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INDC International Nuclear Data Committee

International Nuclear Data Evaluation Network (INDEN) on the Evaluation of Light Elements (3)

Summary Report of the IAEA Consultants' Meetings

6th Meeting on R-Matrix Codes for
Charged-Particle Reactions in the Resolved Resonance Region
15-16 March 2021
(virtual event)

3rd Meeting of the
International Nuclear Data Evaluation Network (INDEN)
on the Evaluation of Light Elements
17-19 March 2021
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July 2021

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ABSTRACT

The INDEN for Light Elements network (INDEN-LE) held two virtual Consultants' Meetings, one on R-matrix calculations for charged-particle reactions in the resolved resonance region, from 15 to 16 March 2201, and one on the evaluation of light systems produced by neutrons, from 17 to 19 March 2021. The purpose of the meetings was to review the status of the inter-comparisons of covariances and the full evaluation of the $^{7}Be^{*}$ system on the one hand, and the evaluation of n+^{9}Be, n+^{14,15}N, and n+^{23}Na systems, on the other. A session dedicated to the emerging data needs for (α,n) reaction data was held on 18th March 2021. Summaries of the presentations and discussions can be found in this report.

July 2021

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1. R-MATRIX CODES FOR CHARGED-PARTICLE REACTIONS IN THE RESOLVED RESONANCE REGION

1.1. Introduction

The IAEA Nuclear Data Section is coordinating an international effort to (i) compare and verify existing R-matrix codes on charged-particle reactions in the resolved resonance region, (ii) produce evaluations of charged-particle cross sections for applications and, finally, (iii) disseminate the evaluated data through general and special purpose nuclear data libraries.

Five IAEA consultants' meetings have been held since the start of this project, to address the capabilities of existing R-matrix codes and the translatability of the corresponding R-matrix calculations. So far, three exercises have been performed in the course of the project, the first one on an inter-comparison of R-matrix algorithms implemented in the codes, published in Ref. [1], the second on the inter-comparison of minimization techniques and fitting procedures applied by the evaluators, and the third and final one on the evaluation of the ^{7}Be system. The exercises involved the two incident channels ^{3}He+^{4}He and p+^{6}Li forming the ^{7}Be compound system at sufficiently low excitation energies to exclude other reaction channels. Details of the exercises, the results as well as additional comparisons that were performed, can be found in the summary reports of the five meetings:

INDC(NDS)-0703 (https://www-nds.iaea.org/publications/indc/indc-nds-0703/)
INDC(NDS)-0726 (https://www-nds.iaea.org/publications/indc/indc-nds-0726/)
INDC(NDS)-0737 (https://www-nds.iaea.org/publications/indc/indc-nds-0737/)
INDC(NDS)-0767 (https://www-nds.iaea.org/publications/indc/indc-nds-0767/
INDC(NDS)-0787 (https://www-nds.iaea.org/publications/indc/indc-nds-0787/

The sixth meeting was held virtually from 15 to 19 March 2021, with the purpose of monitoring the progress in the last two exercises. Seven codes are involved in this project: AMUR, AZURE2, CONRAD, EDA, GECCCOS, RAC, SFRESCO, SAMMY.

The meeting was attended by the developers of the seven codes listed above: H. Leeb, T. Srdinko (Austria); Z. Chen (China); P. Tamagno (France); S. Kunieda (Japan); R.J. deBoer, M. Pigni, I.J. Thompson, G. Hale, M. Paris (USA), as well as by additional interested members of the international scientific community: J. Hu, Q. Wu (China); D. Odell, C. Brune, D. Philips, Z. Meisel, K. Brandenburg, G. Arbanas (USA); B. Raab, T. Stary (Austria); S. Kopecky (EC), making a total of 23 participants from 4 members states (MS) and one international organization, including IAEA staff P. Dimitriou (Scientific Secretary) and R. Capote (Deputy Section Head).

Roberto Capote gave a welcoming address and the scientific secretary of the meeting and project officer, Paraskevi (Vivian) Dimitriou gave a short summary of the goals of the meeting and the status of the project. Ian Thompson was elected chair of the meeting and Helmut Leeb rapporteur. The meeting continued with status reports and presentations by the participants, followed by technical discussions.

The summaries of the presentations are given in Sections 1.2, while the summary of the technical discussions is provided in Sect. 1.3. The adopted Agenda and List of Participants are given in Annexes 1 and 2, respectively. Links to participants' presentations are given in Annex 3.

References:

[1] I.J. Thompson, R.J. deBoer, P. Dimitriou, et al., Verification of R-matrix calculations for charged-particle reactions in the resolved resonance region for the ^{7}Be system, Eur. Phys. J. A **55** (2019) 92.

1.2. Presentation summaries

1.2.1. Report on the global evaluation for light nuclear systems (A=1 to A=27) with RAC, Z. Chen (Tsinghua Univ.)

(Delivered by Q. Wu)

A comprehensive report on the results of the evaluation of partial light elements using the **RAC-CERNGEPLIS** methodology, including reactions in one nuclear system n+p, p+p, n+n, n+d, n+t, (n+^{3}He, p+^{3}He), (n+^{6}Li, t+α), (p+^{6}Li, ^{3}He+α), n+^{7}Li, (n+^{9}Be, t+^{7}Li), (n+^{10}B, α+^{7}Li), (n+^{11}B, α+^{8}Li), (α+^{12}C, ^{12}C(α,γ)^{16}O), (n+^{16}O, α+^{13}C), and preliminary work on n+^{12}C, n+^{14}N, n+^{19}F, n+^{23}Na, n+^{27}Al was given. The experience gained from these evaluations shows that the RAC-CERNGEPLIS methodology is a very useful model for nuclear data evaluation.

This comprehensive report focussed on the discussion around the following issues of concern:

How to extend to higher projectile energies? How to deal with conflicting data? How to treat gamma production? The recommendation is to use the **RAC-CERNGEPLIS** method to resolve the problems mentioned above.

The capital letter in the **RAC-CERNGEPLIS** evaluation method have the following meaning:

RAC — **R-matrix** Analysis Code with multi-levels and multi-channels theory from Lane1958;
C — **Covariance** statistics and 'Generalized Least–squares Method' are used;
E — Law of **Error** propagation is used to get accurate Covariance Matrix;
R — **Relativistic** calculation for energy;
N — **Normalizing** data-set relative to the evaluated values;
G — **Global** database for a nuclear system is fitted;
E — **Elimination** of channel is used to expend analysis energy range;
P — Smith **PPP** modification method is considered;
L — **Lett**'s criteria is used to minimize the effect from occasional 'outliers';
I — **Iterative** fitting procedure is used to get the best evaluated values;
S — **Systematic** error is updated according to the errors of fitted values.

The report also argues that it is worth discussing whether the χ^2 expression first proposed by **J.R. Bergervoet, P.C. van Campen, Phys. Rev. C.38.15 (1988)** is reasonable or not.

$$\chi^2(p) = \sum_A \chi_A^2 = \sum_A \min_{\nu_A} \sum_{i=1}^{N_A} \left[(\nu_A M_{A,i}(p) - E_{A,i}) / \epsilon_{A,i} \right]^2$$

<u>Discussion:</u>

- Some features of the method need to be clarified such as: correlation between statistical and systematic errors; can GLS treat systematic errors properly?
- The reduced R-matrix parametrization and evaluation methodology implemented by Z. Chen in RAC was further discussed via E-mail exchange in the course of the meeting. A summary is given here:
  - i. Bad experimental data points are treated by amplifying their errors;
  - ii. Relativistic corrections: usually the difference of the fitting results is far smaller than the error of the experimental data;
  - iii. Replication? Since different fitting methods are used in RAC, a simple comparison is not useful. It is impossible to replicate the results of the RAC with other codes;
  - iv. The exact methods used by RAC for 'reduced widths' are still not clear and have not yet been replicated by anyone using another code. It is not clear how to account for the flux that goes in to the 'eliminated' or 'removed' channels after use of the 'reduced' formalism.

1.2.2. Tests 2 and 3 for $^{7}Be^{*}$, I. Thompson (LLNL)

We are continuing the work for the IAEA project *R-Matrix Analysis of Charged Particle Reactions*. Our 'Test 2' consisted of fitting a specified collection of data for the p+^{6}Li and ^{3}He+^{4}He channels and transitions between them in the ^{7}Be* compound-nucleus system. Among the R-matrix parameters, 5 poles and 11 widths were selected as subject to variation, leading to different groups producing values for the 16 parameters as well as their covariance matrix. We also needed to determine the effect of using relativistic kinematics as defined by the LANL specification recently included in the ENDF6 format.

The preliminary results of Test 2 were shown: covariance matrices from the codes AZURE, CONRAD, EDA and RFLOW/FRESCO, were presented as a magnitude plot of the 16*16 covariance matrices. This required considerable custom coding and channel reordering to give comparable plots. The plots had some general similarities, but still individual different features. The LANL relativistic kinematics specification, at least as implemented in FRESCO, produced differences of several percent in the predicted cross-sections. These differences remained even when the data was refit using the new kinematics. Considering that the effects are supposed to be very small in the reference channel (here ^{3}He+^{4}He), further work is needed to confirm the accuracy of the implementation, for energy, Q values, wave numbers and Sommerfeld parameters.

Finally, a preliminary comprehensive fit of the ^{7}Be* system up to a center-of-mass energy of 20 MeV was shown. No-Core Shell-Model (NCSM) energy levels were used to suggest spin/parity assignments (in the Brune basis) above known RIPL levels. The p1 channel was included for the ^{6}Li 3^{+} excited state at 2.18 MeV. Generalized Reich-Moore damping widths were fitted for all poles above the p1 threshold, to maybe take the missing breakup channels into account. Several difficulties were reported. Sparse data in the higher-energy region led to over-fitting: points end up being fitted by individual resonances where the prior expectation is to have smooth cross-sections. Secondly, Reich-Moore widths for particle reactions lead to significant absorption cross-sections even below thresholds. At the CNR18 conference, a method of scattering-energy-dependent widths was suggested, but now it turns out that this method, though solving the below-threshold problem, almost always makes for worse fits at higher energies. Overall, the fit to angular-data and angle-integrated cross-sections was promising and should provide a good starting point for a more complete evaluation once the above three problems are resolved.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Discussion:

(a) **Results for Test 2:** the comparison of correlations in parameter space for Azure, Conrad, EDA, Rflow, and SAMMY, show similarities at a coarse level.

- Relativistic kinematics for fixed parameters: there is a large impact when fitting the Fiedler data. The differences between relativistic and non-relativistic kinematics are quite pronounced. A comment was made that complete agreement at thresholds is not expected. A detailed comparison with EDA is required, however, EDA does not use consistent masses and Q-values. But even if they were to be made consistent, it is not expected to cause changes in the normalisations.

(b) **Results for evaluation of h+a (Test 3):** making a full evaluation to higher energies

- The use of Reich-Moore damping for the missing breakup channels is still open for discussion. The threshold behaviour could be problematic.
- As one goes to higher excitation energies, one needs many more energy levels than given in RIPL3 to reproduce the experimental data.
- Question to Chen – whether they use the same normalisation for each angle in the excitation function.
- Uncertainties (related to the normalization) should be included in the covariance matrices.

- Fitted parameters and their final uncertainties are listed in the supplemental txt file FIT-Be7r-psdu-b.txt that was distributed to the participants of the meeting. These have been obtained in the Brune basis and thus can only be compared with other calculations in the same basis.
- Should one distinguish between Reich-Moore damping with complex energy averaging at these higher energies?
- Transformation of Reich-Moore basis – proposal to extend the model beyond the capture channels where it has been shown to be a reasonable approach.
- Is it reasonable to have a Reich-Moore damping term on every pole?

1.2.3. Bayesian work in the ^{7}Be system, D. Odell (Ohio Univ.)

For many years, researchers have employed frequentist techniques to apply phenomenological R-matrix models to data. Recent interest in Bayesian methods across the nuclear physics community raises the question: What could be gained from the application of Bayesian methods to R-matrix analyses?

Bayesian inference goes hand-in-hand with Markov Chain Monte Carlo. Conveniently, the output allows for a simple summation to take the place of potentially difficult expectation value integrals. The result is a marginalized posterior for astrophysically relevant observables where parameter uncertainty is readily accounted for.

At the center of our work is an implementation that pairs AZURE2 with a commonly used MCMC package written in Python, emcee. The implementation has been benchmarked with the Vogl data on $^{12}C(p,\gamma)$ and extended to leverage the multithreaded capabilities of the sampling package.

The $^{3}He(\alpha,\gamma)$ reaction is of significant astrophysical interest, and the analysis requires a nontrivial R-matrix model even at low energies, so it serves as a good starting point for our work. We have successfully analyzed $^{3}He(\alpha,\alpha)$ scattering and $^{3}He(\alpha,\gamma)$ capture data using our MCMC+AZURE2 implementation. Our analysis also includes recent scattering data that extends to lower energies. However, predictions of threshold observables with these low-energy data sets are not consistent with previous results. Resolving these discrepancies is the substance of our future plans.

Discussion:

- MCNP cannot solve problems related to discrepant data. Were the data rescaled? If yes, was normalization included in the uncertainty quantification?
- What are the times needed for a typical run with the Monte Carlo method? It is quite time consuming, typically one week.
- With inconsistent data set it is difficult to reach the result. Is the capture data aligned with the scattering data? D. Odell will check whether there is a shift in the two data sets.
- In the MC calculations, the random walks are generated by the emcee package.
- Optical model fit – normally one uses a number of data points in different observables, how do they enter the fitting scheme?
- D. Odell clarified that the following convergence criteria are enforced: the stability of correlations and the almost vanishing parameter changes.

1.2.4. Reduced R-matrix calculations, H. Leeb (TU Vienna)

In the presentation the motivation and ideas behind the Reduced R-matrix formalism were revisited. Analytic results for the elimination of one or two channels were presented for a simple one-pole approximation. Essential ingredient is the L-function which allows to account in a proper way for the thresholds of eliminated channels in the Reduced R-matrix formalism. The similarity of the obtained expressions for the reduced R-matrix in simple example cases is suggestive of a possible parametrization of the reduced R-matrix for phenomenological analyses of reaction data.

Discussion:

- The method has similarities with the Reich-Moore parametrization, but in addition, it accounts for the threshold of eliminated channels.

1.2.5. Three-body R-matrix calculations, B. Raab (TU Vienna)

The presentation focussed on the development of an R-matrix formalism for three-body channels based on the Faddeev equations following the ideas of Glöckle. The key idea of Glöckle is the division of the space of Jacobi coordinates. Thus, he avoided the problem of having an interaction region in a three-body problem that is not restricted to a finite volume in the 3-dimensional space. The 3-body wave function is expanded at small values of the Jacobi coordinates into a set of two-dimensional basis functions which have to match the asymptotic solution of the 3-body wave function at the boundary values of the Jacobi coordinates. This procedure leads to a set of linear equations for the transition operator elements which allow the calculation of elastic and breakup cross sections. The original proposal of Glöckle contains some weaknesses which make it difficult to apply in practical calculations of nuclear data. In order to transform the original formalism to an applicable algorithm, a complete reformulation of the algorithm was required that contains completely different definitions of the set of basis functions, improved representation of the asymptotic wave function and, most importantly, a regularization procedure to overcome the ill-posed character of the linear system of equations. Thus, apart from the idea of division of the space of Jacobi coordinates, a completely novel algorithm has been developed. The first numerical results on the neutron-deuteron system were presented. Both the breakup and the elastic scattering cross sections can be well reproduced within a common factor. These results are very promising as there are strong indications that the additional factor of divergence can be reduced to one.

Discussion:

- The handling of two-charged particles is possible as they only need to change the asymptotic form of the three-body wave functions.
- Furthermore, solving with additional Coulomb potential should not be a problem since the formalism is set up in the Jacobi coordinate space.

1.3. Technical discussions

1.3.1. Relativistic Kinematics: exact masses, verification

The effort to clarify the impact of using relativistic kinematics on R-matrix calculations is ongoing.

Care must be taken to use precisely consistent Q-values and masses when applying relativistic kinematics. This use of inconsistent Q-values and masses in Test 2 led to non-negligible differences between the results obtained with SFRESCO and EDA, using relativistic kinematics as was demonstrated by low energy ^{6}Li(p,^{3}He)^{4}He calculations.

1.3.2. Discrepancies in experimental data

Identifying outliers in the experimental database and removing them from the evaluation process is an important step for any evaluation. The question asked was whether a unique policy could be defined and adopted by all the participants of the project.

Ian Thompson referred to the book on Outliers in statistical data as useful source of ideas (Barnett V., and Lewis T., John Wiley & Sons, 1994).

Participants acknowledged that different criteria exist to identify and treat outliers in statistical analysis, such as Chauvenet's, Lett's, etc.

RAC, for example, uses Letts' method, according to which the experimental error is augmented so that the deviation is less than 3 times the standard error. It is not clear however, whether this operation is done at every iteration or at the end of the fitting process.

Participants agreed to create a common 'modified' experimental data repository in addition to the repository of original experimental data from EXFOR or other sources. The manipulated data files will be stored along with information on what was modified and the justification for the modification.

Ultimately, this 'modified' experimental database will become the recommended corrected experimental database for use in the evaluation. Ideally, all the participants should use this recommended experimental database in the joint evaluations.

For the needs of Test 3 (evaluation of ^{7}Be), all available experimental data up to the stated excitation energy should be considered. To create the common 'recommended/modified' experimental data repository, it was suggested that each evaluator submits a folder with data files and comments on what was modified in the data files as well as the reason for the modification.

It has been proposed that Test 3 is split into two parts: one for an evaluation up to 15 MeV and then another up to as high in energy as an individual participant wants to go. More specifically, the energy limit is a centre-of-mass energy of 10 MeV for Test 3, or 11.5 MeV ^{7}Be excitation energy. Excited states up to the second excited state in ^{6}Li should be included.

G. Hale and M. Paris have already performed a complete evaluation of ^{7}Be so they could provide their 'modified' experimental database to GitHub. However, it is important to provide comments on what and why it was changed as well. The same holds for Z. Chen's modified experimental database which he used for his ^{7}Be global evaluation. Although the experimental data files have been provided, the corresponding comments are missing so it is not straightforward to track the changes.

1.3.3. Covariance matrices

Tests 2 and 3: it was agreed that full covariance matrices for R-matrix parameters **and** normalization should be provided. A standardized format for the covariance matrix was proposed, with the central parameters in the same order as the covariance matrix. An order for the data set normalizations and the experimental data should also be agreed on.

Participants, however, expressed their concern that the ENDF format, at the moment, does not accommodate cross correlations with normalization.

Action on I. Thompson: to request from participants their full covariance matrices, re-evaluate the submitted data and prepare a report on Test 2 for publication as an INDC(NDS) report.

1.3.4. Gamma production

Gammas emitted from particle-induced reactions at the incident energies of interest to this project can be classified as follows: a) primary gammas, b) secondary gammas, c) further decay gammas. Measured gammas in categories a) and b) will be accompanied by angular distributions, while gammas in category c) are isotropic. For heavier elements, e.g. ^{16}O, there are a lot of gamma-producing cross-section data available, either a) or b), that need to be considered in the evaluation for completeness sake. Moreover, gamma-production cross sections b) are very important for applications such as nuclear astrophysics and ion beam analysis. Therefore, these data have to be included in the evaluation.

However, not all the available R-matrix codes in this project have the capability of calculating secondary gammas. The modeling of secondary gammas in the R-matrix theory was developed by Brune and deBoer in PRC **102**, 024628 (2020) and PRC **103**, 065801 (2021). It has been implemented in AZURE2. CONRAD, EDA and RAC also calculate secondary gammas angular distributions.

The question is whether the other codes, such as SAMMY and SFRESCO will also include this capability.

1.3.5. Issues about damping via Reich-Moore parametrization

Smoothing/Averaging at high energies

Participants discussed how the statistical model at higher energies is essentially based on averaging or smoothing of many overlapping resonances, and that it should be possible to transition from R-matrix resonances to optical model states at high energies. This would allow damping of the many open channels in an imaginary term just as the optical model damps strength from the elastic scattering channel into the reaction channel via the imaginary optical potential. A parameterization similar to the Reich-Moore one could be used to achieve this. The transformation to and from the Brune basis would have to be worked out in this new model.

It is believed that the level energy of RAC has a real and imaginary part, which is the same as the Reich-Moore formalism. However, the group has been unable to reproduce RAC cross sections from parameters. This could be a result of phase conventions, but this information from RAC has not been provided. This is the reason why RAC was not included in the intercomparison of the previous paper.

There was a suggestion to create an experts group of both R-matrix and statistical model theorists and evaluators to discuss the possible ways of connecting the low-energy resonance regime of the R-matrix theory with the higher energy statistical regime of overlapping resonances.

Concerns were expressed that in some cases, code enhancements and developments take time and may not keep up with the developments in theory and evaluation methodology.

A proposal was made to store all aspects of the work performed by the group, model developments and codes enhancements.

For the next meeting, participants agreed to continue with the evaluation work on ^{7}Be, the implementation of gamma-production cross sections in the codes, and the development/implementation of the reduced R-matrix algorithms.

I. Thompson would continue discussions with Zhenpeng Chen via e-mail, to obtain a better understanding of the reduced R-matrix method implemented in RAC.

1.4. Summary

The 6th IAEA meeting on R-matrix calculations for charged-particle reactions in the resolved resonance region was held from 15 to 16 March 2021 virtually. Participants reported on the results of two exercises, the inter-comparison of covariances (Test 2) and the full evaluation of the ^{7}Be* system (Test 3). Discussions focussed on extending the R-matrix algorithm to higher energies where many more channels open. The reduced R-matrix theory proposed by Chen, Leeb and Thompson based on Lane and Thomas and/or the Reich-Moore approach are those currently in use or development. A new method for treating break-up channels based on the Glöckle method was also presented.

Participants agreed to complete the full evaluation of ^{7}Be* and hold an interim virtual meeting in January 2022.

2. INTERNATIONAL NUCLEAR DATA EVALUATION NETWORK FOR LIGHT ELEMENTS (INDEN-LE)

2.1. Introduction

The International Nuclear Data Evaluation Network (INDEN) is an initiative of the IAEA which aims at continuing the success of the NEA CIELO project in expediting advances in nuclear data evaluation through international collaboration among experts.
The network activities are split into three groups focusing on nuclear data for actinides (and heavy elements), structural materials and light elements, respectively (see also: TM_IAEACIELO).

The first INDEN meeting on the Evaluation of Light Elements was held from 30 to 31 August 2018, and brought together the experts in the field to discuss the outstanding issues in the evaluation of light elements in the energy range from a few keV to 20 MeV, such as the lack of experimental data or discrepancies in experimental data, the implementation of R-matrix algorithms at higher energies where many channels open up and/or three-body decays occur, connecting the resolved resonance region with the unresolved resonance region and statistical model regime, treating uncertainties and producing covariance matrices, and data processing codes.

Four light systems were identified as priorities for nuclear criticality and nuclear safety applications at the CIELO follow-up meeting that was held in December 2017 (TM_IAEACIELO): neutrons on ^{9}Be, ^{14,15}N, ^{23}Na. These four light systems as well as (α,n) reactions on F and O isotopes, which are of particular interest in the field of spent fuel management, and the re-investigation of neutrons on ^{16}O following the conclusions of the CIELO project, were discussed, and a work plan was agreed among participants. A summary of the discussions is published in INDC(NDS)-0768.

A follow-up meeting to monitor the progress in the evaluations and re-adjust the work program accordingly was held from 15 to 17 May 2019 at the IAEA Headquarters, Vienna. The meeting was attended by twelve experts from four member states (MS) and two international organizations. The summary report of the meeting is published in INDC(NDS)-0788.

The third INDEN-LE meeting was held virtually, from 17 to 19 May 2021, with the purpose of reviewing the progress in the evaluation work on the four light systems, and discussing in more depth, the need for a concerted effort on improving the evaluations of the (α,n)/(n,α) reactions on light nuclides such as O, F, Si, among others. To scope the needs for reliable and accurate (α,n) data on light systems across various fields of applications, a dedicated one-day session was organized for presentations and discussions on the role of (α,n) data in applications such as spent fuel management, development of accident tolerant fuels, low-background detector systems for dark matter search and nuclear astrophysics.

Summaries of the presentations are given in Sections 2.2. and 2.3.2 to 2.3.7, and discussions in Section 2.4. The meeting agenda and participants' list are found in Annexes 1 and 2, respectively. All the presentations are available on the meeting webpage: https://www-nds.iaea.org/index-meeting-crp/INDEN-LE-.

2.2. Presentation Summaries

2.2.1. Report on n+^{23}Na, P. Tamagno (CEA Cadarache)

The re-evaluation of n+^{23}Na presented in the previous INDEN-LE was continued in 2020. The cross sections provided in the latest evaluation (JEFF-3.2) were discussed. It was shown that, because of the limitations of the processing code at the time the evaluation was produced, the inelastic cross section is entirely provided as point-wise tabulated data, thus preventing default Doppler broadening of the cross sections for energies higher than the inelastic threshold (about 450 keV). It was also shown that the linear representation of the inelastic cross section is unsatisfactory for small resonances. A new analysis has been conducted in 2019, including Doppler broadening and an experimental energy resolution function. It was shown that these features impact small resonances even at energies larger than the inelastic threshold. In 2019, a new analysis was performed using the rigorous energy-independent boundary condition B=-l. As this choice creates a mismatch between pole and resonance energy, it was necessary to start the whole resonance analysis from scratch with serious difficulties in estimating prior values for the poles. These difficulties are removed when using the Brune alternative parameterization. The CONRAD code has thus been extended to use both Brune and standard parameterizations. This implementation, not detailed here, was tedious but allowed to preserve the capability to calculate analytical derivatives for both parameterizations. In the new analysis, four resonances had their spin-parity reassigned. A resonance doublet present in the former evaluation has been removed by using two entrance channels for the same resonance (l=0 and l=2). It yielded a much better agreement with experimental data compared to the resonance doublet. This analysis work has been carried on up to the inelastic threshold where it was found that the structure near 430 keV is not possible to be reproduced with a single resonance. The analysis will continue in 2021 and will be extended to higher energies above the inelastic threshold, where the change in boundary condition will be tested on angular cross sections, as experimental data are only available for energies above the inelastic threshold.

Discussion:

- Is the Brune parameterization causing the improvement in the fit? It should be independent of the basis.
  It is more likely that the Jpi changes, Doppler broadening and resolution played an important role in improving the fit. It is not clear why the previous JEFF evaluation neglected this.

2.2.2. Report on n+^{16}O evaluation, M. Pigni (ORNL)

Updates to the n+^{16}O evaluation work were presented. The fit of the resonance parameters was performed on transmission data sets converted from total cross sections found in EXFOR. This allowed us to include experimental corrections such as resolution broadening mainly related to the ORELA facility. The fit of the (n,α) channel was performed by using Bair's data normalized of -20% on data converted from the ^{12}C(α,n)^{16}O to the reverse reaction ^{16}O(n,α)^{12}C. The fit converged but for a few narrow resonances the fit is still an open problem. Another topic of the presentation was the generation of resonance parameters for the two boundary conditions B=S and B=-l. Visually, the fit to the cross sections for both cases is comparable. For the B=-l basis, the resonance parameters were tested for convergence to the Brune basis whose energies were reported in the presentation.

Discussion:

- The emphasis was on fitting data step by step to really get a good fit and to understand the issues with each data set at a very precise level. However, we do want to be as comprehensive as possible in the end and add all of the data.

2.2.3. Report on n+^{9}Be and n+^{16}O evaluations, M. Paris, G. Hale (LANL)

We outlined new developments in light-element R-matrix evaluations and code modernization and development work at Los Alamos in the Theoretical Division. We spoke specifically about the data evaluation methodology (our "EDA pipeline"), which includes all ("non-defective") observed data relevant for the given compound system being evaluated for all (unpolarized and polarized) differential data. We gave a theoretical overview of the Wigner-Eisenbud R-matrix approach that we employ for the evaluation work and a detailed discussion of the uncertainty quantification for both parameter uncertainties and observable (cross section) uncertainties for the evaluated data. Highlights of recent code development work was provided.

This has occurred in three areas: front-end data handling via the perl script c5toeda.pl, which converts EXFOR/CSISRS c5 formatted data to EDA native format; evaluation code modernization of eda5 to edaf90, a modern Fortran 2008 implementation that is numerically exactly equivalent to eda5; and back-end processing and visualization coding developments that employ the NJOY/ENDFtk suite via python bindings. Recent evaluation work on ^{10}Be compound system evaluation was described in detail; a description of the state of the ^{17}O compound system evaluation was given in summary form. The ^{10}Be system evaluation has been improved up to 5 MeV by incorporating a more complete data set compared to the previous evaluation work and the inclusion, for the first time, of inelastic data from the ^{9}Be(5/2^{-}) excitation. The new evaluation results in a good-quality fit of the observed data with a χ^2/DOF of 1.75 and results in the reassignment of resonances in the region of 2.7 MeV incident neutron energy from (4^{-}, 3^{+}) to (4^{+}, 3^{-}). Excited states make an important contribution to the (n,2n) cross section and this has been revised in the evaluation's ENDF-6 formatted encoding from MT=16 (n,2n) to MT=24 (n,2nα). The resulting n+^{9}Be ENDF evaluation file has been tested with various studies (pencil-beam, quasi-integral MCNP simulations, criticality perturbation studies, and pulsed Be-sphere simulations) and found to be comparable to the previous evaluation and consistent with the differential data. Current effort on the ^{10}Be system are focused on taking the evaluation to higher energies. The ^{17}O system is currently undergoing an overhaul with the ongoing inclusion of ^{13}C* and ^{16}O* excited-state contributions. We showed some comparisons of the existing evaluation to recent measurements by Febbraro (^{13}C(α,n) at zero degrees) and Brandenburg (^{13}C(α,n) integrated cross section up to 5 MeV, where the evaluation ends); these indicate that the existing evaluation is very close to the data in the fit region. However, more effort will be required among experimentalists and evaluators to address inconsistencies between existing observed data.

Discussion:

- Mark Paris will supply information on error estimation and eliminating the dependence on the number of fit parameters when using χ^2 = 1.
  Trying to move towards an R-matrix fit above 5 MeV for the ^{16}O+n system.

2.2.4. Report on n+^{14}N measurement and R-matrix analysis at Notre Dame Univ., R.J. deBoer (Notre Dame Univ.)

A global R-matrix analysis of the ^{15}N system is underway at the University of Notre Dame, in conjunction with new experimental measurements for astrophysics applications. Measurements of alpha-induced reactions on light nuclei like lithium and boron are motived by the unique conditions present in first generation stars, that is a hot environment with no carbon, nitrogen, or oxygen seed nuclei. The global R-matrix analysis includes all ^{14}N+n, ^{11}B+α, and ^{14}C+p data ranging from about 11 to 13 MeV excitation energy in the ^{15}N compound system. The fit includes about 20 levels with widths ranging from a few to 100s of keV. New measurements at UND include angle integrated measurements of the ^{11}B(α,n) reaction and a 90 degree differential cross section measurement of the ^{11}B(α,p) reaction. Both measurements use thinner targets than previous work in order to better resolve narrow resonances that have widths that are similar to the energy loss of the beam through the targets (usually less than 10 keV). This was particularly relevant for the measurements of the ^{11}B(α,p) reaction. A consistent R-matrix fit is close to completion, but there is an inconsistency with a level at an excitation energy of about 12.14 MeV. This is likely the result of an incorrect spin-parity assignment. Further calculations are underway.

2.2.5. Report on n+^{14}N and other reactions producing ^{15}N*, I. Thompson (LLNL)

Reactions in this system are to be evaluated as part of the INDEN project. The thresholds for n+^{14}N, p+^{14}C and α+^{11}B are close to each other, and so all three channels must be fitted simultaneously. ENDF has a 1992 evaluation with these three channels up to 2 MeV, and Notre Dame is re-evaluating them up to 2.5 MeV to date. Here I report on a preliminary assessment up to 6 MeV (17 MeV in the ^{15}N* system) that includes the first excited states of ^{14}N and ^{11}B each around 2.1 MeV, but not yet the triton or deuteron channels which have thresholds above 4 MeV, nor the weaker capture channel.

The Notre-Dame parameters were used as a starting point for levels up to 2.5 MeV, and then the energy levels specified in the RIPL3 database were used up to 6 MeV. These are the energies in the Brune basis, to be kept fixed while fitting the widths. Afterwards, adjustments are made to both the energies and widths together. In this preliminary fit I do not yet assess alternative spin assignments to the levels, so some of the peaks will have incorrect interference shapes. Thus, 12 spin/parity channel sets are fitted, with a total of 84 poles and 644 partial widths to fit. These are determined to best fit to 4905 angular points, 2491 angle-integrated measurements, and 5083 neutron total cross-sections. No Breit-Wigner damping terms were used. To stop the fitting procedure driving widths to values too large to be converted from the Brune basis to regular form, a term depending on $\Sigma_i |\gamma_i|^2$ was increased in value until the Brune transformation was unhindered by negative eigenvalues of its norm matrix.

All data apart from some Van Der Zwaan datasets could be plausibly fitted, with overall χ^2/dof = 2.96 using the GPU code RFLOW. The result is a promising beginning for the 2.5 – 6.0 MeV range, though some resonances were missing, and Jpi assignments for higher energy poles need to be reassessed. Ideally more excited residual states are needed, to give more gamma production data. Fitting at higher energy, $E_{cm}(\alpha) > 6$ MeV, should be possible with GPUs with more memory, but it needs more levels than in RIPL. Energy levels from shell-model calculations could be considered for starting that kind of search. When successful, this project will give three GNDS evaluations for: n+^{14}N, α+^{11}B and p+^{14}C.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Discussion:

- We need to develop tools to evaluate the URR, making R-matrix and HF calculations merge seamlessly.

2.3. Session on (α,n) measurements and data needs for applications

2.3.1. Introduction

Reliable estimates of the neutron yield from (α,xn) reactions for actinides embedded in reactor fuel materials are of high importance for Nuclear Safeguards. The alpha particles originating from spontaneous α-decay of actinides in the fuel, subsequently produce neutrons by interacting with the light elements in the compound fuel materials. The study published in INDC(SEC)-0111 and subsequently in Nuclear Data Sheets, v. 139, January 2017, p.190, found that for (α,xn) reactions on oxides, such as UO_2 and PuO_2, there was agreement between the newly evaluated cross sections plus stopping powers and thick target yields and the reference data published in 1991 by the Los Alamos National Lab at the 10% level. However, for fluorine, i.e. for UF_6 and PuF_4 fuel materials, the differences were at the 25-50% level. The main reason for these discrepancies is the ^{19}F(α,n) reaction cross section, which suffers from inadequate experimental data and consequently, a largely uncertain evaluation. To address the inadequacies in these data, the IAEA is planning to organise a Technical Meeting dedicated to (α,n) measurements and evaluation. This one-day session within the INDEN-LE meeting serves as a means of scoping other fields of applications where (α,xn) reaction data are considered important and therefore, require a concerted effort in measurements, modeling and evaluation.

2.3.2. Overview of (α,xn) data needs, D. Cano-Ott (CIEMAT)

An overview of (α,n) data needs was provided. (α,n) reactions are relevant for modeling neutron emission rates for UF and MOX pins. They are also important for modeling backgrounds for large-volume dark matter detectors, since neutrons can mimic WIMP recoil signals. For this application, Ar(α,xn) data is needed but experimental data do not exist. Correlated neutron and gamma-ray data is also required. The code SaG4n, a neutron yield calculator (freely distributed), has been developed in Spain. This GEANT4-based code performs microscopic calculations on the materials (directly simulating the particle tracks and the (α,n) interactions) instead of using the integral over the cross section and the stopping powers. It has an MCNP-like input deck and uses custom-made nuclear data libraries. At the same time, an experimental campaign to measure (α,xn) cross sections has started in Spain and is led by the MANY collaboration. The collaboration will make use of the experimental facilities available in Spain, including high-energy resolution Van de Graff accelerators that can produce up to 15 MeV alpha particles. It will also use neutron detectors developed in the past decade, such as ^{3}He long counters (MiniBELEN with a flat efficiency curve (7%)) and ToF liquid scintillators (MONSTER array with up to 50 detectors).

Discussion:

- (α,n) data are also present in the nuclear database for medical applications
- Neutron spectra will be measured with ToF facility
- The nuclear data libraries used are custom-made from a combination of JENDL-2005AN, TENDL-2005, TENDL-2017, and TENDL-2019 files. The library is available on the web at http://win.ciemat.es/SaG4n/

2.3.3. (α,xn) reactions for nuclear astrophysics, A. Tarifeno-Saldivia (UPC)

(alpha,n) reactions play an important role in nuclear astrophysics. In particular, the reactions ^{22}Ne(α,n) and ^{13}C(α,n) provide the neutron source for the s process [1, 2]. The measurement of these two reactions is particularly challenging since they require special targets and low background conditions. Moreover, (α,n) reactions contribute significantly to the nucleosynthesis of lighter heavy elements (30<Z<45) in the weak r process in neutrino-driven winds [3]. In this case, direct measurements of (α,xn) cross sections are very difficult due to the need of radioactive beams on ^{4}He targets and inverse kinematics. Besides that, solar neutrons are produced, among other mechanisms, by alpha-reactions on stable isotopes from C up to Fe [4]. Neutron spectral observations from solar flares provides a probe to explore the sun's particle acceleration mechanism. The proper interpretation of the measured data on solar neutrons relies on the knowledge of the production yields and energy spectra of (α,xn) reactions. The status of nuclear data and the need for new experimental measurements on (α,n) reactions with implications for nuclear astrophysics was briefly discussed.

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Discussion:

- The need for measuring partial cross sections and angular distributions was emphasized.

2.3.4. Report on (α,n) scoping study, M. Pigni (ORNL)

An (α,n) scoping study was recently performed by the United States Department of Energy and released in 2020 (C. Romano, D. Brown, S. Croft, et al., ORNL/TM-2020/1789).

The study concluded that there exist discrepancies between the measured (α,n) cross sections, and also between the measured and evaluated data. The neutron emission spectra suffer from even larger uncertainties. The available experimental data are incomplete and do not provide information on all possible reaction channels and excitation states. Stopping powers need to be studied and measurements of partial cross sections of each excitation state and reaction channel of the compound nuclei are needed to provide insight into the energy spectrum of the neutrons. Additionally, modeling and simulation capabilities need to be modernized to use the optimal data and codes such as SOURCES 4C have to be updated accordingly.

2.3.5. New measurement of $^{13}C(\alpha,n)^{16}O$, Z. Meisel (Ohio Univ.)

This talk presented recent results on direct measurements of the $^{13}C(\alpha,n)$ total cross section performed at the Edwards Accelerator Laboratory at Ohio University with the newly developed HeBGB detector. A brief synopsis follows.

The $^{13}C(\alpha,n)$ cross section is an important one for a variety of astrophysical and applied settings. The cross section in the α-decay energy range is of particular interest for backgrounds of dark matter and geoneutrino detectors. The effective omnipresence of carbon results in $^{13}C(\alpha,n)$ caused by alphas produced in effectively omnipresent actinide decay produces a neutron source inside such detectors. The neutrons cause nuclear recoils that mimic the recoils of the neutral particles of interest. At present, the $^{13}C(\alpha,n)$ cross section is only constrained by one direct measurement above Eα = 5.5 MeV, which is known to have issues due to an incorrectly assumed neutron detection efficiency. A Hauser-Feshbach-based correction reduces the cross section by ~50%, but has an unknown uncertainty due to the questions about validity of statistical estimates for such a light nucleus.

The HeBGB detector at Ohio University was designed and commissioned to solve this issue, providing a nearly-constant neutron detection efficiency for neutron energies from 0.1-10 MeV. HeBGB incorporates other features to reduce backgrounds and uncertainties including a target-ladder for background measurements and tuning checks at each beam energy, as well as borated polyethylene and gold-lining of beamline components to reduce background.

Measurements were performed from E_α=3-8 MeV, resulting in a cross section with an uncertainty of ~15%, including all systematics. The results are in remarkable agreement with the Hauser-Feshbach-based correction to the published cross section in this energy region. Detailed comparisons in other energy regions indicate general agreement with literature results, but a more detailed comparison has yet to be done. Results from this work will be published shortly.

2.3.6. Measurements of $^{13}C(\alpha,n)^{16}O$ at Notre Dame Univ., R.J. deBoer (Notre Dame Univ.)

Measurements of the $^{13}C(\alpha,n)^{16}O$ reaction are ongoing at the University of Notre Dame Nuclear Science Laboratory. The motivations for study are far reaching, encompassing nuclear astrophysics, nuclear structure, neutrino detection, and applications. Recent measurements have focused on the range above 5 MeV, where excited states in the ^{16}O final nucleus can be populated. Several applications require partial cross sections, as the neutron energy spectrum from the reaction is of interest. Recent measurements include those of secondary gamma-ray 7-point angular distributions of the second, third, and fourth excited states, 20-point angular distributions of the ground-state neutrons using the ODeSA array for direct neutron detection, and the first direct measurement of the first excited state neutrons using a ^3He spectrometer. While initially this data will be supplied to collaborators who already have detailed R-matrix analysis of the ^{17}O system, a global analysis is also planned using AZURE2 in the future. Additional (α,n) measurements on oxygen and magnesium isotopes have also been made, and their analysis is underway.

2.3.7. Measurement of $^{16}O(\alpha,n)^{13}C$ at LANSCE, Hye-Young Lee (LANL)

While multiple experimental data sets for the ^{17}O system exist up to date, the currently available evaluations [1-3] differ by 30 - 50 %, which questions the fidelity of this reaction cross section to be used for various applications.

Previous measurements were performed not only on the $^{16}O(n,\alpha)$ reaction [1, 4-7], but also on the $^{13}C(\alpha,n)$ reaction [8-10] as a time-reverse reaction, using the principle of detailed balance.

The compound nucleus of ^{17}O, presenting well resolved resonances at the energy range of interest, imposes challenges like experimental energy resolutions, angular resolutions, or timing resolutions, either in (n,α) or (α,n) reaction measurements. We have presented the preliminary angle-integrated, energy-differential cross sections based on the ^{16}O(n,α) measurements performed in 2016 and 2017 using the LENZ (Low Energy NZ) instrument at Los Alamos Neutron Science Center (LANSCE). With the same data sets, we demonstrated the Forward Propagation Analysis in MCNP [11] by varying nuclear libraries of ENDF/B-VII.1 and ENDF/B-VIII.0 and observed the yield shape sensitivity to different libraries. We presented the upcoming experiment plan in 2021 at LANSCE, in order to provide improved LENZ angular distributions with at least a factor of 2 better angular resolutions and about 30 % improvement for energy resolutions than the current LENZ data. The current LENZ data for the ^{16}O(n,α) reaction is being analysed for the differential cross sections and compared with available libraries, and is to be published in 2021 (LA-UR-21-23064).

This work benefits from the LANSCE accelerator facility and is supported by the U.S. Department of Energy under contracts DE-AC52-06NA25396.

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2.4. Technical discussions

- Recommendation was made for James deBoer to put preliminary $^{13}C(\alpha,n)$ data on the shared IAEA OneDrive [Note: done during meeting].
- The group finds that, in general, (α,n) reaction data are good candidates for R-matrix analysis. However, currently there are lots of cases (light systems with important applications) with insufficient available experimental data. This means that in the evaluation process there is a struggle between the need to maintain a unitarity R-matrix and the lack of a complete experimental database that covers all the open reaction channels.
- Multi-body channels are a real challenge, as they cannot be treated within the standard R-matrix

formalism. An alternative formalism or a 'reduced' R-matrix approach is required and this needs to be addressed, if the group is to extend evaluations to higher energies. When moving to higher energies, one may additionally encounter a "parameter catastrophe", where there are many levels and sparse data and it just becomes too numerically challenging to perform an R-matrix analysis.

- The problem of sorting the experimental data, identifying outliers, correcting for normalization etc., was raised once again. Experimentalists have a special role to play in reviewing older data and publishing corrections to the data. However, experimental evaluation is not considered a traditional role for experimentalists, therefore it is not funded or systematically practiced. Funding is clearly a roadblock, and to overcome this problem, the importance and broad implications of experimental evaluation need to be emphasized.
- Experimental evaluation, on the other hand, should be a standard part of the evaluation process. However, it is extremely time consuming and often requires expert knowledge of the different types of experiments. Is a more concerted effort needed to address this issue in (α,n) and (n,α) reaction studies? This is highlighted by the very different experimental conditions and experimental corrections that go into charged-particle vs neutron-induced experiments.
- Can the unitary constraint be a better constraint of the absolute cross section, in some cases, than the systematic uncertainties that we try to estimate as experimentalists? This may result in a larger uncertainty, but should provide a more well-defined probability distribution function in the uncertainty of the cross section.
- A complete review of the n+^{16}O system will be conducted. It was suggested that a paper on the re-evaluation of n+^{16}O be prepared in the following year which will consider the recent experimental data analysis as well as the impact of "inelastic" channels. A detailed discussion of the issues regarding the data and the challenges in evaluating the system should also be included.
- Mark Paris mentioned that a new EDA evaluation, up to 10 MeV, will become available for n+^{16}O in three months. It will include the inelastic channels. Marco Pigni plans to first extend the evaluation up to 7 MeV, but it may take longer to extend it up to 10 MeV.
- The proposal to treat the statistical model as a special form of R-matrix theory, with an optical potential used to calculate the level widths and without interference among the reduced width amplitudes was made. The convenience of such an assumption is that the statistical models could predict the level structure needed for higher energies and could also treat multiparticle breakup as two-particle exit channels very successfully. The link between the statistical model and R-matrix to facilitate evaluation to higher energies should be the subject of a future focused meeting. The idea being, that a highly constrained optical model can be used to predict single particle states to inform R-matrix calculations.

2.5. Summary

The INDEN-LE held the third meeting from 17 to 19 March 2021 virtually to discuss the status of the evaluations of the five light systems n+^{9}Be, n+^{14,15}N, n+^{16}O and n+^{23}Na. Discussions focused on the importance of identifying reliable experimental data and extending the R-matrix theory to higher energies where the statistical model regime begins. A special session was devoted to (α,n) reaction data needs for a range of applications including detector development for basic research, waste management and nuclear astrophysics. Apart from the importance of re-evaluating the ^{13}C(α,n)/^{16}O(n,α) reactions on the basis of recent experimental data and re-analyzed data, it was also recognized that (α,n) reaction data are needed for a range of other light and medium-light nuclides for which the available experimental data are incomplete and/or the currently available codes and evaluated libraries use extrapolations to the low-energy region that are far from satisfactory. Participants agreed that a Technical meeting focused on all aspects of (α,xn) data would be beneficial to the community.

The INDEN-LE group will hold an interim virtual meeting in January 2022 and the next INDEN-LE meeting in spring 2022.

ANNEX 1

International Nuclear Data Evaluation Network on Light Elements (INDEN-LE)

6th Meeting on R-Matrix Codes for
Charged-Particle Reactions in the Resolved Resonance Region
15-16 March 2021
(virtual event)

3rd Meeting of the
International Nuclear Data Evaluation Network (INDEN)
on the Evaluation of Light Elements
17-19 March 2021
(virtual event)

Adopted Agenda

Monday, March 15th: R-matrix calculations for charged-particle reactions in the RRR

15:00 – 18:00 CET

15:10 Welcome address – Arjan Koning, SH-NDS
Election of chairman and rapporteur, Adoption of agenda, administrative matters

Presentations:

15:20 Introduction: Status of project(s), P. Dimitriou (IAEA)

15:30 Results of global evaluation of all light systems up to A=23, Z. Chen (Tsinghua Univ.)

16:15 Results of Test 2 and Test 3, I.J. Thompson (LLNL)

17:15 Bayesian analysis of the ^{7}Be compound system, D. Odell (Ohio Univ.)

Break as needed

18:00 End of Day One

Tuesday, March 16th: R-matrix calculations for charged-particle reactions in the RRR

15:00 – 18:00 CET

Presentations cont'd:

15:00 Reduced R-matrix formalism on n+^{9}Be system, H. Leeb (TU Vienna)

15:30 Novel R-matrix formalism for three-body breakup reactions in light nuclei,
B. Raab (TU Vienna)

16:00 Roundtable Discussions

Topics:

1. Test 2 results/conclusions/publication
2. Experimental database
3. Be-7 evaluations: how to proceed

Common to INDEN-LE

4. how to extend to higher projectile energies
5. how to deal with conflicting data
6. how to treat gamma production

Break as needed

18:00 End of Day Two

ANNEX 1

Wednesday, March 17th: INDEN-Light Elements

15:00 – 18:00 CET

Presentations:

15:00 Improvement perspectives for ^{23}Na in the RRR, P. Tamagno (CEA)

15:15 Report on n+^{14}N system, J. deBoer (Notre Dame Univ.)

15:30 Report on n+^{16}O system, M. Pigni (ORNL)

16:00 EDA R-Matrix Evaluations Report on n+^{9}Be and n+^{16}O, M. Paris (LANL)

16:30 Towards R-Matrix evaluations of n + ^{14}N and other reactions producing ^{15}N, I.J. Thompson (LLNL)

Break as needed

18:00 End of Day Three

Thursday, March 18th: (alpha,n) reactions

15:00 – 18:00 CET

Presentations:

15:00 (α,n) data for applications, astro-particle physics and detector simulation codes, D. Cano-Ott (CIEMAT)

15:30 (α,n) reactions for nuclear astrophysics, A. Tarifeño (Univ. Politécnica de Cataluña)

15:45 Updates on the α+^{17,18}O reactions, M. Pigni (ORNL)

16:15 New reaction cross section measurement of ^{13}C(a,n) using the 4pi HeBGB detector, Z. Meisel (Ohio Univ.)

16:45 Measurements of partial and differential cross sections of the ^{13}C(α,n) reaction, J. deBoer (Notre Dame Univ.)

17:15 Update and plans for LENZ ^{16}O(n,α) data, H.Y. Lee (LANL)

17:35 Discussions

Break as needed

18:00+ End of Day Four

Friday, March 19th: INDEN-Light Elements

15:00 – 18:00 CET

Roundtable discussions:

Topics:

1. EXFOR + shared experimental database
2. Status of evaluations
3. Review of assignments/list of actions
4. How to proceed – next meeting(s)

Cont’d:

5. How to extend to higher projectile energies
6. How to deal with conflicting data
7. How to treat gamma production

Break as needed

18:00 End of meeting

ANNEX 2

International Nuclear Data Evaluation Network on the Evaluation of Light Elements (INDEN-LE)

6th Meeting on R-Matrix Codes forCharged-Particle Reactions in the Resolved Resonance Region
15-16 March 2021 (virtual event)

3rd Meeting of the International Nuclear Data Evaluation Network (INDEN) on the Evaluation of Light Elements
17-19 March 2021 (virtual event)

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ANNEX 3

Presentation Links

Presentations for R-matrix calculations for charged-particle reactions

#	Author	Title	Link
1	Zh. Chen	Results of global evaluation of all light systems up to A=23	PDF File 1 File 2 File 3 File 4 File 5
2	I.J. Thompson	Results of Test 2 and Test 3	PDF
3	D. Odell	Bayesian analysis of the ^{7}Be compound system	PDF
4	B. Raab	Novel r-Matrix Formalism for Three-Body Breakup Reactions in Light Nuclei	PDF

Presentations for INDEN-LE (neutron-induced)

#	Author	Title	Link
1	H. Leeb	Reduced R-matrix formalism on $n+^{9}Be$ system	PDF
2	P. Tamagno	Improvement perspectives for ^{23}Na in the RRR	PDF
3	R.J. deBoer	Report on $n+^{14}N$ system	PDF
4	M. Pigni	Report on $n+^{16}O$ system	PDF
5	M. Paris	EDA R-Matrix Evaluations Report on $n+^{9}Be$ and $n+^{16}O$	PDF
6	I.J. Thompson	Towards R-matrix evaluations of $n+^{14}N$ and other reactions producing ^{15}N	PDF

Presentations for (α,n) session

#	Author	Title	Link
1	D. Cano-Ott (CIEMAT)	(α,n) data for applications, astro-particle physics and detector simulation codes	PDF
2	A. Tarifeno (Univ. Catalunia)	(α,n) reactions for nuclear astrophysics	PDF
3	M. Pigni (ORNL)	Updates on $\alpha+^{17,18}O$ Reactions	PDF
4	Z. Meisel (Ohio Univ.)	New reaction cross section measurement of $^{13}C(\alpha,n)$ using the 4pi HeBGB detector	PDF
5	R.J. deBoer (Notre-Dame)	Measurements of partial and differential cross sections of the $^{13}C(\alpha,n)$ reaction	PDF
6	H.Y. Lee (LANL)	Update and plans for LENZ $^{16}O(n,\alpha)$ data	PDF

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