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(alpha,n) Nuclear Data Evaluations and Data Needs

Summary Report of the Technical Meeting
8-12 November 2021
(virtual event)

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ABSTRACT

A 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 organised by the IAEA from 8 to 12 November 2021. Over 60 participants from fifteen Member States attended the virtual event. Participants reviewed the status of (α,n) measurements, models, codes and evaluated libraries with a view to identifying the gaps in the above areas and proposing the necessary actions to address them and produce reliable (α,n) data for the applications. 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/283/.

March 2022

CONTENTS

1. INTRODUCTION

(α,n) reactions are relevant for a wide range of applications. In nuclear fission reactors, considering that the core consists primarily of water (H_20), energy-dependent neutron interactions with O isotopes are of primary interest. A comprehensive nuclear data evaluation for such interactions requires knowledge of the inverse reactions induced by alpha particles leading to the same compound system. (α,n) reactions on ^{13}C are therefore crucial for the correct determination of the cross sections of the ^{16}O(n,n) reaction. In nonproliferation, waste management and homeland security applications, alpha particles produced by actinide decays in fresh/irradiated nuclear fuels and interacting with the light fuel compounds such as C, O, F, produce neutrons that can be used in non-destructive assays of the irradiated fuel to determine the fuel enrichment. The (α,n) reaction is also an important neutron source in deep geological repositories of spent fuel. In underground studies of rare events, such as Dark Matter candidates, neutrinos, and reactions with extremely low rates relevant to nuclear astrophysics, alpha particles emitted from naturally decaying isotopes can interact with the light mass components of the detector systems or surrounding rock and contribute to the background of the measurements, thus inhibiting the detection of the true rare events.

In the above-mentioned applications, the alpha particles produced by decaying radioisotopes interact with light to medium-light nuclides with incident energies ranging from several keV to 9 MeV, via the formation of an excited compound nucleus whose resolved energy spectrum can be described by the R-matrix theory. With increasing nuclide mass and incident energy, the nuclear reactions occur in the overlapping resonance (statistical) region, in which case they are described by the statistical model.

All these applications and calculations depend on accurate and precise experimental data. However, most of the available experimental data was measured decades ago, is incomplete and/or the uncertainties in the cross sections and neutron emission spectra are rather large. Furthermore, the evaluated libraries are incomplete or based on evaluations that are now outdated. The need to update evaluated nuclear data libraries for (α,n) or, more generally, charged-particle induced reactions has led the IAEA Nuclear Data Section (NDS) to start an international effort to produce updated evaluated data for charged-particle-induced reactions. The first task of the international network of experts was to compare the capabilities of existing R-matrix codes and, within common capabilities, to verify the calculated integral and angular cross sections in the case of charged-particle reactions in the resolved resonance region. (α,n) evaluations naturally form part of this network activity and were discussed extensively in a dedicated session on (α,n) data needs at the recent 5th Consultant's Meeting of the International Nuclear Data Evaluation Network for Light Elements (INDEN-LE) (Consultants' Meeting on INDEN for Light Elements).

NDS has also carried out a detailed study of (α,n) reactions on light elements O and F for spent fuel applications. The study which was published in INDC(SEC)-0111, and subsequently in Nuclear Data Sheets, v. 139, January 2017, p.190, showed that for oxides, such as UO_2 and PuO_2, the newly evaluated (α,xn) cross sections and thick target yields agreed at the 10% level with the reference data published in 1991 by Los Alamos National Laboratory. On the other hand, for UF_6 and PuF_4 fuel materials, the differences between the new evaluations and the 1991 reference data were at the 25-50% level. The main reason for these discrepancies is the lack of reliable experimental cross-section data (existing data are discrepant) resulting in highly uncertain ^{19}F(α,n) reaction cross sections.

The need for improved experimental data and evaluated data libraries extends beyond the case of ^{19}F and involves (α,n) reactions on a range of light and medium-light elements relevant to the broad range of applications mentioned above. In addition, to better quality data, nuclear reaction codes performing R-matrix and/or statistical model calculations and source codes used to calculate the neutron sources from the existing cross-section and stopping-power data also need to be updated. These requirements for new measurements, improved data libraries and advanced software can be efficiently addressed by an international cooperation among the inter-disciplinary groups actively involved in (α,n) studies.

With these developments in mind, 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 over 60 registered participants from 15 member states covering the application fields of (i) fission and fusion reactors, (ii) spent fuel management and nonproliferation, (iii) rare-event experiments, and (iv) nuclear astrophysics.

The purpose of the meeting was to review the status in (α,n) measurements, models, codes and evaluated libraries, identify the gaps, and propose the necessary actions to fill the gaps with a view to producing reliable (α,n) data for applications. Presentations covered data needs in measurements, evaluations and software.

The meeting was opened by the Head of the Nuclear Data section, Arjan Koning, with a welcome address. The Scientific Secretary of the meeting, Paraskevi Dimitriou, introduced the motivation behind the meeting and the goals as listed above. Subsequently, chairpersons and rapporteurs were elected for the five days of the meeting as follows:

Day 1: Helmut Leeb (Chair), Shawn Westerdale (Rapporteur)
Day 2: Daniel Cano (Chair), Arnd Junghans (Rapporteur)
Day 3: Arjan Plompen (Chair), R. James deBoer (Rapporteur)
Day 4: Roberto Capote (Chair), Marco Pigni (Rapporteur)
Day 5: Paraskevi Dimitriou (Chair), Shawn Westerdale (Rapporteur)

This summary report is organized in seven sections: Sections 2-5 include summaries of participants' presentations and subsequent discussions corresponding to the four application fields addressed in different sessions at the meeting. Section 6 presents a comprehensive list of the requirements for all the applications, while Section 7 gives a summary of discussions and recommendations.

Presentations and the list of participants are available at the meeting webpage:
https://conferences.iaea.org/event/283/.

2. LOW-BACKGROUND RARE-EVENT MEASUREMENTS

2.1. Low-energy cross-section measurements of $^{13}C(\alpha,n)^{16}O$ at LUNA, A. Best (Univ. of Naples Federico II/INFN)

This is the main reaction producing neutrons that induce the s process, with alpha-particle energies in the range E_α= 140-230 keV (and the i-process, with E_α = 285-510 keV, respectively). The LUNA facility at Gran Sasso currently covers energies in the range 50-400 keV, although the LUNA MV facility, already under construction, will extend this range up to 3500 keV. Direct low-energy measurements are limited by natural backgrounds, which is why the facility is built underground, where one of the main backgrounds is neutrons produced by (α,n) and fission in the surrounding rock.

Targetry: 99% enriched ^{13}C evaporated on Ta disks. Neutron detection efficiency: ~30%, Background: rate of 1-2 counts/hr.

The S factor was measured at energies in the range 235-300 keV. The problem remains the analysis of all available experimental data and setting the respective normalizations. For nuclear astrophysics applications, the determination of the $^{13}C(\alpha,n)$ reaction rate is of high priority. A new global R-matrix analysis of the world data sets is needed.

Q&A:

- Degradation of solid beam-stop targets under high intensity beam bombardment restricts the number of measured data points and prevents measurements from extending to lower energy.
- Lower energy points could be measured using inverse kinematics and ^{13}C on a ^{4}He target.
- Depending on how low a beam current can be tolerated at LUNA, we will also be able to perform measurements with beam energy up to 3.5 MeV (around 2.3 MeV center-of-mass energy) to address the issue of normalization of experimental data sets.
- The ^{17}O compound nucleus is also important for nuclear astrophysics.
- The R-matrix evaluation presented was performed with Azure2 and goes up to 1.2 MeV alpha-particle energy.
- The ANC of Avila et al. [PRC **91**, 048801 (2015)] is accurate to ~20%. This uncertainty along with all other uncertainties was included in the MC analysis.

2.2. (α,n) Reactions in low-background neutrino experiments, V. Lozza (LIP Lisbon)

Neutrino experiments are often based on water and/or liquid scintillators such as LXe, LAr, and organic scintillators. Important elements for study of (α,n) reactions include C, O, N, F, Ar, Xe, Si, and other materials used to build detectors, including Al, Ti, Cu, stainless steel, Be, etc.

The main sources of alpha particles are the U and Th alpha emitters. The ^{238}U sub-chains are also important sources, especially ^{210}Po, which can be produced from long-lived ^{210}Pb decay or Rn decay. The main sources of neutron background are alpha captures or inelastic scattering. Detectors are mostly sensitive to MeV-scale signals:

- For the $^{13}C(\alpha,n)^{16}O$ reaction, given that the first excited state of ^{16}O de-excites by internal pair production, it is important to know the cross sections to the excited states and how the nucleus is de-excited to the ground state, to model the background; the reaction $^{18}O(\alpha,n)^{21}Ne$ is also important; $^{40}Ar(\alpha,n)^{43}Ca$ from ^{222}Rn decay is important for the DUNE experiment. Either the models suffer from significant uncertainty, or the data are too scarce; Another example of an important reaction is $^{136}Xe(n,\gamma)^{137}Xe$ because ^{137}Xe can produce 0vbb background in the neutrinoless double-beta decay experiment nEXO. Other (n,γ) reactions are also important.
- Partial (α,n) cross sections to the excited states are particularly important information.

Q&A:

- Top priority: C is probably most important, then Ar because of there being only one measured data point at present.
- Regarding needs for a specific characterization, for the moment, we just need to understand the cross sections on specific isotopes. As a next step, we can focus on characterization of specific materials.

2.3. Impact of (α,n) reactions on direct search of Dark Matter, R. Santorelli (CIEMAT)

Significant efforts are made to minimize the impact of (α,n) reactions on the experimental background; there have been extensive assay campaigns to measure U and Th in the surroundings; in addition, care is taken to select extremely radiopure materials for the detector components.

Assay campaigns use multiple techniques to measure various parts of the ^{238}U chain. In particular, the ^{238}U are measured with ICP-MS (Inductively Coupled Plasma Mass Spectrometry), the middle chain is measured with gamma counting, while the lower chain containing Pb-210/Po-210 is measured with radiochemical techniques.

Materials are chosen based on known and small (α,n) cross sections: we try to avoid Be, B, and F, although it is not always possible. Resistors consist of Al, N, B, Si, Mg; PCBs consist of C, N, O; PTFE of C, F; and, acrylic of C, O; mechanical parts have stainless steel, Ti, Cu; sensors have Si; targets are made from Ar, Xe, and Ge. Materials are considered important if the cross section is large or if the material mass is large.

(α,nγ) is also particularly important for Dark Matter experiments, especially because the γ-rays are often used to reject backgrounds (e.g. by using veto detectors).

Recently, a group of particle physicists working in low-background experiments and interested in (α,n) yields formed an (α,n) Working Group (WG) (alphan@ciemat.es) at a Snowmass meeting. The first goal of this group is to produce a White Paper (work in progress).

Q&A:

- The most crucial data are cross sections; stopping powers are a second order effect.
    - IAEA is hosting a database of experimental stopping powers (https://www-nds.iaea.org/stopping) and is interested in stopping data needs for applications.
- Producing a list of the most important isotopes that need cross section measurements is experiment-dependent, so it is hard to produce a universal ordering, but there are some common needs for many experiments; this is something the Snowmass (α,n) WG is trying to establish (e.g. the problem with Argon).
- To determine the most important elements for which cross sections are needed, several factors must be considered: materials that are present in experiments with high masses, such as Ti, Cu, and stainless steel, are of high priority; in addition, isotopes with high neutron yields, like ^{13}C, ^{14}N, Al, F, etc. Cases where the available experimental data are not consistent with each other, and a choice of a single experimental data set is required. For example, there exist several measurements for F, however the data are discrepant in the energies we are interested in. These discrepancies need to be resolved.

2.4. Facilities, measurements, and experimental verification of (α,n) for Dark Matter, A. Villano (Univ. of Colorado)

An effort is underway to determine the elements, nuclear reactions, and energies for which cross-section information and evaluations are needed for rare-event experiments.

There are some reactions for which data exist, but still need to be analyzed. Many different measurements/evaluations have significant discrepancies that can matter a lot for these rare-event experiments. Stronger disagreement is found in (α,nγ) reactions (e.g. $^{13}C(\alpha,n\gamma)$).

North American facilities in Montreal, Notre Dame (a large nuclear lab with 10 MV tandem and 5 MV single ended high current machine), and Ohio Univ. can be useful for carrying out experimental campaigns to measure new data in a systematic way.

Q&A:

- The preparation of the White Paper by the (α,n) WG is ongoing. The aim is to produce a first more or less complete draft of the White Paper by the end of the year 2021 (timescale), and a version ready for circulation sometime next year.
- The (α,n) WG is open to a collaboration with the IAEA and participating in an IAEA project as it would be beneficial to have exchanges with nuclear physics and nuclear data experts and share the latest developments in those fields.
- In terms of facilities in North America, Notre Dame, Montreal, and Ohio U. have active programs measuring (α,n) reactions. The possibility of TUNL getting involved needs to be investigated.

2.5. (α,n) Cross section data improvement needs for next generation low-background neutrino and Dark Matter experiments, J. Reichenbacher (South Dakota School of Mines and Technology)

(α,n) backgrounds are important for rare-event experiments. They mostly come from alpha particles produced in U and Th decay chains, especially in the early and late ^{238}U chain, or the split at ^{226}Ra;

alpha-decaying radionuclide ^{222}Rn can also emanate and diffuse, and ^{210}Pb is long-lived and can accumulate.

Extensive radiological assays for gamma rays, alpha particles, and emanation are performed. Al in Rock/shotcrete is critical for determining (α,n) yields. Knowledge of this yield defines the shielding needs; Fe in cryostat is particularly important, the corresponding (α,n) yields have significant uncertainties, tension in the few measurements. Therefore, more measurements are needed; Fluorine in Teflon has a high (α,n) yield -which makes it especially important.

There are very few data for Ar and Xe, however, these are important components of extremely large detectors that are being developed for future experiments.

(α,n) reactions are also needed for neutron calibration sources: e.g. AmLi source; we need to know the (α,n) cross sections to determine how to finely tune the source to the experimental needs.

Q&A:

- Instead of using experimental (α,n) data directly, one could use evaluated libraries (ex. JENDL-AN) which are based on an assessment of the available data. The IAEA INDEN projects (INDEN - International Nuclear Data Evaluation Network) place a lot of importance on the assessment of available experimental data as well as on documenting the arguments for selecting, discarding, or modifying data.
- There are no immediate plans to collaborate with experimental nuclear physics groups to carry out such experiments. However, future collaborations with Notre Dame and CIEMAT could be feasible.
- We will need comparisons of different neutron yields and energy spectra. See presentations of Vitaly Kudryavtsev (4.4) and Shawn Westerdale (3.4), who are working on this using SOURCES-4C and NeuCBOT, respectively.
- We mostly need production yields and energy spectra; currently there are a lot of disagreements between data and models. All these difficulties are compounded as we build larger detectors for which we need to perform simulations that require accuracy and precision.

Discussion Session 1

- Needs in terms of neutron energy resolution:
    - Good neutron energy resolution is not super critical for these experiments. 1 MeV would work: 0.5 or 0.1 MeV better. More important is the total yield and the branching ratios for cross sections to different excited states. Energy resolution matters most near thresholds.
    - If the branching ratios to the excited final states are known, the spectra can be calculated well enough. It depends also on whether we are in the resonance regime.
    - Availability of cross sections in databases is important; feedback on which data to trust is also important; this is the job of evaluators.
    - Neutron energies (resolution) might be more important when used as calibration sources.
- Required accuracy for cross-section measurements have an impact on experiments:
    - A 10% improvement would be good. Often the existing discrepancies in measurements are about a factor of 2.
    - More important than knowing the cross sections with biggest impact is to know which cross sections to use when evaluations and data differ and to measure cross sections that are missing entirely. In general, we would be happy with 30% uncertainty in the cross-section data to be compatible with the other sources of uncertainty (e.g. the uncertainty in our assays). Filling in blanks is the key issue (where data is missing/scarce/highly discrepant).

- For ^{13}C, a 30% discrepancy observed in the data at present would make a significant impact on the analysis
    - For neutrino experiments better accuracy is needed;
    - The discrepancy is worse for excited states -> factor of 2 uncertainty;
    - Generally, bringing down the discrepancies to 10-20% would be a good goal;
    - For nuclear astrophysics applications, a 30% uncertainty, however, is too large. A ~10-15% uncertainty is acceptable.
- Ge(α,n) makes a negligible contribution to the background.
- At Notre Dame one can measure (α,n) cross sections to 1 keV alpha energy resolution and 10 keV alpha energy uncertainty with deuterated LS array, and cross sections to high precision; absolute cross section measurements can be highly target dependent. One can also measure partial cross sections to excited states and do neutron spectroscopy with detectors as well. The biggest constraint is person power and funding:
    - (α,n) WG White Paper on measurement needs would be extremely helpful for funding as would support from the international community and the IAEA.
- Measuring (α,nγ) with gamma spectroscopy at Notre Dame:
    - Notre Dame has Ge detectors which can achieve a limited resolution for measuring emitted γ rays. There is also a LaBr array, with even more limited resolution.
    - Using large NaI detectors would not enhance the (α,nγ) measurement campaign at ND. The issue is not really with equipment but mostly with shortfall in personnel for data analysis and lack of funding. Funding is also needed to support evaluators.
    - Angular distribution of outgoing γ rays for analyzing the neutron background in rare-event measurements is not needed.
    - Energy and angular distribution for γ–ray detectors is useful for separating γ rays of interest from the background spectrum.
- Relevant article: Alpha capture to the giant dipole resonances of ^{42}Ca, ^{44}Ca and ^{52}Cr, G.S. Foote, et al., Nucl. Physics A 263 (1976) DOI: 10.1016/0375-9474(76)90177-9.

3. (α,n) DATA FOR APPLICATIONS AND CODES (I)

3.1. The MANY project: measurement of neutron yields and spectra from (α,n) reactions in Spain, A. Tarifeno-Salvidia (Univ. Politécnica de Cataluña)

The MANY project (Measurements of (α,n) yields) relevant for neutron background in underground experiments, nuclear technology and nuclear astrophysics is a coordinated effort of Spanish research groups and facilities. The project partners include experimental facilities HISPANOS, Seville, and CMAM, Madrid which have H, D, He continuous and ns pulsed beams. The project started with the Workshop on (α,n) yield in low background experiments, 21-22 November 2019 at CIEMAT, Madrid, Spain.

The currently available (α,n) detection systems in Spain are:

- MONSTER for ToF, liquid scintillators with pulse shape discrimination, 50 cells 20 · 5 cm BC501A 5" photomultiplier tubes with > 10% efficiency per module;
- miniBELEN, 3-He with moderation (for beta-delayed neutron studies) or for (α,n), modular detectors with different geometry and efficiency up to 10 MeV including two-ring or three-ring-3-He counter geometries with 5-8 % total efficiency surrounding a central target position assembled; operative since January 2021;
- LaBr3(Ce) gamma array FATIMA with digital DAQ.

The commissioning status of (α,n) dedicated set ups is as follows:

- Commissioning at CNA HISPANOS: using ^{27}Al(α,n) and Monster with continuous alpha beam is done, pulsed beam is planned for 2022.

- Commissioning at CMAM: using $^{27}Al(\alpha,n)$ and 5 MONSTER detector modules with continuous alpha beam + LaBr3 is done, pulsed alpha beam commissioning with 5-8 MeV is planned for 2022. Using miniBELEN@CMAM-10A for $^{27}Al(\alpha,n)$, on Ta thick target background, at 5-6 MeV: problems were encountered with target setup (suppression).

Newly measured production yields for ^{27}Al underestimate the existing neutron yields by a factor of 0.63±0.02. The beam current on target (secondary electrons) needs to be improved and for this reason a new target holder and suppression electrodes will be introduced.

To summarize,

- CMAM commissioning of continuous beam is in progress, a new run is scheduled in Dec 2021 with miniBELEN; commissioning of pulsed beam will take longer.
- CNA HISPANOS: commissioning of pulsed beam with MONSTER detectors will be completed in 2022, and with miniBELEN after the summer of 2022.

Q&A:

- The MANY project is foreseen to have at its disposal several weeks of beam time per year at the two facilities (CMAM, CNA).
- So far, 1.5 days have been spent for commissioning at both facilities involving 1 PhD and 2 Master thesis students.
- The MANY project will benefit from an expression of endorsement by the meeting participants in the final list of recommendations
- Measuring thick target yields is equally important as measuring excitation functions. (J. De Boer)
- The parameters of the pulsed beam at CNA are given in this summary. The CMAM pulsed beam is in preparation and will take 1-2 years to become operational.

3.2. Constraining (α,n) cross sections with indirect measurements, P. Adsley (Texas A&M)

The main source for the s process (slow neutron capture) of nucleosynthesis is $^{22}Ne(\alpha,n)^{25}Mg$. The following reactions act as neutron poisons: $^{16}O(n,\gamma)$: $^{17}O(\alpha,n)$/ $^{17}O(\alpha,\gamma)$ + weak r –process.

The main issue is to know the resonance levels and corresponding spins, parities, and alpha partial widths. $^{22}Ne+\alpha$ studies benefit from indirect measurements to locate and characterize resonances. These include scattering (p,p'), (α,α'), transfer reactions, (n,γ) + transmission from nTOF and JRC.

Open questions are:

- $^{22}Ne(\alpha,n)$ at E_{cm} = 550 keV where experimental results are not conclusive.
- $^{17}O(\alpha,n)/(\alpha,\gamma)$ where discrepancies were observed in number, energies of levels, properties, and in n/γ strengths. Only guesses can be made below E_{cm} = 660 keV.
- $^{20}Ne(d,p)^{21}Ne$ at 14 MeV TUNL measured with magnetic spectrometer, implanted foil: the background remains a problem. DWBA analysis performed, partial widths Γ_n were extracted leading to estimates of the strength of the s process, with however large uncertainties.

$^{17}O+\alpha$ is going to be measured at DRAGON (Matt Williams), while the results of the $^{17}O(^{7}Li,t)$ Munich experiment Q3D is in preparation. Nonselective scattering may help determine number of levels, spins/parities: measuring proton scattering at 10-20 MeV would be helpful.

Comparison of TALYS $^{22}Ne(\alpha,n)$ calculations using the $^{22}Mg(\alpha,p)$ input parameters with experimental data and reaction rates. It may help find alpha-particle resonances with $^{22}Ne(\alpha,n)$.

The issue of biased selectivity is discussed for $^{25}Mg(d,p)$ in PRC 103, 035809: the ^{26}Mg levels are misassigned in the (α,α') measurement because of incorrect comparison with (γ,γ') data. Most reactions are selective in terms of the final states they populate, but not always with respect to the same property.

Q&A:

- There is room for improvement of the $^{22}Ne(\alpha,n)$ measurements at energies below 0.9 MeV. Higher resolution compared with Jaeger, PRL 87 202501, is needed.
- Where are the initial spin parities and resonances taken from? Above neutron threshold they use neutron resonances from C. Massimi et al., Phys. Rev. C **85** (2012) 044615, and gamma-ray decay data from G. Lotay et al., Eur. Phys. J. A. **55** (2019) 109. In these calculations, TUNL/ENSDF nuclear structure and decay data databases (TUNL stops at A = 20, ENSDF continues from A = 21) could be useful.
- Improved energy resolution is required for radioactive beam measurements. The $^{17}O(\alpha,n_0)$ cross section is discrepant (main issue is the neutron detector efficiency) by a factor of 2!

3.3. Recommendations from an (α,n) Nuclear Data Scoping Study, C. Romano (IB3 Solutions)

The focus of the scoping study was on (α,n) data for nonproliferation activities to include UF_6 enrichment measurements, SNF safeguards, passive NDA measurements of special nuclear material, and neutron source characterizations (PuBe, AmBe). The natural neutron background was not addressed. The goal was to determine the state of the nuclear data libraries (JENDL, TENDL, and ENDF), prioritize the nuclear data needs, assess the modeling capabilties of SOURCES4C and recommend activities to resolve identified needs. The study included contributions from the US nuclear data community (from BNL, LANL, ORNL, LLNL) and those who developed relevant NDA techniques.

Key points of the study

- ENDF (α,n) libraries are mostly theoretical (TENDL) or based on JENDL. The new GNDS format was recommended to expand the libraries to include neutron spectra, gamma-ray energies, and covariance information.
- Evaluated data suffer from large uncertainties, mainly because they are based on old experimental data and do not include information on excitation states and neutron spectra.
- Neutron angular distributions are not well known, which has an impact on differential nuclear data measurements using beams.
- New measurements should provide gamma emission energies, stopping powers, and excited state populations to improve the evaluation of cross sections and neutron spectra.
- UO_2 (α,n) spectra are not well known, even when the cross section has low uncertainty.
- For UF_6 cylinders, LANL tested the Passive Neutron Enrichment Meter (PNEM). The (α,n) source term was taken from SOURCES4C using updated stopping powers. The total neutron yield was found to have the highest impact because the PNEM detectors were not sensitive to the neutron energy.

Priorities

Include SOURCE4C modernization, new evaluation of fluorine, oxygen, and carbon (α,n), fluorine thick target experiments, modernization of ENDF libraries in GNDS format, and updates to processing codes. More specifically:

- Update SOURCE4C to use new ENDF libraries or user-supplied libraries (similar for stopping powers). The code should be validated, maintained, and distributed to include the latest libraries. The code should also provide an interface with MCNP, SCALE/ORIGEN and GEANT4
- Evaluate current data on fluorine, oxygen, carbon, and related R-matrix formalism.

- Perform integral measurements of total neutron emission from thick fluorine targets.as well as fluorine activation and neutron spectrum measurements to reduce uncertainties in the recent differential measurements.
- Update ENDF evaluated library in GNDS format.
- Top priority data needs for nonproliferation: ^{13}C, ^{17}O, ^{18}O, ^{19}F; Secondary priority: ^{7}Li, ^{9}Be, ^{11}B, ^{10}B, ^{27}Al; Lower priority for molten salt reactors and advanced fuels: ^{23}Na, ^{25}Mg, ^{26}Mg,^{29}Si,^{30}Si, ^{37}Cl, ^{41}K.

The Workshop for Applied Nuclear Data Activities (WANDA2022) will be held 28 February – 4 March 2022 [Virtual] and stopping powers will be addressed.

Q&A:

- What effect does the JENDL O(α,n) evaluation have on the UO_2 (α,n) spectrum? The excited state population in O(α,n) has a strong influence on the (α,n) spectrum.
- The recommendations in this scoping study are not yet funded. The development of a multiplicity counter has been funded and will allow for more integral measurements of (α,n) neutron emission as well as benchmarks.
- The evaluation of ^{13}C(α,n) by LANL has taken the contribution of excited states into consideration.
- Regarding the UF_6 enrichment assay, neutron counting is preferred to gamma rays as neutrons provide a better way of determining the total amount of uranium due to gamma-ray attenuation. The weight is included in the measurement data, but the geometry of the UF_6 inside the cylinder is unknown.
- IAEA Safeguards division expressed interest in improved (α,n) yields: the study conducted at NDS concluded that ^{19}F(α,n) is of the highest priority while O is better known. Better measurement data and evaluations are required for ^{19}F.
- The strongest alpha-particle emitter within the UF_6 is ^{234}U which creates most of the neutrons by (α,n).
- The ^{18}O(α,n) data taken at Notre-Dame is being analyzed by a graduate student at Rutgers (B. Toomey) and will hopefully be completed by spring 2022 or early 2023. They just finished a calibration run at LANL to get the response matrix for the high energy neutrons which is needed to complete the analysis.
- How will the alpha-particle stopping-power data be updated in SOURCE4C? Stopping powers can be improved by measuring thick target yields for different fluorinated compounds and comparing with calculations. The stopping powers can be updated by the user within the SOURCES4C code.
- The proposed (α,n) measurements on ^{19}F will be made at 10 keV energy steps including the neutron and γ-ray spectra and should be benchmarked against the recommended integral measurement data.

3.4. (α,n) Neutron yield calculations with NeuCBOT, the neutron calculator based on TALYS, S. Westerdale (Yale Univ.)

github.com/shawest/neucbot

Code overview

The Neutron Calculator Based on Talys (NeuCBOT) was developed for use in low background experiments to estimate (α,n) background. The code is written in Python and user friendly. It allows the user to input material composition, as well as the alpha source description. It calculates total neutron yields and spectra for different isotopes and uses SRIM stopping powers to estimate the energy loss before (α,n) capture. The correlation between emitted neutrons and energy deposited by the alpha particle is currently lost in the calculation due to steps that speed up the calculation, but future updates are being developed to enable slower calculations that preserve this information. The database used for the calculations is created locally and can be downloaded, based on TALYS calculations. NeuCBOT systematically gives somewhat higher yields that other calculations by about 30%.

Uncertainties: improvements

The material compositions, natural abundances have small uncertainty (upper limits) of a few percent, contaminants (primordial alpha emitters in the system) have assay uncertainties of 10 % and the secular equilibrium is not always given.

Stopping power of alpha particles is fairly accurate to within 5%; The code currently uses Ziegler SRIM stopping powers, but an option will be added to choose between Ziegler and IRCU 49 report. Bragg's rule of summing by mass fraction has a 20% uncertainty.

Future plans

Implement different stopping powers and (α,n) cross sections based on TALYS: an open question is what uncertainty should be attributed?

Improve neutron energy spectra (currently anisotropies are not known, grain boundaries are not included, and materials are treated as homogeneous).

Planned features: Data driven corrections, different stopping powers, alternative cross section libraries, correlated gamma rays as function of neutron energy, total alpha energy loss, prior to capture, non-homogeneous materials.

Q&A:

- Apart from the default parameters, TALYS offers a choice of several input parameters to perform sensitivity calculations and get an estimate of the model.
- TALYS is used for masses as low as lithium, however, it does not include resonances, therefore, cannot reproduce the resolved resonance region. In this respect, it should be used for light nuclei only if no other R-matrix code is available.
- TALYS partial yields to excited states, and ground states branching ratios sometimes disagree with measurements by a factor of 2-3. This is partly due to direct (α,n) reactions to discrete low-lying states not being correctly implemented in the code. An alternative code to use is FRESCO by I. Thompson. However, at such low energies, one expects compound nuclear reactions to prevail over direct reactions. The problem may be the unknown spin distribution of the level density and/or unknown branching ratios.

3.5. TENDL-2021 Library for (α,n) cross sections, A. Koning (IAEA)

TENDL introduction

TENDL is being used in various applications such as nonproliferation, safeguards, criticality, astrophysics, medical isotopes, detector development for fusion.

Every odd year a new version is released.

The TENDL library has a good reproducibility and completeness. The quality is improving with each updated version.

TENDL has been extended to include neutrons, gammas, protons, deuterons, tritons, ^{3}He, alpha particles, on 2813 target nuclides, and for energies 0-200 MeV. It is also used in total Monte Carlo calculations to produce covariances.

For alpha-induced reactions, the global TALYS calculations are comparable to detailed isotopic evaluations. The EXFOR experimental data library and the ENDF evaluated nuclear reaction data library have been converted to directory structure data bases /projectile/element/mass/reaction/...

Through this conversion systematic tests with calculations can be done. The source codes and data files are available from nds.iaea.org as EXFORTABLES and ENDFTABLES.

Nuclear reaction models

The default optical potential for alpha particles is from V. Avrigeanu, et al., Phys. Rev. C **90** (2014) 044612, and for outgoing neutrons and protons from A.J. Koning, J.P. Delaroche Nucl. Phys. A **713**, (2003) 231. Preequilibrium and direct reactions are from A.J Koning, M.C. Duijvestijn, Nucl. Phys. A **744** (2004) 15, and stripping/knockout reactions are based on C. Kalbach, Phys. Rev. C **71**, (2005) 034606.

Examples

New improved results for (α,γ) using the IAEA 2019 CRP photon strength functions. All 93 (α,n) plots using TENDL show that TALYS could be used to find errors in experimental data files in EXFOR. However, TALYS does not provide the resonance structure. For ^{27}Al(α,n) there is one experimental data set which does not agree with TENDL. The ^{65}Cu(α,n)^{68}Ga is another reaction important for medical isotope production. The TALYS excitation function has a narrower peak than the data.

Currently a new interface and search engine (nds.iaea.org/dataexplorer) for comparison of EXFOR and evaluated libraries is being developed.

To summarize, TENDL has a complete (α,n) library that reproduces available experimental data with a global accuracy of 20-40 %. This might be adequate for scoping studies; however it does not satisfy safeguards requirements. We have blended into TENDL the JENDL/AN files for (F,O) as they include the resonance structure.

Q&A: postponed to main discussion

3.6. (α,n) Cross section needs for fusion, M. Gilbert (UKAEA)

Alpha particles are important in a magnetically confined fusion plasma because the heating is sustained by the energy returned to the plasma by the alpha particles before they escape. Monitoring of produced α's, and particularly their rate of release from the plasma, is therefore essential.

ITER is exploring fast-ion loss detector (FILD) technology for alpha-particle detection, which, however, does not have proven radiation hardness. As a backup, the complementary activation foil approach has been proposed.

The activation foil measurements for alpha particles are challenging (for neutrons it is a well-established method). The problem is to discriminate the gamma signal from background gammas coming from neutron-induced activation; the foil must be placed close to the first wall, to receive a measurable alpha flux, which is also where the neutron fluxes are highest. It is important to have data to compare & evaluate the different candidate monitor foils. The ^{79m}Se peak is visible above the background neutron noise produced by ^{76}Ge(α,n), hence the latter reaction is a suitable candidate.

Real-time foil measurements were proposed by Fenyvesi and Zoletnik (Hungary): A thin Be window separates the foil from the plasma chamber allowing extraction of ^{19}F(α,n). Other candidate reactions are: ^{10}B(α,n), ^{76}Ge(α,n), ^{43}Ca(α,p). No ^{76}Ge(α,n) data are available at present in EXFOR.

A low threshold is required to detect fusion alpha particles; while the alphas are born at 3.5 MeV, the majority will be lower energy when they reach the first wall. Thus a 1-3.5 MeV detection range is preferrable.

Validation with 14 MeV neutron and 3.5 MeV alpha experiments to prove detection over neutron induced gamma-background is necessary.

Q&A:

- Is it not possible to use existing material in the ITER chamber to get signals directly, e.g. tungsten?
    - It would be challenging to measure the gamma fields for materials still inside the reactor; the most suitable approach is to remove small sample foils for measurement at an external location.
- The priority list of potential targets is given in Bonheure, et al. Fus. Eng. Des. **86** (2011) 1298. ^{76}Ge(α,n) is a suitable candidate. Some data have been published in reports and could be compiled in EXFOR.
- Data requirements are for low-energy alpha particles where the compound nuclear mechanism is dominant; preequilibrium reactions are not relevant.

Discussion Session 2:

- ^{19}F(α,n): should compare different measurement techniques to determine systematic uncertainties; one should use active target's approaches.
- ^{18}F(n,α): important for core collapse SN (time-reversed reactions using stable targets). Also (α,n) reactions at higher energies are important to collect.
- Meeting participants should compile reaction priorities for the different fields and applications.
- Would a selection of data sets be useful for improvement of TALYS? Huge discrepancies with TALYS can be used to find errors in the EXFOR library. Outliers can be found, but if there is only one data set that is not possible.
- Models are not expected to be perfect, as they are based on approximations and use a limited set of adjustable parameters to reproduce the data.
- Data evaluation helps with the selection of consistent data sets by applying a normalization on different data sets and thus identifying systematic uncertainties. The INDEN light element group is working on evaluations of light elements, e.g. ^{19}F(α,n).
- How relevant is the resonance structure in the determination of neutron yields? Neutron yields are a function of alpha energies, and the U, Th decay chains. It is not easy to draw a conclusion.
- R-Matrix evaluations can be included into TENDL to cover resonance region. The JENDL/AN library has already been included for some cases.

4. (α,n) DATA FOR APPLICATIONS AND CODES (II)

4.1. A correction to the non-resonant process for elastic channels in R-matrix analysis, S. Kunieda (JAEA)

R-matrix calculations require both communication and collaboration between theorists and experimentalists since the R-matrix fits rely directly on the existence of the experimental data, their accuracy and the uncertainties associated with them.

A personal R-matrix Code AMUR has been developed in C++ using the KALMAN method GLSQ for fitting.

An IAEA R-matrix meeting was held in 2016 (https://www-nds.iaea.org/index-meeting-crp/CM-R-matrix-2016/). The ^{7}Be system was used to compare different codes. A quite simple system, few channels, few levels. Experimental data was taken from EXFOR.

Starting from the standard approach of "real levels" plus distant, background levels, it was not possible to fit the ^{3}He(α,α) data together with all other data. A solution was found by adding an independent background level for elastic channels only.

Why do these elastic channels need strong background levels? Some direct reaction mechanism correction? Shape-elastic? Correction to the hard-sphere phase shift? These remain open questions.

In the case of Heil's (2004) R-matrix fit to the ^{16}O+n system, they also used a separate fit for ^{16}O+n and ^{13}C+α channel, however, this is due to a coding limitation of SAMMY which does not allow simultaneously fitting of multiple entrance channels.

Ongoing work also involves improving the calculation of (α,n) thick target yields on BN neutron spectra.

Q&A:

- Multiple scattering and other experimental corrections cannot be handled currently.
- EDA (Hale, Paris) can get quite a good simultaneous fit for the ^{17}O system.
- Input files for different codes can be translated and directly compared using the Ferdinand code developed by I. Thompson within the INDEN-LE project.
- deBoer also very often needs to add pole contributions to fit scattering data when using AZURE2.

4.2. (α,n) Data for applications and detector simulation codes, D. Cano Ott (CIEMAT)

Neutron emission rates for MOX pins: neutrons come from Pu and Am chain decay, but (α,n) makes up most of the remaining contribution. Neutron-gamma correlations provide additional constraints and must be analyzed with Monte Carlo (MC) codes. To study neutron emission as a function of burnup and spent fuel evolution, we need (α,n) data. This will allow us to understand the long-term evolution of stored fuel.

SaG4n code (Geant4):
Most codes are integrating over stopping power and (α,n) cross sections to get thick target yields. The existing codes use a variety of cross-section libraries.

Our goal is to use a complete MC code for the following reasons: Complex geometries are now possible and are being developed and implemented in experiments. Standard evaluated files are more easily implemented. The same code can be used for neutron transport simulations. Geant4 is open source and widely used. The downside is that the computation time is much longer.

The code has an easy interface for non-programmers. Libraries being used at present: JENDL-AN-2005, TENDL. Several different versions of TENDL have been investigated.

The results for ^{14}N(α,x) show disagreement between TENDL and JENDL. The two libraries seem to agree in other cases.

Looking at cases where the partial cross sections are available for comparison: the results for the ^{11}B(α,n) spectrum are not in agreement. JENDL is usually off from the experimental data.

Recommendation to use SaG4n with JENDLTENDL01 library: a combination of the two libraries using JENDL/AN in the region of resonance structure and TENDL for the higher energies.

A comparison of yield calculations obtained with other codes like NeuCBOT, USD, NEDIS and SOURCES4C and experimental values shows that NEDIS, G4-JENDL, and SOURCES agree within 20%. USD underestimates the yields.

Conclusions: (α,xn) measurements and calculations are needed for non-destructive assay and fuel burnup. SaG4n has been validated with other codes. Approximately 60% to 40% differences exist between NeuCBOT and SaG4n. New (α,n) evaluations are needed to test and improve the codes.

Q&A:

- When referring to "SOURCES", one must be careful about the version and the nuclear data used. Some users have their own custom versions to do their own calculations. Authors must be consulted directly; the changes in SOUCES have not been documented.

- V. Kudryatsev confirmed that the results shown in Fernandes, et al (https://www.epj-conferences.org/articles/epjconf/abs/2017/22/epjconf_icrs2017_07021/epjconf_icrs2017_07021.html) are based on SOURCES-4A using the latest version of Empire.
- TENDL (α,n) only gives the information for one single channel. TALYS calculates cross sections to excited states, but this is not in TENDL since it is much more complicated to format. It would be helpful to have this information in TENDL, so TENDL developers will try to include partial cross sections up to Si.
- To simulate these types of reactions in MCNP, one must convert the ENDF libraries to ACE files which is not straightforward. Although Geant4 does not read ENDF files directly, it is easy to process them into the Geant4 format. Also, code developers can process data on request.
- Comparisons with calibration sources (AmBe) have not yet been performed.

4.3. Preliminary analysis of $^{9}Be(\alpha,n)^{12}C$ integrated and angular experimental differential data at energies below 4 MeV, O. Bouland (CEA Cadarache)

The aim of this work is to model reactor spectra. Our interest focuses on medium to heavy isotopes, and less on light isotopes. CEA contributes evaluations to the JEFF library. Evaluations are performed in two distinct energy ranges:

Low energy range: R-matrix (SAMMY, CONRAD)
High energy range: TALYS

There is an interest in (α,n) reactions for several reasons mentioned in previous presentations. The goal is to evaluate (α,n) data and associated uncertainties. We are in the learning phase.

$^{9}Be(\alpha,n)^{12}C$ example:
We have evaluated this reaction at energies up to 4 MeV, including partial cross sections $(\alpha,n_{0,1,2,3})$, (α,α_{01}). We used the SAMMY code "sequential" analysis based on the Reich-Moore approximation. No time-reversed data were used, and no breakup reactions were considered. For this limited R-matrix analysis we already needed to include states up to 9/2 below 4 MeV.

At low energies, several measurements are available. The Ramstroem data has a lot of experimental features. The fit to the Kunz data is good. Some angular measurements are available, however large normalization corrections are needed.

At medium energies, many data sets are available. Most data sets are in good agreement, though some of the older data sets require large normalization corrections. The fit is reasonable up to 3.2 MeV.

Calculation of PuBe source with the new evaluated cross sections:
Several source codes are available, but we need to customize them to our needs, therefore, it makes sense to write our own sources code. There are lots of sources, UX and PuX, compounds to compare our new code with. The new code, iSourcesC is an updated C++ code.

Simulation of PuBe13 data: spontaneous fission and (α,n) spectra are available to compare with.

Simulation of UPuAmO: Investigation of non-resonant vs resonant (α,n) calculations is possible. However, we need (α,n) measurements above 4 MeV.

Accurate angular distributions are needed for spin discrimination. These data can also impact the observed spectra. Resonant vs non resonant impact is being tested.

Q&A:
- Regarding R-matrix analysis with SAMMY, the boundary condition B=-l is used.
- Angular distribution measurements are really needed. (α,n_2) has not been measured at all. Below 4 MeV there are no data needs, data are needed above 4 MeV.

– Considering data needs from a general point of view: very few angular distributions are available, so measuring angular distributions would be a priority. We also need to check what is available in EXFOR before recommending what is needed for each element.
– iSources is not public but can be used in comparison calculations.

4.4. Calculation of neutron production in (α,n) reactions with SOURCES4A, V. Kudryavtsev (Univ. of Sheffield)

Sources4A is based on the publication in NIM A **972** (2020) 164095. The code is used to calculate neutron yields and spectra, both total and partial, up to an alpha energy of 9 MeV, for Dark Matter (DM) and other rare event searches. We are interested in both neutrons and gammas.

Neutron yields are important for A < Cu. We are particularly interested in materials present in large masses in DM experiments or having high neutron yields: F, Al, Si, C, O, N, and Ar. We are mostly looking for cross sections above the Coulomb barrier (a few mb or more) and seek the guidance of nuclear physicists for recommended data.

Sources4A/C are the most well-known versions of the code (LANL, 1999). We have been working historically with Sources4A. We use reaction codes to calculate the cross sections and take the stopping powers from Ziegler's compilations. Thick target approximation is always assumed.

Modifications: we have extended the energy range from 6.5 to 10 MeV, and have added cross sections from EMPIRE 2.19, TALYS1.9 and EMPIRE 3.2.3. The code is used by several experimentalists working in DM and other rare event searches.

Advantages: Flexible use of libraries and fast calculations. We can cover a lot of reactions.

Disadvantages: Written a long time ago in FORTRAN. Does not calculate gammas. Cannot read ENDF format directly. Cannot deal with 'surface' problems (treats only simple geometries).

Other tools available: USD tool, NeuCBOT, NEDIS, GEANT4.10.6. Several papers have been published comparing the different codes. Several differences are observed!

Inputs: Q-values, cross section as a function of energy, alpha-particle lines, and intensities for decaying isotopes (or alpha-particle energies), stopping power, spontaneous fission spectra, material composition. ^{252}Cf is off but corrected in SOURCES4C.

Outputs: Neutron yields, Spectra for SF and (α,n) reactions.

Comparison with data:
^{19}F(α,n): the experimental data show a lot of scatter and discrepancies. It is difficult to judge which experimental data to use. Branching ratios are also important, however, there is not much difference in branching ratios between the different codes.
Cross sections for Al: Significant discrepancies exist in the experimental data, which extend up to 6 MeV only, whereas we need data up to 9 MeV.
^{13}C(α,n): None of the codes can reproduce the resonance structure. However, the integrated yields produced by the codes are not so different.
Comparisons of thick-target yields: These are in much better agreement for both ^{19}F and ^{27}Al. Spectrum comparisons show some differences, but it is not too bad.
Spectra from decay chains for compounds: Differences are at the level of 30%.
Optimization of cross-section libraries: Experimental data are complemented with models. Branching ratios (BRs) are taken mostly from models due to the lack of experimental data. Significant differences are observed between USD, NeuCBOT, and Sources4A and GEANT4.
We need to be careful about complicated compound comparisons. For isotopes of interest, we have an agreement of about 20-30%. Cross-section data are inadequate to obtain better results. Neutron yields are slightly higher in general compared to older calculations. Differences are in the 20-25% level.

Q&A:

- Primary interest is in low background experiments, and although a 30% disagreement with experimental yields is not that bad, ideally, for the most important isotopes we need 10%.
- It is important to know what the best recommended nuclear data are to use in our thick-target yield calculations.
- We have used recommended input parameters for EMPIRE. We take default parameters in TALYS.
- We do not know about any other evaluated libraries other than JENDL which has a limited number of isotopes and was released in 2005, therefore is out of date. If we can have a new evaluated (α,n) library, we would use it.
- Resonances can have an impact, although in the case of ^{13}C(α,n), the effects observed in the cross sections seem to average out due to the integration and finally the yields have an uncertainty of 30%.
- The BRs we use are taken from the reaction codes such as Empire or TALYS. We use experimental data for the cross sections only.
- A higher energy measurement at 15 or 20 MeV would not be helpful for the determination of the yields for this application, we only need up to 9 MeV. However, it may help improve the models and the evaluation of the cross sections. This is a question for the nuclear data physicists to consider.
- LANL is working on an update to the ^{17}O evaluation. For the record, JENDL/AN for ^{13}C is based on the inverse ^{16}O(n,α) from ENDF/B VI.8.
- NeubotV2 is a very recent version which is different from version 1.

4.5. HeBGB: the Ohio University neutron long counter, Z. Meisel (Ohio Univ.)

HeBGB is a neutron detector designed specifically for (α,n) cross section measurements. There are many overlapping motivations for such measurements. There are many isotopes where (α,n) measurements have not been made yet, especially at higher mass. There are also many cases where several data sets exist, but there are big disagreements. We can use models, however, calculated (α,n) cross sections are quite uncertain because of our poor knowledge of the alpha optical model potential, especially at low energies where the cross sections can vary by an order of magnitude.

HeBGB is a classic type of counting detector, but with upgrades to make it less sensitive to neutron energy.

We measured the ^{13}C(α,n) cross section as it is important in astrophysics, for background in large mass detectors. ^{16}O(n,α) is also very important. At present, the available ^{13}C(α,n) total cross section data are: Sekharan '67, Bair and Haas '73, Harissopulos '05. It has been known for a while that there is an issue with the Harissopulos data above 5 MeV. This is because inelastic channels open above 5 MeV which changes the neutron detection efficiency. Peter Mohr made a Hauser-Feshbach estimate of the branchings that can be used to correct the efficiency above 5 MeV. However, this is still incorrect since he has employed the statistical model in a non-statistical resolved-resonance regime.

HeBGB was designed to have a flat efficiency. Careful background subtraction was also done using a target ladder setup. Gold leaf was used to line any surface that the beam might see. Differences in the yields in the different rings give a very rough estimate of the neutron energy. A well-known resonance at 1 MeV was used to determine the efficiency. Above 3 MeV, the efficiency relies heavily on simulations. The overall efficiency is 7.6(6) % or 8% if you do not know the energy.

We performed ^{27}Al(α,n) and ^{65}Cu(α,n) thick target calibration experiments. Good agreement was found. The 3He detectors are moved outwards in the matrix to prioritize constant efficiency. This leads to a reduction of the overall efficiency which; however, is not a problem for these types of measurements.

Measurements were done at Ohio University with a 4.5 MV Tandem, with an alphatross He ion source. The target was a ^{13}C foil on Cu backing. And target thickness was determined from 1 MeV resonance, and alpha scattering. Angular distribution effects were estimated from R-matrix calculations by Carl Brune. As predicted by Mohr, a lower cross section is found above 5 MeV. The Mohr TALYS BR corrections are quite close to the new data.

It should be noted that this approach does not work very well for the partial cross sections. Notre-Dame measurements of partial cross sections will be particularly useful to compare with.

Surprising results are observed when comparing the new measurements with the data of Bair and Haas and Harissopulos. The new data agrees with the other measurements in different energy ranges, however it does not match any one of them over the entire energy range.

The ring ratio can be combined with simulation to get a rough estimate of the neutron energy.

Q&A:

- Low-energy measurements down to 1 MeV are hard to do at Ohio because of the background. LUNA measurements are planned. The different data needs will be discussed at a meeting organized in Rome by the NucAstro community.
- Systematic uncertainties are 8% from the efficiencies and 5% from stopping power.
- The data analysis is done but it is not published yet.
- The $^{65}Cu(\alpha,n)$ data will be published. We will also consider publishing the $^{27}Al(\alpha,n)$ data since the measurement was fairly comprehensive.
- It was found that “Reynolds Wrap” is purer than even “pure” aluminum from a supplier.

Discussion Session 3

- The CASPAR underground accelerator at Sanford Lab in South Dakota will also go online again in about 1-2 years (contact person is e.g. Frank Strieder at SD Mines, and Notre Dame collaborators).
- Systematic intercomparison of neutron spectrum codes: Sources4 does not seem to be supported for further development. Comparisons between Sources4a/4c, NeucBOT, and experimental data are published in several journals. However, a comparison of the codes at a basic level with the same input data has not been done. Tried to compare SOURCES4 and NEUCBOT using TALYS input data, but the versions of TALYS used were different.
- Paper on comparison of the codes SOURCES, NEDIS & USD: Comparison of thick-target (alpha,n) yield calculation codes, EPJ Web of Conferences **53** (2017) 07021, https://www.epj-conferences.org/articles/epjconf/abs/2017/22/epjconf_icrs2017_07021/epjconf_icrs2017_07021.html
- These systematic code intercomparisons are not a priority for the experimental groups, since time and funding are limited. Such an effort would require international coordination by the IAEA, and could be linked to the Snowmass (α,n) WG priorities. Previous experience has shown that such intercomparisons are helpful to improve the codes.

5. ^{17}O EVALUATION

5.1. A new evaluation of the ^{17}O system (preliminary), Z. Chen (Tsinghua Univ.)

A new evaluation of the ^{17}O compound system generated with the RAC code (within the reduced R-matrix formalism) was presented.

The system included $n+^{16}O$ and the inverse reaction $\alpha+^{13}C$ (9 particle pairs/channel). Reduced channels were introduced for inelastic and $(n,\alpha x)$. A total number of 139 levels for the ^{17}O compound system in the energy range 1e-7-32 MeV was considered. Figures on (n,tot), (n,el), (n,α), (n,inl) up to 20 MeV comparing experimental data, ENDF/B and RAC results were shown.

- Overall, ENDF and RAC evaluations are similar below 10 MeV, but different above that energy.
- The agreement with $^{13}C(\alpha,n)$ data of Borozima (2020) is not good.
- (α,n_1) data (deBoer) were difficult to fit and only by using a small value for the scaling factor could a fit be found.
- The (α,n_2) cross section is expected to be larger than (α,n_1) because the 0+ --> 0+ transition is hindered. However, the experimental data of deBoer show the opposite trend which should be further investigated.

All figures on uncertainty quantification and covariance matrix for (a,n) are available on the meeting website (https://conferences.iaea.org/event/283/).

Q&A:

- How many (jp)ls are included? How many channels? How many parameters are used in the fit? Note: in the evaluation, the first excited state for ^{16}O was assumed to be 0- instead of the correct value 0+. However, the evaluators claim that this had no effect on the evaluation of the ^{17}O system which involves the level scheme of ^{17}O not ^{16}O.
- The final ENDF-6 file can be tested and validated at the IAEA.
- In the analysis of the $(\alpha,n\gamma)$ presented here, the neutron and gamma are assumed to be emitted in opposite directions in the center of mass. This does not agree with the mathematical derivation of the R-matrix formalism for $(\alpha,n\gamma)$ by C. Brune in PRC **102** (2020) 024628.
- The GLS approach used is based on changing the scaling factors at each iteration. Are the scaling factors stored in a file and are their values available?
- Comment: The $(\alpha,\gamma6050)$ data (deBoer) correspond to the 511 keV gamma yield and therefore should not be directly compared with the $(\alpha,n\gamma)$ R-matrix fits. Similarly, the (α,n_1) data sets at 95 deg should not be used as there is no capability at Notre-Dame to discriminate the gamma for the correct process so this data cannot be treated as cross sections. Comparisons should be limited to the (α,n_1) data at the remaining angles.

5.2. $^{16}O(n,\alpha_0)^{13}C$ Cross section normalization based on a new Time-of-Flight measurement using a Frisch Grid Ionization Chamber, S. Urlass (HZDR)

A new $^{16}O(n,\alpha_0)$ measurement at GELINA using a Frisch Grid Ionization Chamber was presented.

Extraction of ToF for the fission chamber and detection of fission fragment was easy. The difficult part was to analyze the pulse-height signal. The neutron Spectrum for H19 agrees with an earlier measurement.

Several branches of specific particle reactions are detected. Several lines cannot be distinguished corresponding to remarkably close reaction thresholds ($^{16}O(n,\alpha)$ and $^{12}C(n,\alpha)$). Comparison with evaluated data and other measured data. A total uncertainty of 5.8% is estimated, dominated by the uncertainty in the target thickness. A comparison with thick target yields helped derive scaling factors for the $^{13}C(\alpha,n)$ data of Bair and Hass, Harrisopulos, and Shekharan, respectively.

Q&A:

- This work will be published in a peer-reviewed journal paper.
- Figures on slides 9 and 10 of the presentation (https://conferences.iaea.org/event/283/) show that the new data have a different energy resolution compared to the other existing measurements. Is energy resolution considered in the comparisons?
    - Comment: In the comparison to the new $^{16}O(n,\alpha_0)$ measurement the experimental energy resolution has been considered. The difference by comparing the scaling factors derived from data folded with experimental resolution and not taking the experimental resolution into account is small (less than 0.5%).

- Consistency with total cross-section data depends on which total cross-section data are adopted. If Cierjack's total data are accepted, then with EDA there is an issue with trying to fit total and (n,α) arising from the unitary constraint.
    - Comment 1: In the low energy region, the total neutron cross section is 3-4 barn while the (n,α) contribution is minor. Constraining a small component by a large component can lead to such issues with unitarity, especially when the elastic contribution is poorly known.
    - Comment 2: Unitarity holds between total and reaction cross section even when the reaction cross section is small. In such cases, because the total cross section is better known, even a slight change in the reaction can violate unitarity due to the correlation among reaction channels.
- What is the neutron attenuation in the chamber? Is there an estimate?
    - Answer: scattering corrections are included in the efficiency for ^{16}O chamber and fission chamber.

5.3. Measurement of the cross section for the ^{13}C(α,n)^{16}O reaction and determination of the cross section for the ^{16}O(n,α)^{13}C reaction, P. Prusachenko (IPPE)

The ^{13}C(α,n_0) reaction cross section was measured and used to determine the inverse ^{16}O(n,α).

The ToF method was employed to separate n_0 from n_1 and n_2 and reduce the neutron scattering background. Two rounds of measurements were performed using two different targets. First, 38 points measured in the 2-6.2 MeV energy range used a ^{13}C target on gold backing. In the second round, measurements were performed at 0 deg with ^{13}C amorphous deposited on Mo to verify the results of the first round. A He++ pulsed beam was used with collimators (5—6 mm) at 380 mm from each other. A flight path of 71.3 cm was used in the first run and 65.2 cm in the second run.

The ^{13}C atoms surface density was measured separately using the ^{13}C(d,p_0) and ^{13}C(d,α_0) reactions. The cross sections were taken from Colaux (Nucl. Instrum. Methods. B **254** (2007) 25). Surface densities for targets from the first and second rounds were 2.2x10^{18} and 2.25x10^{18} atoms per cm^2, respectively. Monitoring of ^{12}C build up was done by periodical measurements of alpha-particle backscattered spectra at beam energy of 4280 keV.

The determination of the cross section depends on the number of counts registered in the neutron peak, multiple scattering neutrons correction, total number of alpha particles hitting the target, surface density of ^{13}C in the targets, neutron detector efficiency and solid angle of the setup.

The intrinsic neutron detector efficiency was simulated by GEANT4 with the NRESP7 model. Three different ToF method experiments were performed to verify the simulation. Multiple scattering influence for these experiments was about 1-2% and the experimental results were within 4% of simulated results.

Multiple scattering neutron correction calculated by GEANT4: correction factor is the ratio of the neutron peak integral calculated only for the detector material (all other excluded) and that for the full experimental geometry.

Uncertainty table for each contribution is given. Angular distribution for ^{13}C(α,n_0) vs cos(θ_{cm}) is given at energies between 2-6 MeV.

Measurement results agree with ENDF/B-8 but disagree with the Febbraro data.

Q&A:

- The simulated efficiency wasn't used to fit the experimental one. The latter was independently calculated based on the detector characteristics.
- The energy loss in the target is in the range from 70 to 36 keV depending on the beam energy.

- The energy range of the inverse reaction does not overlap with the Notre-Dame (ND) data. The measurements at IPPE could be extended to higher energies and the plan is to measure thick target yields too.
- The measurements are sensitive only to (n,α_0).

5.4. First LANSCE result on differential cross sections of the $^{16}O(n,\alpha)$ reaction, H.Y. Lee (LANL)

The measurement was performed using low energy NZ (LENZ): LENZ, ALSOLENZ, hotLENZ.

Validation of MCNP simulations with LENZ data. MCNP is used for neutrons but not for charged particles. Improving charged-particle emission in evaluated data is important. Optimization of the experimental configuration (timing and resolution but also background).

Differential cross sections were compared with reconstructed data from ENDF/B-8 with consistent energy resolution.

The LENZ 2016 and new 2021 data obtained with optimized configurations and thinner Ta backing were also compared.

The actual angular coverage is limited due to the realistic beam size and distance between sample and detector. However, the setup was optimized in 2021 for the new $^{16}O(n,\alpha)$ measurement to reduce systematic uncertainties (new oxide sample was used). The energy resolution was improved.

Q&A:

- In the TOF-ΔE spectra the $^{16}O(n,\alpha_{1,2,3})$ events occur at lower time of flight, and because they are kinematically close to $^{12}C(n,\alpha)$ might be difficult to resolve experimentally.
- The normalization to the target thickness when using a Ta oxide sample may be an issue due to the difficulty in determining the amount of O in the target.
- In addition, Ta could be in the sample and in the backing, so it may be worthwhile reducing the Ta background using the acid bath technique.

5.5. (α,n) Measurements at University of Notre Dame and AZURE2 R-matrix analyses, R.J. deBoer (Notre Dame Univ.)

Recent measurements at Notre Dame and R-matrix analysis of the ^{17}O system were presented. A brief motivation from basic science and astrophysics was given. Level diagrams: the compound system has many levels and is complicated. We need experimental data to constrain all those levels. However, there are discrepancies among the different data, and different scaling factors are needed also over different energy ranges. Above 5 MeV inelastic channels are open and populated in the reaction. This causes problems with the determination of the detector efficiency, especially in measurements of the (α,n_0) reaction.

Low energy scaling factor: at low energies there are large discrepancies among the scaling factors used for the different measurements. For R-matrix analysis, we need a comprehensive set of measured and angular distributions. Only a few (α,α) data exist. At higher energies, there are very few (α,nx) partial differential data available.

Measurements were performed at the Nuclear Science Laboratory at Notre Dame. This facility has a 10 MV FN tandem that can produce pulsed alpha–particle beams up to a few 10s of nanoamps. The facility also has a 5 MV single ended machine that can produce high currents up to around 100 uA of alpha–particle beams.

Another way to address the discrepant data is to improve the uncertainty analysis: a method has been developed to perform Bayesian uncertainty analysis with the Azure2 R-matrix code output. This work is done by Odell at al. in collaboration with Brune.

$^{13}C(\alpha,n_1)$ is difficult to study because (α,n_1) and (α,n_2) are close in terms of threshold and magnitude. Measurements have been performed at Notre Dame and the data analysis is almost complete. Preliminary results are shown. The uncertainty analysis with BRICK MCMC gives a similar scaling factor to the previous measurement (summary of Sebastian URLASS).

The ODESSA array by Febbraro is composed of deuterated liquid scintillation detectors and has also been employed for measurements of $^{13}C(\alpha,n)$. Spectrum unfolding is a complex procedure because there is no single clear peak as in discrete g-spectroscopy and it is difficult to simulate.

Angular mapping made between 5 and 6.5 MeV at 20 unique angles in 10 keV energy steps. Additional measurements are underway.

The data analysis of the $^{18}O(\alpha,n\gamma)$ measurements by Rebecca Toomey (Rudgers Univ.) is almost finished. The comparison with JENDL/AN shows some disagreement as expected.

How can one improve the data for (α,n) type reactions? One should obtain consistent results from total cross section measurements and differential partial cross sections. We should be able to angle integrate the differential measurements and sum the partial cross sections to obtain a total cross section that is consistent with the total cross section measurements. This is a good method because the two types of experiments use different detector types with different underlying uncertainties in their efficiencies.

Q&A:

- Regarding the agreement with the scaling factors of Urlass et al., the agreement or disagreement of scaling factors for Harrisopulos data depends on the energies at which you normalize. It is promising that different approaches are starting to converge.
- The unfolding algorithm LEAM developed by Febbraro and described in NIM paper (2021) is used.
- The (α,n_0) data confirm the Febbraro data within 15% uncertainty. The upper and lower limits are based on experimental uncertainty (statistical plus systematic). It is possible that there is an energy dependence in the scaling factors.
- This is a full R-matrix analysis using the standard R-matrix theory.
- There are large discrepancies above 5-6 MeV where many channels are opening (α,n_0), (α,n_1). One should try to constrain the calculations to the total (α,n) cross section.

5.6. R-matrix evaluations of (α,n), M. Paris (LANL)

There is an ongoing evaluation effort at LANL. A brief overview of the light-element R-matrix evaluations was given.

ENDF/B-8 is based on the Hale evaluation up to 7 MeV. Above 7 MeV other evaluation methods are used. ENDF8 includes $n+^{16}O$, $\alpha+^{13}C$, $n_1+^{16}O$, $n_2+^{16}O$.

New preliminary evaluation configuration: 45 channels, 81 levels, 322 reduced widths. Neutrons are evaluated up to 8.8 MeV. Alphas are considered up to 8.0 MeV.

The preliminary fit of (α,n_0) angular distribution data at 5.275, 5.895, 6.504 MeV and (α,n_1) at 5.135, 5.466 from Notre Dame was shown. For normalization one should consider the Cierjack total neutron data to see if (n,α) requires additional scaling.

Future: complete the ^{17}O system evaluation up to 10 MeV neutron energy. Plans to work on (α,n) evaluations for larger A>20 compound systems.

Q&A:

- There are two total cross-section measurements by Cierjack, one from 1968 and one from 1980. The one adopted in ENDF/B-8 is 1980 Cierjack's scaled by +3.5%. Yaron Danon's scaling factor is based on Cierjack 1968 and goes in the opposite direction. The earlier 1968 Cierjack data is recommended for use in normalization. This has been confirmed by a recent measurement of the total cross section of ^{nat}O on the 1st resonance at nELBE, HZDR. The latter data agree with Cierjack 1968 whereas no conclusions can be drawn about Cierjack 1980 data due to poor resolution.

- In ENDF/B-8, at energies above 7 MeV, the ^{16}O evaluation is based on the work by Phil Young using the Hauser-Feshbach model. This evaluation dates back to ENDF/B-6.8 (also adopted by Murata in JENDL-AN).
- The quality of the fit to a huge amount of data is defined as acceptable if the value of the reduced chi2 is between 1 or 2, but for $^{13}C(\alpha,n)$ we are an order magnitude higher. What should we do when the measured data uncertainty is underestimated? In practice, we use multiplication, normalization (augmentation) factors over the energy range. But how does one estimate the normalization for the uncertainty? Is it worrisome when one makes large adjustments to the original point-to-point uncertainties?
- Higher-energy measurements may be used to fix a problem in a low-energy measurement since different energy regions are correlated. It may be possible to separate low and high-energy regions in experimental data, but not in an R-matrix analysis. The tails from the high-energy region reach down to the low-energy region.
- At higher energies, the new LANL evaluation has adopted the new Notre Dame data, not Giorginis' data.
- Work is ongoing to reproduce the structure at 5.5 MeV in the (α,n_1) data.
- EDA can handle all versions of polarization data with all spins (2.5, 3.5, ….). The Wolfenstein general formalism is implemented in EDA.

6. DISCUSSION

6.1. Experimental data needs

In this section we provide a complete listing of the needs in experimental data, evaluated libraries and modelling codes, as well as neutron source codes, for the main applications considered at the meeting.

6.1.1. Low-energy background experiments

All elements in the following are material used to construct detectors and other instruments used in low-background underground experiments aiming at detecting rare events in Dark Matter searches, neutrino detection, nuclear astrophysics, and are thus potential targets for studying alpha-induced reactions. The alpha particles are produced by the decay of naturally occurring radionuclides such as U and Th isotopes, Rn emanation.

Material: Mastic; Stainless steel; Nylon 66; Al; Cu; PPS; PEEK fiber; Clevios; Ar; PEI; Sapphire; Teflon; Tin; Solder InAg; Plywood; Fused silica; Acrylic; PEN; Arlon55NT; Kapton; IGEPAL_Co-520; PET; Si; TPB; Ti alloy; Brass.

Some of the essential elements of which the above materials consist of are:

B, Be, Li, Na, Ca, K, Zn, Cr, Mg, **C**, **O**, **F**, N, **Al**, Si, Ge, **Ar**, Ti, Cu, Fe, Ni, Co, Mn, Ne, Cl.

The elements in bold are the top priority needs due to (i) the high (α,n) yields these elements produce, (ii) the high abundance of these elements in material, and/or (iii) discrepant or missing data in the current databases.

Energies: <9 MeV (down to ~Coulomb barrier).

Type of data: cross sections, partial cross sections, yields (also for ground/excited states), stopping powers, n-γ correlations, neutron spectra.

Precision: 10-20% for observed cross sections; evaluations should be provided with covariance matrix information.

Energy resolution of neutrons: not important for neutron spectra.

Important condition: experimental and evaluated data should be available in databases (EXFOR and ENDF, respectively).

6.1.2. Nuclear astrophysics (s process, weak r process, type 1A supernovae)

In nuclear astrophysics, nucleosynthesis calculations depend on the solution of networks of reactions involving hundreds and thousands of reaction rates. For the s process, weak r process and nucleosynthesis occurring in type 1A supernovae, (α,n) reactions on the following list of nuclides are important (energies in brackets):
$^{10,11}B$ (~200 keV), ^{13}C (~100 keV), $^{17,18}O$ (~300 keV), ^{15}N (6.4-7 MeV), ^{21}Ne (> 1MeV), ^{22}Ne (~565 keV), ^{23}Na (3-4 MeV), $^{25,26}Mg$ (>1.2 MeV), $^{29,30}Si$ (>1.2 MeV).
Type of data: cross sections, angular distributions (for spin/parity identification).
Precision: 10-20% (better precision is required for ^{13}C and ^{22}Ne).
Energy resolution: ~keV.

6.1.3. Nonproliferation, spent fuel management, homeland security

(α,n) reactions are used in nondestructive assay techniques to determine enriched uranium and other actinide inventories during or at the back-end of the nuclear fuel cycle. The top priority targets for which accurate and precise (α,n) data are needed are components of the nuclear fuels:
^{13}C, $^{17,18}O$, **^{19}F,** $^{10,11}B$.
Energies: <6.5 MeV.
Type of data: cross sections (total, partial), angular distributions, thick target yields, stopping powers, gamma emissions, (α,nγ), neutron spectra.
Precision: 5% on cross section, 2% on yield, 10% on neutron spectrum.

6.1.4. Reactor applications, reactor safeguards

For reactor applications, including advanced reactors, molten salt reactors and FLiBe reactors, (α,n) reactions are important on the following targets:
^{13}C (and inverse ^{16}O(n,α)), ^{27}Al, molten salts (^{23}Na, $^{25,26}Mg$), $^{29,30}Si$, ^{37}Cl, ^{41}K, Al, ^{7}Li, ^{9}Be.
Energies: 2-10 MeV.
Type of data: cross sections (total, partial), angular distributions, thick target yields, outgoing neutron spectra, gamma emissions, alpha stopping power data for alphas, energy resolution for ^{16}O(n,α) is important, uncertainties in alpha energies and angles.
Precision: 1-2% for total neutron cross section on ^{16}O (already satisfied, to be published), for ^{13}C measurements the precision is set by the uncertainty on ^{13}C abundance.
New measurement of ^{16}O(n,α) will be made at GANIL, however, we need new measurements above 4 MeV on ^{13}C, including angular distributions.

6.1.5. Fusion applications

For nuclear fusion applications, it is important to identify reactions that occur at energies below 3.5 MeV and produce radionuclides with gamma signals detectable against neutron-induced gamma background.
Candidate reactions: ^{76}Ge(α,n)^{79m}Se, ^{19}F, ^{10}B, ^{43}Ca(α,p), Sc, ^{41}K, others.
Energies: up to 3.5 MeV.
Type of data: need cross section libraries that can be used to design alpha-particle diagnostics.
Precision: uncertainty on threshold is important.

6.2. Models, evaluations, codes

6.2.1. R-matrix codes

For cross-section calculations in the energy region in question, it is important to implement the reduced R-matrix formalism to handle the growing number of channels (currently RAC code can do this, GECCCOS in development), and thus enable dealing with heavier systems and higher energies. It is also pertinent to develop an approach for multi-body breakup in the R-matrix formalism (3-body breakup is being developed at TUW, 3 body and higher is developed at LANL).

Experimental data for $^{13}C(\alpha,\alpha)$ elastic scattering are needed for a complete R-matrix fit. Polarization data are also needed (https://www.annualreviews.org/doi/10.1146/annurev.ns.06.120156.000355; https://journals.aps.org/pr/abstract/10.1103/PhysRev.75.1664).

Secondary gamma emissions, including angular distributions, remains to be implemented in some R-matrix codes (C.R. Brune, R. J. deBoer https://doi.org/10.1103/physrevc.102.024628). EDAf90 is developed to handle larger-dimension systems. Need to develop a way to consider the non-zero width of excited-state channels in R-matrix codes (like treatment of break-up channels).

6.2.2. Statistical model codes

Although users require clear instructions about which input parameters to use for different isotopes and energies, it is difficult to make recommendations for light systems with A<20 since the statistical model is at its limits of validity with such light compound systems. In the absence of evaluated data, users could test different input parameters to see which ones best reproduce the data.

Recommended parameters for heavier systems (A>20) could be provided as a Reference Input Parameter Library for alpha-induced reactions, like the existing RIPL for incident protons and neutrons. Such a reference input library would help the different applications communities interested in calculating (α,n) cross sections as discussed at this meeting.

6.2.3. Evaluated libraries

It is clear from the meeting that up-to-date evaluated libraries with cross sections, angular distributions, and neutron spectra, are needed for the various applications.

ENDF/B-VIII.1 will include a new updated evaluation of $^{13}C(\alpha,n)$ integrated cross sections, angular distributions, at least for ground states and the first two excited states. It will also include alpha elastic scattering cross sections. This version is expected to be released in Spring 2024. ^{7}Li and ^{9}Be evaluations will also be included.

JENDL-5 was released in December with an updated (α,n) library, however, only spectra and angular distributions will be different while the (α,n) cross sections will be the same as in the existing JENDL-AN-2005 library. The new release will also include alpha elastic scattering cross sections.

6.2.4. Application codes: SOURCES4A, SOURCES4C, NEUCBOT, SAG4N, etc.

SOURCES4A libraries are continually being updated (by the U. Sheffield group) with experimental data where they exist. In SOURCES4A, the optimum data are chosen by comparing yields computed with SOURCES4A and experimental yields. When the available datasets disagree, however, one needs to know which dataset to use. Questions also arise about the branching ratios which are needed to calculate the neutron energy spectra. They are often not measured so where can one find them or how can one calculate them? Libraries can also be used with SOURCES4C (new libraries can be obtained upon request). SOURCES4C code must however be modified to allow for energies above 6.5 MeV. SOURCES4C code is currently not being maintained. The scoping study by ORNL and other labs has proposed a new vision for the SOURCES4C code: open source, interfacing with libraries, automatically updated when libraries update, interfacing with Geant4 and MCNP. The project to develop SOURCES4C is however, not yet funded (might take a couple of years to write and validate code).

NeuCBOT updates are currently underway to add renormalization to data/JENDL, and account for uncertainties in data and evaluations.

SAG4N will evolve with Geant4, so future improvements in Geant4, including improvements in particle propagation, will improve the accuracy of simulations performed with SAG4N. The code will furthermore benefit from more/updated evaluations, adding correlated neutron-gamma data, neutron and gamma spectra, and updated branching ratios. It will continue to use combinations of evaluated libraries in different energy regions, such as TENDL+JENDL-AN.

There is a need to develop the infrastructure to handle covariances in neutron sources calculations. Monte Carlo sampling is one approach. SAG4N is set up for such calculations.

Libraries: ACE data format is used in transport codes such as MCNP. Evaluated (α,n) libraries should be easily converted to ACE libraries for use in such codes.

7. CONCLUSION AND RECOMMENDATIONS

The Technical Meeting (virtual) on `(α,n) data evaluation and data needs', held from 8 to 12 November 2021, brought together international experts from different fields such as particle physics, nuclear astrophysics, fission and fusion reactor physics and non-proliferation applications. Participants reviewed the status of (α,n) cross-section data and yields at incident energies up to 10 MeV for all the above fields, including the performance of nuclear reaction and source codes, and evaluated libraries. Presentations and discussions covered a broad range of applications and data needs and lead to the identification of cross-cutting priorities and recommendations.

The well-defined needs for improved (α,n) cross-section data and neutron yields have led experts in the various fields of applications listed above to self-organize into working groups with the purpose of addressing their specific needs efficiently and timely. These organized efforts are as follows:

- The particle physics community has formed the (α,n) Working Group with the aim of coordinating efforts to improve (α,n) data needed for low-background rare-event detection (Dark Matter, neutrinos). The group consists of 35 international experts and is charged with the task of preparing a White Paper on (α,n) data needs for particle-physics measurements.
  Apart from establishing the data needs, the White Paper also aims at promoting a collaboration among low-background particle-physics groups and nuclear physics groups with a view to fostering exchange of technical expertise and knowledge on the topic of (α,n) reactions, for example, on the topic of determining the optimal input model parameters for (α,n) cross-section calculations.
- Experimental nuclear physics groups in Spain have formed a collaboration (MANY) with the aim of performing (α,n) measurements needed for applications in low-background measurements, reactor and nonproliferation and nuclear astrophysics. The MANY collaboration is working on the commissioning of existing equipment (continuous and pulse-beam accelerators, neutron, and gamma detector systems) at the facilities of CMAM (Centro de MicroAnálisis de Materiales), Madrid, and Centro Nacional de Aceleradores (HISPANOS), Seville. Following this, it (MANY) will establish additional long-term needs for equipment, such as detectors, data acquisition systems, additional hardware, and beams, with the ultimate view to measuring underground at the future underground electrostatic accelerator planned to be built in the laboratory of Canfranc.
- Several laboratories and universities in the US are forming collaborations to address (α,n) experimental data needs using available facilities at Notre Dame Univ. and Ohio Univ., with the long-term view to performing underground measurements with CASPAR/DIANA at Sanford Lab (US), and with LUNA at Gran Sasso (Italy).

Meeting participants recognized the importance of the above organized efforts to address specific data needs and recommended that they be supported on both the national and international level.

  - The Particle Physics (α,n) Working Group White Paper will help determine a close collaboration between particle physics and nuclear physics groups with mutual benefits for either group.
  - The MANY and US laboratories/universities efforts to measure new data will have a significant impact on the worldwide efforts on improving (α,n) data as they will provide

experimental information with better accuracy and precision and/or fill the gaps where data are missing altogether.

Several source codes have been developed in recent years and their use in the applications would benefit immensely from coordinated benchmark exercises aimed at validating neutron yields, neutron spectra, and angular distributions calculated by these codes. A pre-requisite for performing such exercises is the selection of suitable datasets to serve as benchmarks.

Targetry was recognized as a crucial element of improving the (α,n) data by way of performing new measurements. Participants recognized the need for enriched target materials, and for easy access to target production facilities. A recommendation was made for facilitating/allowing sharing of radioactive isotopes amongst experimental facilities in support of (α,n) measurements.

[Sec. Note: Following the meeting, a discussion took place over email exchange on the availability of reference (α,n) cross sections for use in relative measurements, and beam monitor cross sections needed to determine the incident alpha-particle flux. The following reactions were suggested as potential candidates with advantages and disadvantages: ^{27}Al(α,n), ^{9}Be(α,n) and ^{13}C(α,n). As a result, the following recommendation is included in the meeting report.
Establishing reference (α,n) reactions and suitable beam monitor reactions with accurately and precisely known cross sections as a priority for experiments involving relative measurements and for determining the incident alpha-particle flux precisely, preferably through an internationally coordinated effort.]

Overall, participants acknowledged that the above recommended activities and actions would benefit significantly from international coordination by the IAEA. The purpose of the IAEA coordinated activities would be to (i) facilitate the exchange of knowledge and expertise, communication of new results and sharing of experience, (ii) minimize duplication of effort, and (iii) maximize the access to and use of available resources. The organization of meetings such as the current one, to review the status, assess the needs and propose future actions is strongly recommended.

APPENDIX: ADOPTED AGENDA

Monday 8 November 2021

Introduction: Welcome & Introduction (15:00-15:20), A. Koning; P. Dimitriou

Session 1: Presentations (15:20-16:35)
15:20 Low-energy cross section measurement of $^{13}C(\alpha,n)^{16}O$, A. best

15:45 Impact of (alpha,n) reactions on direct search of Dark Matter, R. Santorelli

15:45 (alpha,n) Reactions in low-background neutrino experiments, V. Lozza

Break (16:35-16:40)

Session 1 cont'd: Presentations (16:40-17:30)
16:40 Facilities, measurements, and experimental verification of (alpha,n) for Dark Matter, A. Villano

17:05 (alpha,n) Cross section data improvement needs for next generation low-background neutrino and Dark Matter experiments, J. Reichenbacher

Discussion (17:30-18:00)

Tuesday 9 November 2021

Session 2: Presentations (15:00-16:15)
15:00 The MANY project: measurement of neutron yields and spectra from (alpha,n) reactions in Spain, A. Tarifeno-Saldivia

15:25 Constraining (alpha,n) cross sections with indirect measurements, P. Adsley

15:50 Recommendations from an (alpha,n) Nuclear Data Scoping Study, C. Romano

Break (16:15-16:25)

Session 2 cont'd: Presentations (16:25-17:30)
16:25 (alpha,n) Neutron yield calculations with NeuCBOT, the neutron calculator based on TALYS, S.S. Westerdale

16:50 TENDL-2021 Library for (alpha,n) cross sections, A. Koning

17:15 (alpha,n) Cross section needs for fusion, M. Gilbert

Discussion (17:30-18:00)

Wednesday 10 November 2021

Session 3: Presentations (15:00-16:15)
15:00 A correction to the non-resonant process for elastic channels in R-matrix analysis, S. Kunieda

15:25 Preliminary analysis of $^{9}Be(\alpha,n)^{12}C$ integrated and angular experimental differential data at below 4 MeV, O. Bouland

15:50 (alpha,n) Data for applications and detector simulation codes, D. Cano Ott

Break (16:15-16:25)

Session 3 cont'd: Presentations (16:25-17:15)
16:25 Calculation of neutron production in (alpha,n) reactions with SOURCES4, V. Kudryavtsev

16:50 HeBGB: the Ohio University Neutron Long Counter, Z. Meisel

Discussion (17:15-18:00)

Thursday 11 November 2021

Session 4: Presentations (14:00-15:15)
14:00 A new evaluation of ^{17}O system (preliminary), Z. Chen

14:25 $^{16}O(n,\alpha_0)^{13}C$ Cross section normalization based on a new Time-of-Flight measurement using a Frisch Grid Ionisation Chamber, S. Urlass

14:50 Measurement of the cross section for the $^{13}C(\alpha,n)^{16}O$ reaction and determination of the cross section for the $^{16}O(n,\alpha)^{13}C$ reaction, P. Prusachenko

Break (15:15-15:25)

Session 4 cont'd: Presentations (15:25-16:40)
15:25 First LANSCE result on differential cross sections of the $^{16}O(n,\alpha)$ reaction, H.Y. Lee,
15:50 (alpha,n) Measurements at Univ. of Notre Dame and AZURE2 R-matrix analyses, R. deBoer
16:15 R-matrix evaluations of (alpha,n), M. Paris

Discussion (16:40-18:00)

Friday 12 November 2021

Discussion: Session summaries, Table of priorities, Drafting of report (15:00-16:25)

Break (16:25-16:35)

Discussion: Cont'd, Closing of meeting (16:35-18:00)

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