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International Nuclear Data Evaluation Network (INDEN) on the Evaluation of Light Elements (2)

Summary Report of the IAEA Consultants' Meeting

IAEA Headquarters, Vienna, Austria
15-17 May 2019

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August 2019

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ABSTRACT

A Consultants' meeting on the Evaluation of Light Elements within the International Nuclear Data Evaluation Network (INDEN) was held at the IAEA headquarters in Vienna from 30 to 31 August 2018. The goal of the meeting was to review the existing evaluations for light elements ^{9}Be, $^{14,15}N$, ^{16}O and ^{23}Na, to identify areas for improvements in the evaluations, and to define the timeline to provide improved evaluations.

August 2019

Contents

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 (https://www-nds.iaea.org/index-meeting-crp/TM_IAEACIELO/). The network activities are split into three groups focusing on nuclear data for actinides (and heavy elements), structural materials and light elements, respectively.

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, lack of experimental data or discrepancies in experimental data, 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 (https://www-nds.iaea.org/index-meeting-crp/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 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

Austria, China, France, USA and two international organizations, the European Commission and the OECD/NEA Databank, including IAEA staff Paraskevi Dimitriou (Scientific Secretary) and Roberto Capote (Deputy Section Head). Gerry Hale (LANL) was elected chairman and James deBoer (Univ. Notre Dame) rapporteur of the meeting. R. Capote welcomed the participants and P. Dimitriou briefly presented the goals of the meeting. The meeting continued with presentations by the participants which were followed by technical discussions.

Summaries of the presentations are given in Section 2 of this report, while the technical discussions are summarized in Section 3. The meeting agenda and list of participants are provided in Annexes 1 and 2. Links to the presentations are given in Annex 3.

2. Summaries of presentations

2.1. LANL R-matrix work on n+^{14}N, G. Hale (Los Alamos National Laboratory)

We continued our R-matrix fitting of data for the reactions in the ^{15}N system, as summarized in the table below. The top part of the table gives the arrangement-channel configuration of the analysis, and the bottom part summarizes the data fit for each reaction.

channel	a_c (fm)	l_{max}
n+^{14}N	2.5	2
p+^{14}C	4.3	3
α+^{11}B	5.1	2

Reaction	Energies (MeV)	# data points	Types of data	χ^2
^{14}N(n,n)^{14}N	$E_n = 0 - 2.5$	931	σ_T, $\sigma(\theta)$	1027
^{14}N(n,p)^{14}C	$E_n = 0 - 3.0$	362	σ_{int}	781
^{14}N(n,α)^{11}B	E_n=1.33 – 2.32	104	σ_{int}	316
^{14}C(p,n)^{14}N	E_p=1.17 – 3.1	407	$\sigma(\theta)$	1160
^{11}B(α,n)^{14}N	E_α=0.516 - 2.393	159	σ_{int}	586
^{11}B(α,p)^{14}C	E_α=0.598 - 2.94	145	σ_{int}, $\sigma(\theta)$	560
	Total	2108	$\sigma(\theta)$, σ_{int}	4430

χ^2 per degree of freedom=2.245

Overall, the integrated cross sections are fit much better than the differential data, which is probably a reflection of the relative quality of the measurements. We fit new measurements of the ^{11}B(α,n) integrated cross section from U. Notre Dame quite well, and they reinforce the level structure we are finding from the other reactions, some of which differs from the accepted J^π assignments.

The present analysis needs to be expanded in two directions: more reactions and measurements need to be added to the data set in the current energy range (below about 3 MeV neutron energy) and then the analysis needs to be extended to higher energies. For this latter effort, a representation of multibody breakup channels in R-matrix theory using hyperspherical coordinates could be useful.

2.2. n+^{14}N evaluation and new data for ^{28}Si system, R.J. deBoer (University of Notre Dame)

Reactions that populate the ^{15}N system have implications for nucleosynthesis through the ^{11}B(α,n)^{14}N and ^{14}C(p,γ)^{15}N, and ^{14}N(n,p)^{14}C reactions and the ^{14}N(n,p)^{14}C reaction is also a key component in modeling atmospheric ^{14}C production. A convenient characteristic of this system is that the α-particle, proton, and neutron separation energies are all within 1 MeV of one another. Further, it has been observed that ^{11}B+α, ^{14}N+n and ^{14}C+p induced reactions all populate many of the same resonances near their reaction thresholds. This strongly facilitates the simultaneous analysis of data for all three of these entrance partitions using a global *R*-matrix analysis, which in turn provides a method of comparing the systematic uncertainties among the different experimental measurements.

A new measurement has been made of the ^{11}B(α,n)^{14}N reaction at the University of Notre Dame Nuclear Science Laboratory, which gives a more accurate description of the cross section over an important interference region in the cross section. This new data has been combined with a preliminary data set motivated by the previous ^{14}N+n evaluation by Gerry Hale. This preliminary analysis is now in the process of being expanded to include all the low energy data below an excitation energy of about 13 MeV. This expanded analysis includes reaction data that have not been included in the previous compilation such as ^{14}C(p,γ)^{15}N and ^{11}B(α,α)^{11}B data sets. Difficulties with the fit include strong subthreshold state contributions that effect the ^{14}N(n,total) data, reproducing the angular distributions of the ^{14}N(n,n)^{14}N data, and what appears to be the presence of one or more unidentified broad resonance in the energy range of the data.

New experimental results have also been presented for the $^{24}Mg(\alpha,p_1\gamma)$, $^{24}Mg(\alpha,p_2\gamma)$, and $^{24}Mg(\alpha,\alpha_1\gamma)$ reactions, which were made at the University of Notre Dame. These are the first measurements of this type of reaction reported in the literature and extend from near the threshold (at about 4 MeV) up to an α-particle energy of 5.5 MeV. This data complements the very comprehensive ^{27}Al+p study by Nelson *et al.* as well as a previous $^{24}Mg(\alpha,\alpha)^{24}Mg$ study. A comprehensive global fit is underway.

New measurements have also been made for the $^{17}O(\alpha,n)^{20}Ne$ reaction at the University of Notre Dame that extend up to 7 MeV. These measurements include direct neutron detection via deuterated liquid scintillators and measurement of the secondary γ-rays using HAGRiD. They yields for these data are still be processed but cross sections should be obtained over the next year. In addition, a global R-matrix fit is being developed that will also include ^{20}Ne+n data.

For all the secondary γ-ray data, the derivation of the angular distribution by C.R. Brune has been used as implemented in the R-matrix code AZURE2. So far this has been very successful in describing all observed angular distributions.

2.3. Preliminary evaluation of n+^{9}Be, Z. Chen (Tsinghua University)

We tried to perform a global fit of the ^{10}Be system using RAC, in which we included all available and useful data for n+^{9}Be and t+^{7}Li found in EXFOR. To date, the evaluation of the cross sections has been completed, however the evaluation of the double differential data of ^{9}Be(n, 2n) is still a work in progress. In this report, we present the results of the completed evaluation.

The characteristic of this work is that, in the ^{10}Be system, for the most important reaction channel ^{9}Be(n, 2n), there are 6 reaction paths which proceed via (n,2n) finally.

1 n+^{9}Be*, ^{9}Be*→n+^{8}Be*, ^{8}Be*→α+α, 2 body break;

2 n+^{9}Be*, ^{9}Be*→α+^{5}He*, ^{5}Be*→n+α, 2 body break;

n+^{9}Be→^{10}Be*→3 α+^{6}He*, ^{6}He*→n+ n+α, for the first exciting state, 3 body break;

4 α+^{6}He*, ^{6}He*→n+^{5}He*, ^{5}He*→n+α, for higher exciting state;

5 ^{5}He+^{5}He, 2^{5}He→2n+2α, double ‘2 body break’;

6 n+n+^{8}Be, direct 3 body break; ^{8}Be→α+α, 2 body break;

But not all the 6 reactions have useful experimental data available, therefore it would not be effective to treat each one of them as a separate reaction channel. There are however, some useful experimental data for ^{9}Be (n, 2n), so the contribution of ^{9}Be(n, 2n) can be describe by the ‘Total width of eliminated channels’ Γ, also called ‘Reduced channel Width’ Γ. In this fitting attempt, the χ^2 obtained for n+^{9}Be is for the un-normalization situation, and the mean value is 2.42. Overall the fit to the data looks good.

Table 2.3.1. Reaction channels information in this work

Channel	Ac(fm)	If-search	Step-%	L_{max}	Threshold(MeV)
‘N,BE9’	0.43719975261317E+01	y	0.2	5	0.000000
' T, LI7 '	0.46744082000000E+01	y	0.2	2	-10.439000
' D, LI8 '	0.46465902000000E+01	y	0.2	2	-14.663000
' A, HE6 '	0.48325095166667E+01	y	0.2	3	-0.598000
' P, LI9 '	0.43877392000000E+01	y	0.2	2	-12.825000
'RED-CH'	Used to represent $^{9}Be(n, 2n)$				

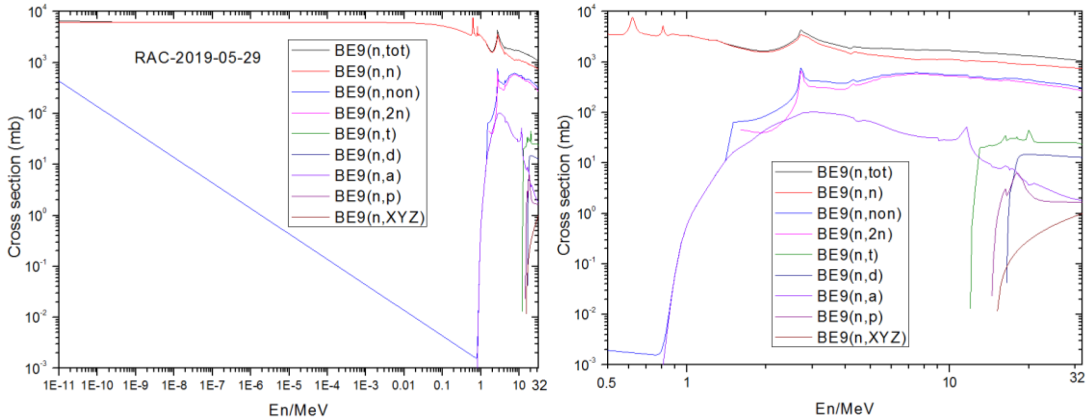
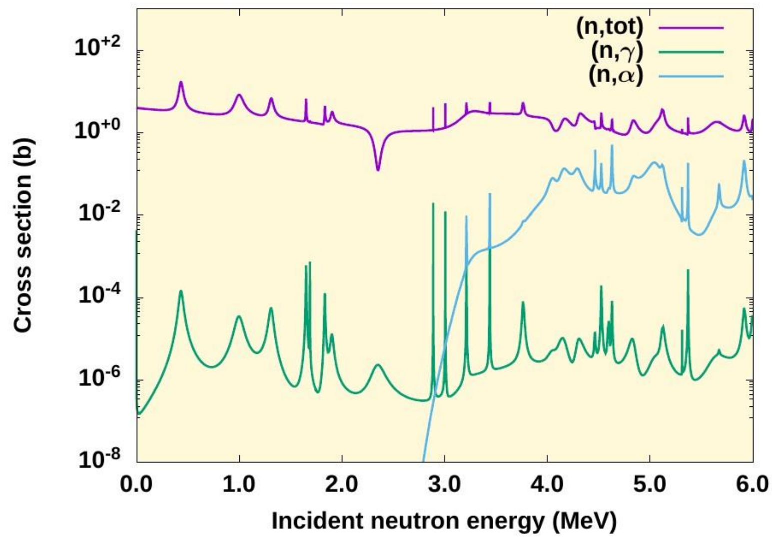


FIG. 2.3.1 Calculation values of RAC for all channels on n+^{9}Be.

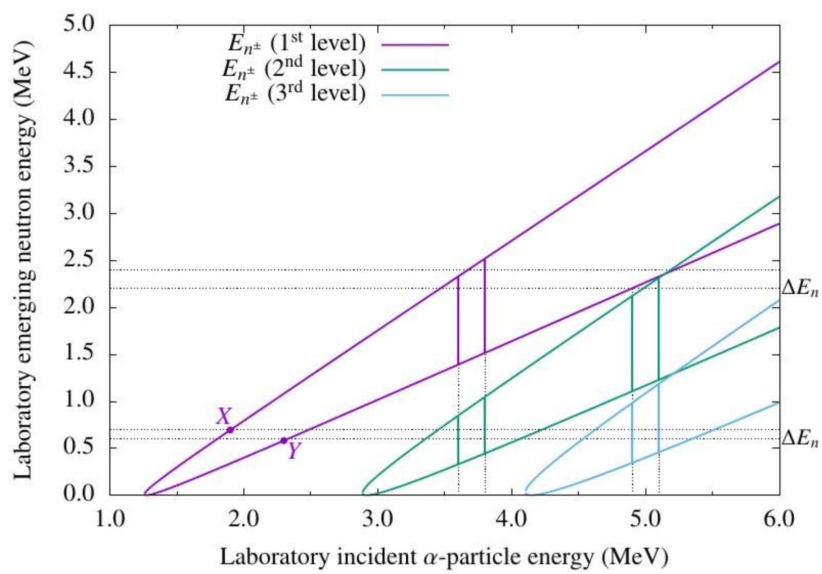
2.4. Evaluation of n +^{16}O, α+^{17,18}O, M. Pigni (Oak Ridge National Laboratory)

The evaluation work on n+^{16}O and α+^{17,18}O isotopes was presented and discussed.

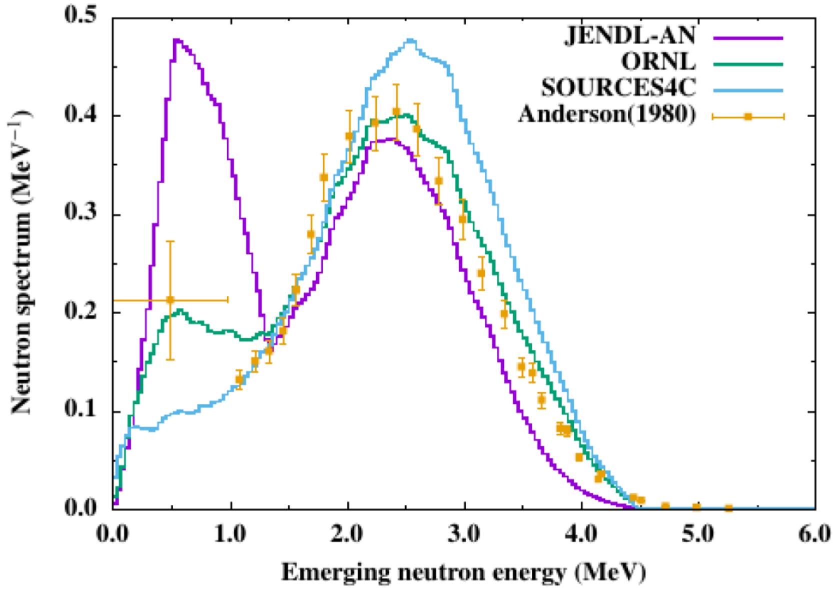
The n+^{16}O resonance parameter evaluation used the SAMMY-8.2b to fit total and (n,α) measured cross sections reported below. The ^{16}O(n,α) reaction channel was fitted on the basis of ^{13}C(α,n) Bair’s measured data (used in inverse kinematics) with a normalization factor of about 20%. The fit was performed treating the (n,γ) reaction channel as particle channels whose penetrability factor is set to be unity. Moreover, the fitted set of resonance parameters was checked to satisfy the Brune transformation. The thermal value for the total cross sections reconstructed from the fitted parameters is consistent with the current ENDF/B-VIII.0 value.



The evaluations on α+^{17,18}O isotopes discussed the recent work devoted to improve the neutron energy distributions in neutron source fissile compounds and showed the importance of the partial cross sections related to the energetically possible excited states. This is clear from the minimum and maximum permissible emission energies plotted below. Here, the effect of the several excited states on the neutron energy distribution is described and the maximum and minimum permissible neutron energies—E± , for three excited levels of the ^{18}O(α,n) reaction—are plotted as a function of incident α-particle energies up to 6 MeV. In the plot, two neutron energy intervals ΔEn are considered. The first interval, which was chosen in the neutron energy range between 0.5–1 MeV, shows the α-particle energies for which each excited level contributes to the neutron distribution, and allows us to understand why the contributions of excited states opening at high α-particle energies are significant at low neutron energies. In this regard, the contribution of the 1st excited state ranges between α-particle energies at about ≈2 MeV, where the (α,n) cross sections are significantly smaller than the cross sections at ≈3.5 MeV (2nd excited state) or ≈5 MeV (3rd excited state). On the contrary, the neutron emissions above 2.5 MeV are dominated by 1st excited state for incident α-particle energies between 4–6 MeV.



The calibration of the partial contributions of (α,n) cross sections allowed for improving the agreement with the neutron spectra (see below). The lack of experimental information on the (α,n0),(α,n1),...,cross sections made the analysis on the neutron source experiments the primary guidance for determining the population of the excited states. In this regard, modern experiments should be designed to measure the partial contributions of the (α,n) cross sections.



2.5. Issues in n+^{9}Be evaluations, I.J. Thompson (Lawrence Livermore National Laboratory)

We compare the cross-sections of n+^{9}Be ENDL evaluations ENDF/B-VII.0 and JENDL with the experimental data from EXFOR. This was done by writing Python scripts to use Fudge to reconstruct evaluated ^{9}Be(n,2n)2α double differential cross sections (DDX), and compare cross sections for multiple reaction channels. For the ^{9}Be(n,el) cross section we also infer uncertainty, which is not given explicitly in the ENDF/B evaluations.

There have been some recent changes in 2018, including fixing the first point in MT=1 and 16. Some JENDL-4 angular distributions have been imported for ENDF/B-VIII to improve some specific energy regions. But otherwise the ENDF/B evaluation was last updated in 2011. It consists of a single-channel R-matrix fit of total cross section only up to 5 MeV, which is stitched together with the preexisting evaluation above 5 MeV. On the whole there is generally good agreement with experimental data, though some issues remain.

The ^{9}Be(n,γ)^{10}Be has large uncertainties. The ^{9}Be(n,2n)αα reaction is important for estimating nuclear heating and material damages in fusion reactor developments, and the existing DDX evaluations are not always satisfactory. In general, other reaction channels also present uncertainties that vary with the energy region of interest. A more advanced multichannel R-matrix fit of this evaluation at low energies is still missing, and attempts should be made to extend that fit to higher energies, at least until the cross-sections become smooth at around 10 MeV.

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

2.6. Evaluation of nuclear data of light nuclear systems-some aspects, H. Leeb (Technische Universität Wien)

The concept of modern evaluation techniques, based on Bayesian statistics, was briefly sketched and recent advances made at TU Wien were presented. At present it is well established that Bayesian statistics is the proper concept to consistently combine experimental data with a-priori knowledge from theory-based models.

Starting with Bayes theorem we outlined the concept of standard Bayesian evaluation techniques which consists of two key elements, i.e. the prior accounting for *a-priori* knowledge and the *likelihood* representing the probability density of experimental data with regard to the *a-priori* values of the observables. Because of recent developments discussed below we focussed on the linearized version which is frequently known as *General Least Square (GLS)* method. Furthermore we emphasized accounting for deficiencies of the model used for the determination of the prior. Neglecting the model imperfections leads to a bias in the evaluation and most importantly an underestimation of uncertainties.

Recently there has been worldwide effort in the improvement of Bayesian evaluation techniques for nuclear data for which nuclear statistical models are applicable. In the resonance regime the situation is less satisfactory and the applied evaluation techniques are essentially reduced compared to standard ones. The main reasons are the strongly varying cross sections with energy as well as the lack of quantitative (semi-)microscopic nuclear models for the resonance regime. Because of these differences in data behaviour and models one usually performs two separate and independent evaluation procedures, one for the resonance range and another for higher energies for which nuclear statistical models are applicable. Sometimes, if possible, a matching at the level of observables in the interfacing energy region is performed in order to achieve at least continuity in the mean value of the observables.

In the group at TU Wien we are working on two major developments of Bayesian evaluation techniques, (i) the inclusion of model deficiencies in the resonance region and (ii) the formulation of a unified Bayesian evaluation technique which covers the whole energy range independent of what nuclear model is applicable. Regarding topic (i) we extended the formalism of model defects based on Gaussian processes to the resonance regime. In particular, we proposed a new type of covariance matrix for model defects which is well adapted to the strong energy dependence in the resonance range. The first application to realistic, but simulated pseudo data was very successful. The second development (ii) requires a more comprehensive treatment. First of all we introduce a combined prior covariance matrix using an energy-weighted superposition of the individual priors associated with the nuclear models. Thus we are able to perform a unique evaluation over the whole energy range simultaneously. The combined prior is constructed in such a way that interdependence between different models is taken into account. Because of the completely different nature of the involved nuclear models their associated parameters are frequently not mutually compatible. Hence we perform the evaluation on the level of the observables which represent a common basis. Consequently we make use of a surrogate model on the level of observables defined on a very dense mesh in energy in order to also include resonant behaviour. This simplification is justified as the prior covariance matrix contains the main features of the original models. In addition we developed an alternative numerical implementation of the Bayesian evaluation technique which speeds up the calculations and allows storing of large scale data sets. The group at TU Wien is currently working to construct a general evaluation code based on the Unified Bayesian Evaluation Technique.

2.7. Sodium evaluation, P. Tamagno (CEA Cadarache)

The presentation on sodium makes a short review of the status of the latest ^{23}Na evaluation JEFF-3.2 that was released in 2014. The improvement brought by the latest evaluation is recalled: extension of the RRR up to 2MeV, switching from MLBW to Reich-Moore formalism, production of full covariance matrices (RRR + high energy), etc. The imperfections for the evaluation are also listed, for instance the resonance parameter description could not be provided in the ENDF file, as NJOY was not yet able to reproduce inelastic cross section in the RRR.

The main deficiency of the present evaluation is related to the angular distribution of the emitted neutrons in the RRR. Indeed no such distribution was used in the evaluation process that yielded JEFF-3.2 and the results for backward angles are very far from experimental data. Last year an attempt has been made to search for new spin-parity for each resonance. The new set of resonance parameters improves the agreement with experimental data yet there is still significant room for further improvements. Several sources of possible improvement have been identified as long as approximations that may bias the results. The main focus points that will be investigated in next year rely on including resolution function and Doppler broadening in the analysis of experimental data; switching from the unphysical boundary condition B = S to B = -l by using Brune transformation. These two points have been briefly tested and seem promising. Additionally Kopecky's angular distribution could be included with a proper normalization or with a special multiple-scattering treatment in the analysis. Finally we also consider using a different (deformed) optical model in the high-energy range and a consistent energy dependency of the effective channel radius.

3. Technical discussions

The main objective of the discussions was to review the light systems of interest, assess the status of the analysis for each and recommend further actions to improve the evaluations.

1) ^{9}Be+n system

Zhenpeng Chen is the only participant investigating this reaction at present. He has made quite a detailed evaluation of the system. To deal with multi-particle breakup he has had to implement the reduced R-matrix theory which is equivalent to an "optical R-matrix" as presented by Ian Thompson. RAC has a low-energy cut-off for the absorption width. The latter is switched on near the (n,2n+2α) threshold. This has allowed for a significantly improved fit to the data. However, the details of his implementation have still not been made clear. According to Chen, the evaluation of the double-differential cross sections is challenging and requires collaboration among the meeting participants.

Zhenpeng Chen agreed to supply the evaluated cross sections in ENDF-6 files to compare with the previous evaluation. This will be possible by the next meeting. He also agreed to provide his parameters to the group (Thompson, Pigni, deBoer, and Tamagno), who would then try to calculate the cross sections using the Reich-Moore approximation to see if this can reproduce Chen's cross sections. Chen will also provide a set of consistent parameters and cross sections for this light system.

Gerry Hale will now also try to evaluate ^{9}Be+n again up to 10 MeV. He is unable to reproduce the high energy scattering data due to the multi-particle breakup channel. He will try to use a hyperspherical coordinate model to do this.

At CEA there is an effort to work from higher energies down to the lower energy RRR using the statistical model, but results may not be available to share with the group.

It is recommended that additional ^{9}Be+n measurements be made. A new neutron white source facility in China may be an ideal place to carry out such an experimental campaign.

2) ^{16}O+n

This system is being investigated by Gerry Hale and Marco Pigni.

The main issue that remains is the problem with the absolute normalization of the $^{16}O(n,\alpha)^{13}C$ cross section. Hale has tried to force the $^{16}O(n,\alpha)$ cross section down by 20%, in order to be consistent with other analyses, but this then causes the total cross section to be increased by about 5%, which is far outside that data's systematic uncertainty. Prospects of decreasing the systematic errors on the experimental data are underway using thick target methods. deBoer's new measurements for $^{13}C(\alpha,n)$, which extend up above the excited state thresholds, will be published in the next few months. Cross sections will promptly be put on EXFOR. Hale intends to extend his R-matrix fit to include the energy range of this new data with the hope of eventually extending up to 10 to 12 MeV.

As part of the discussion of this system, the topic of relativistic treatment has been brought up. For a full relativistic treatment, you would need to re-derive the Coulomb functions relativistically. However, according to Hale there is an old derivation by Breit (G. Breit, Rev. Mod. Phys. 34, 766 (1962)) which shows that if you just correct the wave number for relativistic effects and use it in the Coulomb function calculations, it corrects them up to first order. This Breit relativistic treatment is used in EDA because it is correct at all energies and makes it easier to treat photon channels.

Michael Fleming gave a short tutorial on the NEA Databank High Priority Request List (HPRL) website. According to the HPRL, which is continuously reviewed and revised, the ^{16}O+n reaction data is requested at energies above 2 and up to 20 MeV. This was an outcome from the previous CIELO project.

3) ^{14}N+n & ^{15}N+n

^{15}N+n: Satoshi Kunieda was the only participant working on the ^{15}N+n system. Unfortunately, he has had to drop out of the group for a few years. The group wants to reproduce the very nice fit that Kunieda had obtained for the total cross section data. Dimitriou will request Kunieda's parameters from his fit and Chen and Pigni will test with their codes.

Currently there are total cross section data up to 20 MeV, but no information on branchings to other channels above the inelastic threshold at about 6 MeV. Angular distributions are available from about 2 to 3.5 MeV.

In order to extend the evaluation up to 20 MeV, Marco Pigni will try his statistical model calculations for the intermediate energy part of this reaction. Dimitriou, Leeb and Thompson will also investigate the high energy region using statistical model calculations for both ^{14}N+n and ^{15}N+n.

^{14}N+n: James deBoer and Gerry Hale will work on completing the low energy region and will work to expand the fit up to 12 MeV. Hale has a nearly complete fit from his work back in the mid 1990's. He has added the new $^{11}B(\alpha,n)$ data from Notre Dame and finds reasonably good consistency. However, there seem to be some issues with the $^{11}B(\alpha,n)$ data of Wang et al. from Caltech, possibility this is just the result of underestimated uncertainties.

James deBoer is currently trying to catch up with Hale. He has obtained a reasonable preliminary fitting but is still struggling with some broad underlying resonances that are needed to reproduce the ^{14}N(n,total) and $^{11}B(\alpha,n)$ data. He has also expanded the fit to include ^{14}C(p,p) and $^{14}C(p,\gamma)$ data. Much of this data is not available on EXFOR and Dimitriou has been asked to request that it be digitized from figures in the original papers. Also, Capote and Thompson reminded the group that there are lots of data for neutrons on natural nitrogen in EXFOR. A quick search in EXFOR yielded additional low energy data from ORNL as well as additional total cross section data that extend up to 20 MeV. Hale will try to extend his R-matrix fit up into the higher energy region.

One major issue is to extend the evaluation for these reactions up to 20 MeV. Thompson will do an optical model potential to fit for high energy ^{14}N+n data. He will then expand that to ^{15}N+n data.

4) ^{23}Na+n

Pierre Tamagno and Pascal Archier are working on the ^{23}Na+n system. There is a problem with matching the shape of the angular distributions at backward angles with their current R-matrix fit. They are now trying to use an energy dependent channel radius above 450 keV (hard sphere only). This is also how the calculations were performed in the JEFF3.2 evaluations. The need for the changing channel radius could be a result of deformation. An investigation will be made using the deformed optical model calculations with EMPIRE that Marco Pigni has made previously.

The way forward here is not clear. It seems that the use of the variable radius could possibly be replaced with subthreshold and background poles, but Stephan Kopecky tried this already with little success. Conversion of the parameters to the Brune basis could give to more insight into the problem.

5) ^{17}O+α and ^{18}O+α

Marco Pigni has been making new evaluations for both the ^{17}O+α and ^{18}O+α systems. His evaluation is hindered by very limited information on the partial cross sections for both reactions. New measurements of the partial cross section for the ^{17}O(α,n) reaction have been made at the University of Notre Dame up to 7 MeV. Secondary γ-ray measurements have also been made that give additional measurement of the partial cross sections.

The group recommends that new measurements of the partial cross sections are urgently needed for the ^{18}O(α,n) cross section.

6) Continuing data to higher energies

One of the main challenges for the working group is to produce evaluations that extend up to 20 MeV. For several reactions, a major obstacle in achieving this goal is that multi-particle breakup thresholds are below 20 MeV. Several methods to treat multi-particle breakup channels are underway. Four particle break up is about the limit of what is currently needed.

Ian Thompson will use his damping factor method to investigate fits where 3 body exit channels open. This “optical model” R-matrix should be further extended and investigated. One complication is that one still would like to know the angular momentum distributions of the outgoing particles. Ian Thompson has composed a short paragraph describing his work on the optical R-matrix model which follows.

Optical R-matrix model (I.J. Thompson)

The Reich-Moore approximation has imaginary damping widths for missing channels, and is satisfactory if a specific meaning is given to the missing flux, e.g. capture or fusion. At higher incident energies, there are more and more inelastic or transfer two-body channels. Numbers of partial waves increase, but this is still manageable using standard R-matrix theory. But when breakup channels begin to open, these are more difficult to model as they need three-body dynamics. Sometimes these can be well approximated by cascaded two-body channels, or by using hyperspherical harmonics to model the three-body kinematics in full detail. In the meantime, we could perhaps settle for using damping widths to describe loss of flux to outside the two-body model space in generalization of the Reich-Moore approximation.

Such damping widths describe loss of flux to outside the model space like an optical model, generalizing Reich-Moore for missing particle channels, if there are specific physical channels missing from the model (never for bound states). Then the missing flux (from the unitarity defect) could (for example) be fed into a Hauser-Feshbach decay model built only on the missing physics channels. But if the total width of a damped resonance is large, then the flux will start missing at lower energies, even below the known threshold for the excluded channels! In that case, absorption would still be present below the threshold of the missing channels, and that would be unphysical.

I therefore consider energy-dependent damping widths, which is to include some form to describe the energy dependence of flux going to an excluded channel with known threshold. This makes the damping width energy-dependent, such as proportional to the penetrability in some specified channel. If we know the physics of missing channels we can estimate centrifugal and Coulomb barriers in the penetrability functions. This would even allow M-body exit channels, as the K_{min} approximation for hyper-spherical harmonic K would then suggest $L = K + (3M - 6)/2$. An example was shown where the p+^{6}Li channel was eliminated from our previous ^{7}Be-system fit. This kind of treatment is reminiscent of optical models for elastic scattering, where energy-dependent imaginary terms are added even though the total Hamiltonian is no longer Hermitian or even energy-independent. It is available as a resort above the energy range of a strict Lane and Thomas model, by generalizing the Reich-Moore approximation to particle channels.

7) Group Data repository

The group will now begin to perform evaluations. To facilitate this, the experimental data will be placed in a repository accessible to all members of the group. For each data set, the entire EXFOR entry should be given (five digits of the entry number, without the three-digit sub entry). If data are not available in EXFOR they should be submitted to IAEA. Each participant will have their own subfolder where their data and references should be uploaded. The repository will be restricted to the group members and will be maintained by the IAEA.

In addition to this group-restricted repository, a project has been created on GitHub to facilitate code development and sharing of information and techniques among the group members and an extended community interested in R-matrix codes and calculations. The project is called R-Matrix Analysis of Charged Particle Reactions (RMACPR) and comprises a sub-group INDEN-LE which is focused on the light systems evaluations discussed at this meeting (URL: https://github.com/RMACPR/INDEN_LE-data). Access to this GitHub repository is granted upon request.

8) Recommendations

As a result of the technical discussions summarized above, participants formulated a list of recommendations for new measurements, evaluations and new data in general, that would assist in resolving remaining issues, discrepancies and gaps in data:

- new measurements of (n,α) cross sections to resolve normalization issue in n+^{16}O
- new measurements of partial (α,n) cross sections for ^{18}O for the evaluation of α+^{18}O cross sections and measurements of neutron energy distributions
- measurements of (n,2n), (n,α), (n,p), (n,d), (n,t) cross sections for ^{9}Be
- evaluators to consider submitting requests/needs for new measurements in support of their evaluations to the NEA Nuclear Data High Priority Request List
- new measurements of (n,α), (n,p), (n,t), (n,d) on ^{14}N from 15 MeV to 30 MeV in China
- updated level schemes and resonance parameters for ^{10}Be; ^{15,16}N; ^{17}O and ^{21,22}Ne since the current evaluated structure data date back to the early 90s in most of the cases, although a fair number of new measurements has been published since then.

4. Conclusions

The current status of the evaluations of the light systems identified as being of top priority for nuclear reactor criticality and safety studies was reviewed at the meeting. The list of actions from the previous meeting was updated and recommendations for measurements were also made. A group repository has been created to assist the evaluators in accessing experimental data and sharing information. All the evaluations delivered to the INDEN network will be made available to the user community from a dedicated IAEA website.

The next meeting will be held in Autumn 2020.

5. List of Actions/Tasks

Action/task	Responsible	Deadline	Present
Provide all data on n+^{9}Be to IAEA (N. Otuka) for compilation Send to P. Dimitriou-IAEA-NDS (reminder will be sent)	G. Hale, Zh. Cheng	Next INDEN meeting	 After meeting
For each light element system, subgroups will create an experimental data base and distribute it among each other and the whole group IAEA-NDS: create Onedrive account for INDEN-light elements for evaluators to upload/download their experimental data IJT: create sub-folders per compound on GitHub	All	Continuous	Continuous After meeting
		^{9}Be+n	
Push all of the reactions up to higher energies than in previous analyses up to 10 MeV	G. Hale	Next INDEN meeting	Continue-next INDEN meeting
Preliminary calculations for breakup at higher energies. Extract angular distributions from CDCC calculations.	I. Thompson	Next INDEN meeting	Continue – next INDEN meeting
Implement 3-body R-matrix theory. Use reduced R-matrix and alternative approaches	H. Leeb	Next INDEN meeting	Continue
Consider alternative approaches to break-up	M. Pigni	Next INDEN meeting	See new action below
Perform evaluation Provide final Rmatrix parameters and final evaluated cross sections to IAEA-NDS as a RAC output file and in ENDF-6 format	Zh. Chen	Next INDEN meeting	Done RAC output and Rmatrix parameters after ND2019 ENDF6 files – next INDEN meeting

Use RAC Rmatrix parameters to replicate RAC Reduced Rmatrix results	M. Pigni, P. Tamagno, I. Thompson, R. deBoer		Next INDEN meeting
$^{14}N+n$			
Get a good fit of the low energy region Evaluate E<3 MeV and produce covariances	R. deBoer	Next INDEN meeting	Continue up to 12 MeV Next INDEN meeting
Get a good fit at low energy and extend to higher energies as possible Re-evaluate E<3 MeV and produce covariances	G. Hale	Next INDEN meeting	Almost done up to 3 MeV (to include more data) – continue up to 12 MeV Next INDEN meeting
Collect all data at E> 3 MeV, incl. nat-N and upload onto Onedrive	G. Hale, R.J. deBoer, I. Thompson, M. Pigni		End of 2019
Analyse URR region using various methods	M. Pigni		Next INDEN meeting
Hauser-Feshbach fits at higher energies up to 20 MeV and produce covariance matrices	I. Thompson, H. Leeb, P. Dimitriou		Next INDEN meeting
Fit higher energy region	S. Kunieda	Next INDEN meeting	-
$^{15}N+n$			
Complete R-matrix analysis at low energies and then extend to higher energies	S. Kunieda	Next INDEN meeting	-
Contact S. Kunieda – request Rmatrix parameters to test and continue work Provide these parameters to M. Pigni, Zh. Chen to test their codes.	P. Dimitriou-IAEA-NDS, I. Thompson		After meeting
Analyse URR region using various methods	M. Pigni		Next INDEN meeting
Complete evaluation: Hauser-Feshbach fit and covariances	I. Thompson, H. Leeb, P. Dimitriou		Next INDEN meeting

^{16}O+n			
Provide normalization based on analysis of thick target data	S. Kopecky	Next INDEN meeting	Next INDEN meeting
Define relativistic corrections	G. Hale, I. Thompson	Next INDEN meeting	Done – see new action
Submit proposal for definition of relativistic kinematics and flag in ENDF-6 format to CSEWG meeting	G. Hale, I. Thompson		Nuclear Data week 2019
Improve evaluation of 2005	Zh. Chen	Next INDEN meeting	Continue
Finalize evaluation considering any new experimental information on normalization of (n,alpha) channel	G. Hale, M. Pigni		Next INDEN meeting
Demonstration of unified Bayesian evaluation	H. Leeb		Next INDEN meeting
^{23}Na+n			
Include differential cross sections and produce an ENDF6 file to share with everyone Consider Reduced R-matrix and HF for inelastic channels	P. Archier, P. Tamagno	Next INDEN meeting	Continue
High energy data	S. Kunieda	Next INDEN meeting	
Effect of deformation	I. Thompson	Next INDEN meeting	See new action on Pigni
Provide deformed OP parameters for Na-23 to P. Tamagno	M. Pigni		After meeting
Re-fit using B = -L	M. Pigni, P. Tamagno	Next INDEN meeting	Next INDEN meeting
Provide Rmatrix parameters to Z. Chen for testing with RAC	P. Tamagno		After meeting
$^{17,18}O$+alpha			
Share new (alpha,n) data with M. Pigni	R. deBoer		After meeting
Collaborate on evaluation of both isotopes	R. deBoer, M. Pigni		After meeting

ANNEX 1

Second Consultants' Meeting on

INDEN – International Nuclear Data Evaluation Network

On Light elements (2)

IAEA, Vienna, Austria

15 to 17 May 2019

Meeting Room VIC MOE 10

ADOPTED AGENDA

Wednesday, 15 May

08:30 – 09:00 **Registration (IAEA Registration Desk, Gate 1)**

09:00 – 09:30 **Opening Session**

Welcoming address (Arjan Koning, NDS Section Head)

Election of Chairman and Rapporteur

Adoption of the Agenda

09:30 – 17:30 **Progress Reports:**

1) n+^{14}N evaluation, G. Hale (LANL)
2) n+^{14}N evaluation and new data for ^{28}Si system, R. deBoer (Univ. Notre-Dame)
3) n+^{9}Be evaluation, Z. Chen (Tsinghua Univ.)
4) n+^{16}O and alpha+^{17,18}O, M. Pigni (ORNL)
5) Issues in n+^{9}Be evaluations, I.J. Thompson (LLNL)
6) The Evaluation process, H. Leeb (TUV)
7) R Matrix boundary conditions in low RRR of ^{23}Na, P. Tamagno (CEN Cadarache)

Coffee break(s) as needed

(12:30 – 14:00 Lunch break)

19:00 Dinner at a local restaurant (see separate information in folder)

ANNEX 1

Thursday, 16 May

09:00 – 18:00 **Round Table Discussion**

Open issues for:

- **n+Be-9;**
- **n+O-16;**
- **n+N-14,15;**
- **n+Na-23**
- **alpha+^{17,18}O**
- **Extending R-matrix to higher energies**
- **Treating Break-up channels**

- **How to proceed**

Friday, 17 May

09:00 – 12:00 **Round Table Discussion cont'd**

Drafting of Summary Report

12:30 **Closing of Meeting**

Coffee break(s) as needed

ANNEX 2

International Nuclear Data Evaluation Network (INDEN) Meeting on the Evaluation of Light Elements (2)

15 to 17 May 2019
IAEA, Vienna, Austria

Meeting Room VIC MOE 10

List of Participants

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ANNEX 3

International Nuclear Data Evaluation Network (INDEN) Meeting on the Evaluation of Light Elements (2)

15 to 17 May 2019
IAEA, Vienna, Austria

Meeting Room VIC MOE 10

Presentations

#	Author	Title	Link
1	I.J. Thompson	Optical R-matrix Methods	PDF
2	R.J. deBoer	^{15}N System	PDF
3	P. Tamagno	Improvement perspectives for ^{23}Na in the RRR	PDF
4	G. Hale	Recent LANL R-matrix work on n+^{14}N	PDF
5	I. Thompson	Issues in n+^{9}Be evaluations	PDF
6	M. Pigni	R-Matrix Evaluations for n+^{16}O and a+$^{17,18}O$ Reactions	PDF
	H. Leeb	Evaluation of nuclear data of light nuclear systems-some aspects	PDF

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