background caused by neutrons from spontaneous fission and (α,n) reactions. Neutron yields and energy spectra, due to these reactions, can be calculated by using a variety of codes. We presented the cross-sections of (α,n) reactions and the transition probabilities to excited states calculated with TALYS 1.96 [1] and EMPIRE 3.2.3 [2] nuclear reaction codes considering different optical model parameters and the comparison with the experimental data where available. Furthermore, we presented the calculations of neutron production using the modified SOURCES4 code (adapted SOURCES4A) with recently updated cross-sections for (α,n) reactions and the comparison of the results with experimental ones from thick target neutron yields obtained with alpha beams and radioactive decay chains. The cross-sections for (α,n) reactions in SOURCES4 [3, 4] have been taken from reliable experimental data where possible, and complemented by the calculations with EMPIRE 3.2.3, TALYS 1.96 and JENDL-5 [5] where the data were scarce or unavailable.

References:

[1] A. Koning, et al., Eur. Phys. J. A **59** (2023) 131.
[2] M. Herman, et al., Nucl. Data Sheets 108 (2007) 2655-2715.
[3] W.B. Wilson, et al., Radiat. Prot. Dosim. 115 (2005) 117–121.
[4] W.B. Wilson, et al., Technical Report LA–13639-MS (1999).
[5] T. Murata, et al., Report JAEA-Research 2006-052.

Discussion:

- What is the sensitivity of your calculated yield results on the resonant structure part of the cross section, e.g. Slide 14 ^{11}B(alpha,n)? A reliable average cross section is sufficient to predict the neutron yields.
- SOURCES4 uses the older stopping powers of Ziegler from 1977. It is recommended to update the stopping data in the code to SRIM-2013.

- The effect of the cross-section data resolution or binning on the produced yields has not been investigated yet. The code has 4000 alpha groups. Sensitivity to the resonance structure is because it averages over large range.
- SOURCES4A and SOURCES4C are different versions of the same original code SOURCES (Wilson et al., Prog. Nucl. Energy 51 (2009) 608) with the same libraries. The main difference in the codes is the calculation of the neutron yield from spontaneous fission of Cf-252, which was wrong in version 4A and corrected in 4C. The SOURCES4A code is not free and cannot be shared. Only the libraries of cross section and branching ratios can be shared. The code was developed originally at ORNL and can be obtained upon request. For specific cases we can provide our libraries and make a calculation.

2.17. Updates to the NeuCBOT tool for (alpha,n) calculations, S. Westerdale (University of California, Riverside)

NeuCBOT, the Neutron Calculator Based On TALYS, is a program for calculating (alpha,n) yields for arbitrary materials given some radioactive contamination. The backbone of the code uses TALYS to calculate (alpha,n) cross sections, SRIM stopping power calculations, and ENDF nuclear decay data. Recent updates to the code include an updated TALYS cross section database, the option to draw cross sections from JENDL-5 instead, and the ability to calculate (alpha,n) partial yields. A webapp user interface for NeuCBOT is also under development, planned to be released in the near future. This talk presented an overview of the NeuCBOT software, validation and comparisons with other calculations, and a discussion of recent and upcoming updates.

2.18. Preliminary study of uncertainties on (alpha,n) cross sections with TALYS, H. Kluck

To accurately model the neutron background caused by (alpha, n) reactions in experiments aiming to search for rare events (e.g. Dark Matter), it is important to correctly consider the uncertainties on all “inputs” for a background model. One input is the neutron yield which itself depends on the (alpha, n) cross section. The latter can be obtained from nuclear reaction codes like TALYS [1] which depends on empirical model parameters. Hence, a two-stage propagation of the uncertainties is necessary: first from the model parameters to the cross section, then from the cross-section to the neutron yield.

To study the technical feasibility for the first stage, I used the testcase ^{40}Ar(alpha,n) for cross section calculation with TALYS. ^{40}Ar is a relevant nuclide for Dark Matter searches using Ar targets; furthermore, it is challenging, as EXFOR lists only one data point [2]. In a first attempt, I focused on the uncertainties caused by the parameters for the nucleon-OMP and the alpha-OMP. The impact of other parameters like nuclear mass, nuclear structure, level density, and photo strength function (see [3]) will be studied later.

TALYS together with the TASMAN code can sample the parameter space of the reaction model, based on best values and associated uncertainties for the model parameter. Drawing 2750 samples from the parameter space of the [4] nucleon-OMP showed that the [2] data point is outside the obtained uncertainty band. Similar, testing the six alpha-OMPs that are available in TALYS and which are suitable for ^{40}Ar(alpha,n) showed that the spread between the different alpha-OMPs is smaller than the deviation between the EXFOR data and the TALYS calculated cross section. Especially, the differences between the default alpha-OMP used by TALYS ([4] with Watanabe folding) and the latest alpha-OMP ([5]) is negligible.

This study showed that TALYS together with TASMAN is also for the use case of ^{40}Ar(alpha,n) a suitable and easy way to propagate the uncertainties from the model parameter to the modelled cross section. So far, neither the uncertainties of the nucleon-OMP parameters nor the spread caused by different alpha-OMPs can explain the deviation between the calculated cross section and the data point. The impact of other model parameters, other nuclides of interest, and the propagation towards the neutron yield calculation are topics for future studies.

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[1] A. Koning, S. Hilaire and S. Goriely, Eur. Phys. J. A **59** (2023) 131.
[2] R.B. Schwartz, J.W. Corbett, and W.W. Watson, Phys. Rev. **101** (1956) 1370.
[3] J. Pereira and F. Montes, Phys. Rev. C **93** (2016) 034611.
[4] A. Koning and J. Delaroche, Nucl. Phys. A **713** (2003) 231.
[5] V. Avrigeanu, M. Avrigeanu, and C. Mănăilescu, Phys. Rev. C **90** (2014) 044612.

2.19. Modernized Stopping Power Database, P. Dimitriou (IAEA)

The existing legacy database of stopping powers was established almost 30 years ago by Helmut Paul, Univ. Linz. The database contains all available electronic stopping power data measured since the 1930s. Since 2015, the maintenance and development of the experimental stopping power compilation is the responsibility of the IAEA (https://nds.iaea.org/stopping/).

In 2023, the Stopping Power Database was reviewed and enhanced [1]. A new interface was developed that enables easy retrieval, plotting and downloading of all experimental data, including datasets with only one measurement available.

The new features of the interface are:

- search engine for ions, targets, and publications;
- on-the-fly plots (using plotly);
- download of data and metadata in csv and txt files for ion-target, single ion or target, and all the above;
- retrieval via API (work in progress).

The database is continuously updated and improved. Feedback from the user community is welcome.

References:
[1] The IAEA electronic stopping power database: Modernization, review, and analysis of the existing experimental data, C.C. Montanari, P. Dimitriou, L. Marian, A.M.P. Mendez, J.P. Peralta, F. Bivort-Haiek, Nucl. Instrum. Methods B **551** (2024) 165336, https://doi.org/10.1016/j.nimb.2024.165336.

3. DISCUSSION AND RECOMMENDATIONS

3.1. Experimental data needs

- ^{40}Ar(α,n): top priority – in urgent need of measurements as currently there is only one data point available. Possibility for measurements within MANY collaboration – however there are challenges in target preparation and measurements (gas vs liquid) – requires coordination among MANY groups and other international groups.

- Technical exchanges and cooperation among various expert groups on the following measurement issues would be beneficial:
    1. Targetry;
    2. Calibration;
    3. Allocation of/access to beam time (considering requirements for PAC approvals).

- Reference (α,n) cross sections and/or beam monitoring reactions would be useful for (α,n) cross-section measurements. For this purpose, it's important to establish the conditions/requirements for determining a reference (α,n) cross section, identify possible candidates, and propose additional measurements if needed. This job could be the task of a working group coordinated by the IAEA.

The following possible candidates were mentioned:

1. Consider ^{7}Li(α,n) given that the reverse ^{10}B(n,α) is a cross-section standard;
2. Other possibilities: ^{27}Al(α,n), ^{9}Be(α,n) and ^{13}C(α,n).

- Stopping powers [electronic] are important data for calculation of (α,n) yields from cross sections but also for normalization of measured thick target yields. There is a demand for:
    1. Re-assessment of the quality of existing stopping power exp. data (both accuracy and precision), especially for actinides and F, O, B targets.
    2. Re-assessment of the performance of existing stopping power codes: SRIM, ASTAR, etc. particularly in the case of compounds. Explore the machine-learning tool (ESPNN).
    3. Recommended stopping power data. It is worth investigating if it is possible to make an evaluation of stopping power data.

3.2. R-matrix analyses, reaction codes and calculations needs

- R-matrix analyses/evaluations should include other reaction channels leading to the same compound system including the neutron channel [standard approach in data evaluation].

- An evaluation of the ^{17}O system up to 9-10 MeV to provide recommended ^{13}C(α,n) cross-section data: ongoing evaluation work at LANL (extend to above 5.5 MeV); deBoer (Notre Dame) refining the low-energy region; Chen (Tsinghua U) performing re-evaluation up to 20 MeV with new (n,α) data; Pigni (ORNL) performing evaluation.

- The extension of the ^{19}F(α,n) R-matrix analysis to include neutron channels leading to the compound system ^{23}Na; It would be useful to have the new ELI-NP measurements available, and a new measurement up to 3 MeV (a proposal could be submitted to the ELI-NP PAC for approval in 2024).

- Training of the new generation of experts on R-matrix analysis and evaluation. Various training opportunities should be explored:
    - R-matrix Workshop organized by Notre Dame Univ. and other US universities and national laboratories;
    - Joint IAEA-ICTP Workshop as an introductory training opportunity;
    - Mentorship schemes [supporting the mentoring of new R-matrix experts by experts in the field for short to extended periods].
- Continued efforts to employ Bayesian methods in R-matrix analyses to enable full quantification of uncertainties in R-matrix parameters and predictions.

- Detailed documentation of experimental systematics in papers providing published data so that full experimental covariances can be incorporated in likelihoods used for R-matrix analyses.

3.3. Neutron source codes and yield calculations needs

- Recommended cross sections for the ^{13}C(α,n) reaction at higher energies above 5 MeV. The new ENDF/B-VIII.1 evaluation based on an R-matrix evaluation will extend up to ~5.5 MeV alpha energy.

- Reliable branching ratios [from nuclear structure databases such as ENSDF, RIPL (based on ENSDF)].

- Cross sections to excited states, both experimental and theoretical (currently mostly taken from TALYS) and corresponding neutron and gamma spectra. It is important to compare the results of the various codes and make recommendations [neutron spectra: most important is the fast neutron energy region from > 0.5 MeV up to 10 MeV].

- Measurements of neutron yields from U and Th sources [emitted from equilibrium decay chain].

- Implement uncertainty quantification methods in the source codes. Propagate uncertainties in cross sections and stopping powers with due consideration of covariances and of the limitations of linear error propagation.

Measurements of alpha-beam neutron yields for isotopes for which data are scarce or missing, e.g. Ar, C, Ti, Fe, Cu, and other components of stainless steel such as Ni, Cr, Mo. The required energy region is 0 - 10 MeV.

3.4. General recommendations

The needs and demands for reliable (α,n) data have led groups from various research areas to form collaborations and working groups with specific objectives and tasks. The meeting participants commend these efforts and support the joint activities of these groups which are listed below:

- (α,n) Low-Background Physics Working Group – a White Paper will be released by the end of 2023;

- MANY collaboration (Spain) – focused on measurements of thick target yields and cross sections at Spanish experimental nuclear physics facilities (CIEMAT, CNA HISPANOS);

- ELIGANT collaboration (Romania, Kazahkstan, UK) – performing experiments at ELI-NP - plan to request funding for upgrade of setup;

- US project on alpha-induced reactions on light nuclei – collaboration of US universities and national laboratories to measured and evaluate (α,n) cross sections - to start in 2024.

4. CONCLUSIONS

The second IAEA Technical Meeting on (α,n) data evaluation and data needs was held virtually from 27 November to 1 December 2023. Participants reviewed the status of (α,n) cross-section data and yields at incident energies up to 9 MeV, including the performance of nuclear reaction and source codes, and evaluated libraries for use in the fields of particle physics, nuclear astrophysics, fission and fusion reactor physics and non-proliferation applications.

Participants agreed that the IAEA meetings on (α,n) evaluation and data requirements serve as a common forum for the different communities and experts to share their knowledge and expertise while reaching a consensus on best practices. They also aim at identifying the gaps in the data, models, and software, and proposing recommendations to address these gaps.

The participants recommend the continuation of these meetings to monitor progress and initiate useful follow-up activities.

The next meeting will be held in 2 years as many new measurements, software developments and data evaluations will become available by then. Although the last two virtual meetings were both efficient and productive, an effort will be made to have the next meeting in person to maximize the interactions among the experts.

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