Symposium on Nuclear Data 2020

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Book of Abstracts

Contents

Facility / 1

Nuclear Data Activities in Nishina Center

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Nuclear Data Activities in Nishina Center

Facility / 2

Proposal of 1 A class deuteron single cell linac

NuclearPhysics2 / 3

Development of energy-degraded RI beam and expansion of nuclear reaction studies

Development of energy-degraded RI beam and expansion of nuclear reaction studies

NuclearPhysics1 / 4

Nuclear spectroscopy at KISS

Nuclear spectroscopy at KISS

NuclearPhysics1 / 5

Fission experiment with Es at JAEA tandem accelerator facility

NuclearPhysics2 / 6

Theoretical analysis of deuteron-induced reactions and development of deuteron nuclear database

Theoretical analysis of deuteron-induced reactions and development of deuteron nuclear database

Facility / 7

Nuclear data study for Accelerator Driven System at J-PARC

Nuclear data study for Accelerator Driven System at J-PARC

NuclearMedicine / 8

Production and Applications of Radioisotopes at RIKEN RI Beam Factory - Search for New Elements through Diagnosis and Therapy of Cancer -

Production and Applications of Radioisotopes at RIKEN RI Beam Factory - Search for New Elements through Diagnosis and Therapy of Cancer -

NuclearMedicine / 9

Measurements of production cross sections of medical radioisotopes via charged-particle induced reactions

Measurements of production cross sections of medical radioisotopes via charged-particle induced reactions

NuclearMedicine / 10

Development of Radioisotopes Production Method by Accelerator-based Neutron: Activity at Kyushu University 2020

Development of Radioisotopes Production Method by Accelerator-based Neutron: Activity at Kyushu University 2020

DeepLearning / 11

Deep Learning for Basic Science

Deep Learning for Basic Science

DeepLearning / 12

Nuclear data generation using machine learning

Nuclear data generation using machine learning

DeepLearning / **13**

Data-driven approaches for nuclear shell-model calculations

Data-driven approaches for nuclear shell-model calculations

DeepLearning / **14**

Exploration of automated data processing for mass production of nuclear data at RIBF

Exploration of automated data processing for mass production of nuclear data at RIBF

NuclearPhysics1 / **15**

Unified description of the fission probability for highly excited nuclei

Unified description of the fission probability for highly excited nuclei

NuclearPhysics2 / **16**

Isotope production in spallation reaction of 93Zr and 93Nb induced by proton and deuteron

Isotope production in spallation reaction of 93Zr and 93Nb induced by proton and deuteron

Tutorial / **17**

Introduction to Nuclear Reactor Theory

Tutorial / **18**

Roles and current status of reactor physics experiment in research reactors

Roles and current status of reactor physics experiment in research reactors

19

Opening/Welcome

20

Closing Remarks

Poster / **23**

Detection of Gamma Ray from Sort-Lived Fission Products at KUCA and KURNS-LINAC

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Quantification of radioactivity of fission products (FP) is very important for assessment of decay heat after shutdown of a core, etc. For such assessments, comprehensive data sets of fission yield and decay chain, such as JENDL/FPY&FPD-2011, have been developed. However, validation of each nuclide in such data sets has still been cumbersome. In this work, two detection techniques of FPs are studied to give data for such validation.
In order to characterize reactions occurred in nuclear fuel, gamma ray spectroscopy was conducted at Kyoto university critical facility assembly (KUCA). At KUCA, uranium (U)fuel of 93 wt% 235U enrichment was loaded in C-core. They were moderated and shielded by light water. The core power during the critical operation was 4.6 mW. Outside the tank of the core, a HP-Ge detector of 30 % relative efficiency was set and the gamma ray was measured. As the results, peak spectra of fission products such as 90, 95, 97Y, 90,90m,91Rb, 87,88Br, 136Te, etc. were detected although they were overwrapped by prompt gamma ray components. Due to the prompt components, the relative statistical accuracy was from 2 to 20 %. Thanks to the measurements during the critical operation, gamma rays of half-life shorter than 4 s was achieved.
Contrarily, 238U(n,g) gamma ray spectroscopy was conducted with the same HP-Ge for neutrons of thermal and resonance energy at the KU-LINAC-pulsed neutron source facility. The time of flight (TOF) of neutron was measured associated with beam pulse to identify the incident neutron energy. The repetition rate of the pulse was 50 Hz. In the TOF spectrum after the so called "thermal neutron peak", time-background region was identified. The gamma ray in the region out of phase of the beam pulse was considered emitted by decay of radioactive material of which half-life is longer than 20 ms. The measured peak structure was found fairly resemble to that of measured at KUCA.
The detection efficiency of the gamma rays at KUCA was calculated with MCNP-5. That at LINAC was experimentally determined. With the measured count rate and the efficiency, the gamma ray emission rate was deduced and compared against that calculated based on JENDL/FPY&FPD-2011. The ratio of the measured to the calculated value against each gamma ray by the two experiments show fairly resemble trend. That indicates the both experiments are promising to give reference data for validation of FP yield and decay data sets such as JENDL/FPY&FPD-2011.

Poster / **24**

Evaluation of Neutron Nuclear Data on Cobalt-59 for JENDL-5

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Cobalt (Co) is one of the structural materials in nuclear and accelerator facilities. It is contained in carbon steel and concrete as well as SUS304. ^{59}Co is only stable isotope of Cobalt. The nuclear data of ^{59}Co are considered to be important specifically for radioactivity estimation of ^{58,60}Co related to decommissioning of the facilities. JENDL-4.0 includes the nuclear data of ^{59}Co, which based the evaluation in 1988. Major revision was carried out at the JENDL-3.3 evaluation in 2001, followed by the covariance estimation in 2002. After the release of JENDL-3.3, many measured data for capture, (n,2n), (n,p), and (n,α) reactions have been published. Therefore, the reconsideration of nuclear data is required for JENDL-5.
The evaluation of ^{59}Co was divided into three energy regions: resolved resonance region, unresolved resonance region, and fast neutron energy region. In the resolved resonance region, the resonance parameters and scattering radius were taken from de Saussure et al. (1992). In the unresolved resonance region, the data of thick sample of de Saussure et al. were adopted, supplemented with the data of thin sample for large resonances. In the fast neutron energy region, the nuclear reaction model code CCONE was used to calculate cross sections, angular distributions and double differential cross sections. The evaluation was performed based on many types of measured data. The obtained results are in good agreement with the measured data and will be shown in the poster presentation.

DeepLearning / **25**

Nuclear data generation using machine learning

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We have developed a method to generate nuclear data using Gaussian process regression (GPR) [1], which is one of the machine learning techniques. This method generates nuclear data by treating measured data as the training data in machine learning. GPR is based on nonparametric Bayesian inference, the generated nuclear data are expressed as a predictive distribution including uncertainty information. In this presentation, the basics of the Gaussian process model, some examples of the application to nuclear data generation, and other related topics will be presented.

[1] H. Iwamoto, "Generation of nuclear data using Gaussian process regression", Journal of Nuclear Science and Technology, 50:8, 932-938 (2020).

NuclearPhysics2 / **26**

Theoretical analysis of deuteron-induced reactions and development of deuteron nuclear database

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Since deuteron is a weakly bound system consisting of a proton and a neutron, it easily breaks up and emits a neutron through interaction with a target nucleus. Utilizing this property, intensive neutron sources using deuteron accelerators have been proposed for not only science and engineering fields but also medical applications. For design studies of such facilities, accurate and comprehensive nuclear data of deuteron-induced reactions are indispensable.
Toward evaluation of deuteron nuclear data, we have developed a code system dedicated for deuteron-induced reactions, called DEURACS. In DEURACS, breakup processes of incident deuteron are taken into account. DEURACS was so far successfully applied to analyses of production of nucleons, composite particles up to A = 4, and residual nuclei. In this talk, we will present the results of these analyses and discuss how important it is to consider the breakup processes for accurate prediction of deuteron-induced reactions.
Moreover, we have recently developed JENDL/DEU-2020, a deuteron nuclear database for Li-6,7, Be-9, and C-12,13 up to 200 MeV. DEURACS was employed for evaluation of JENDL/DEU-2020. Validation of JENDL/DEU-2020 was carried out by simulation with the Monte Carlo transport codes. As a result, the simulation using JENDL/DEU-2020 reproduced the measured thick-target neutron yields better than both simulations using the deuteron sub-library of TENDL and the reaction models implemented in the PHITS code. These validation results will also be presented.

Poster / **27**

Experimental plan for displacement damage cross sections using 120-GeV protons at FNAL

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To predict the operating lifetime of materials in high-energy radiation environments at accelerator facilities, Monte Carlo codes such as PHITS, MARS, and FLUKA are used to calculate the number of displacements per atom (dpa) related to the number of Frenkel pairs. The Norgertt–Robinson–Torrens (NRT) model has been widely used to predict the number of "initial" Frenkel pairs (NRT-dpa). For more accurate estimation of the actual damage production, athermal-recombination-corrected displacement damage (arc-dpa) was proposed, recently. For the validation of codes, it is necessary to measure displacement cross-sections of metals in relation to changes in electrical resistivity at cryogenic temperature (around 4 K) where the recombination of Frenkel pairs by thermal motion is well suppressed. The comparison between the experimental data and calculated results for proton irradiation with energies from 0.1 to 30 GeV indicates that the arc-dpa results are good agreements with the experimental data and the NRT-dpa results are larger than the data by a factor of around three.

In this presentation, we introduce our experimental plan for displacement cross sections with 120-GeV protons at Fermilab Test Beam Facility (FTBF) in Fermi National Accelerator Laboratory (FNAL). Experiments will be performed at the M03 beam line high rate tracking area in FTBF for the US fiscal year 2022 (October 2021 – September 2022). For the preparation of experiments, we developed the sample assembly with four wire sample of Al, Cu, Nb and W with 250-μm diameter and 4-cm length.

Annealing under vacuum condition (~10^{-4} Pa) was performed by heating an Al sample at 840 K for 30 minutes, a Cu sample at 1289 K for 30 minutes, a Nb sample at 1923 K for 15 minutes, and a W sample at 2473 K for 15 minutes, respectively. The sample assembly will be maintained at around 4 K by using a Gifford–McMahon (GM) cryocooler in a vacuum chamber. Then, changes in the electrical resistivity of samples will be obtained under 120-GeV proton irradiation. Recovery of the accumulated defects through isochronal annealing, which is related to the defect concentration in the sample, will also be measured after the cryogenic irradiation.

This work was supported by JSPS KAKENHI Grant Number JP19H02652.

Poster / **28**

Theoritical analysis of the fission process by ^{258}Md

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It has been shown that fission has multiple modes, characterized by mass asymmetric fission and mass symmetric fission[1]. In neutron-rich heavy element region,it is argued that several fission modes coexist, with a significant change of their yields in accordance with the number of neutrons contained in the fissionig nucleus. A typical example is found in the isotope dependence of fission for fermium isotopes.
For Fm, the dominant mode transitions from the asymmetric splitting for ^{257}Fm to the symmetric for ^{258}Fm[2].
This transitions was interpreted as due to the lowering of the fission barrier for symmetric fission, and the becoming energy advantage fission path of symmetric fission then asymmetric fission.
It's important to know of the potential energy surface structure and nuclear's deformation process to understand fission mechanism in neutron-rich heavy element region[3].
^{258}Md, which is the target of this work, is located near the boundary line where the transition from mass asymmetric fission to mass symmetric fission is expected to occur, and in recent years, the Japan Atomic Energy Agency has obtained the world's first fission data. As a result of data analysis, it shown that the mode of mass symmetric fission (superlong-mode) and the mode of asymmetric fission (standard-mode) coexist.
In this work, we compared the calculation using the fluctuation dissipation model(Langevin calculation)[4] with the experimental data, and considered the characteristics of the fission mode shown by the experimental data.

Reference

[1] U. Brosa, S. Grossmann, and A. Muller, Phys. Rep. 197,167 (1990).
[2] D.C. Hoffman et al., Phys. Rev. C, 21, 1980 (637)
[3] Y. Miyamoto et al., Phys. Rev. C, 99, 051601(R) (2019).
[4] S. Tanaka, Y. Aritomo, Y. Miyamoto, K. Hirose, and K. Nishio PRC 100, 064605 (2019).

NuclearPhysics1 / **29**

Unified description of the fission probability for highly excited nuclei

Authors: Hiroki Iwamoto[1]; Shin-ichiro Meigo[2]

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Various spallation reaction models have been developed for the use of neutronic and shielding design of high-energy accelerator facilities such as J-PARC and ADS. However, their complicated theory for the de-excitation process has made improving their prediction accuracy difficult. In particular, it has been pointed out that the conventional models underestimate the yield of the spallation products produced from the fission reaction. This work has thus aimed to model the probability was described using a simpler, systematic expression, and then confirmed to predict fission cross sections for various incident energies and target nuclei with improved accuracy [1]. In this presentation, we will present a description of our model and research results.

[1] H. Iwamoto, S. Meigo, "Unified description of the fission probability for highly excited nuclei", Journal of Nuclear Science and Technology, 56:2, 160-171 (2020).

NuclearPhysics1 / **30**

Nuclear spectroscopy at KISS / KISS□□□□□□

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For nuclear spectroscopy in the vicinity of N=126 and U-238, we have developed KEK Isotope Separation System (KISS), which is an argon-gas-cell-based laser ion source combined with an on-line isotope separator, installed in the RIKEN Nishina center [1]. The nuclei around N = 126 are produced by multi-nucleon transfer reactions (MNT) [2] of Xe-136 beam (10.75 MeV/A) impinging upon a Pt-198 target. The KISS facility has a detector station for beta-gamma spectroscopy and a MRTOF system for precise mass measurement. By using these devices, we have successfully performed beta-gamma spectroscopy of Os, Ta [3], and Re isotopes for the half-life measurements and study of beta-decay schemes, and in-gas-cell laser ionization spectroscopy of Pt, Ir, and Os isotopes for evaluating the magnetic moments and the trend of the charge-radii (deformation parameters).
In the presentation, we will report the present status of KISS, experimental results of nuclear spectroscopy in the heavy region, and future plan of KISS activities.

[1] Y. Hirayama et al., Nucl. Instrum. Methods B 353 (2015) 4.; B 463 (2020) 425.
[2] Y.X. Watanabe et al., Phys. Rev. Lett. 115 (2015) 172503.
[3] P. Walker et al., Phys. Rev. Lett 125 (2020) 192505.

Poster / **31**

SCALE6.2 ORIGEN library produced from JENDL/AD-2017

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Oak Ridge National Laboratory released the SCALE6.2 code [1] in 2016 (the latest version is SCALE6.2.4).
The ORIGEN code [1] in SCALE6.2 is completely different from the ORIGEN-S code [2] until SCALE6.0 [2].
1) ORIGEN uses one group cross section data generated from a specified neutron spectrum and a

multigroup activation library with the COUPLE code [1], not three group cross section data with a typical neutron spectrum.
2) The input format of ORIGEN is easy to use and understand.
3) It is expected that the calculation accuracy improves because ORIGEN uses one group cross section data generated from neutron spectra in all calculation points.
4) The calculation time of ORIGEN including COUPLE is at most about twice of that of ORIGEN-S even for 200 groups.
We expect that ORIGEN in SCALE6.2 will be mainly used for activation calculations in nuclear facility decommissioning. Thus we produced a SCALE6.2 ORIGEN library from JENDL Activation Cross Section File for Nuclear Decommissioning 2017 (JENDL/AD-2017) [3] with the AMPX-6 [4] in order to popularize JENDL/AD-2017 widely. The processing conditions are as follows.
- Temperature : 300 K
- Group structure : 200 groups (the same as one of libraries attached in SCALE6.2)
- Weight function : Maxwell+1/E+Fission spectrum + 1/E (above 10 MeV)
- Infinite dilution
We tested the SCALE6.2 ORIGEN library of JENDL/AD-2017 with the JPDR decommissioning data [5], which demonstrated the library had no problem.

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[2] (Ed.) W.A. Wieselquist, R.A. Lefebvre, M.A. Jessee, "SCALE Code System," ORNL/TM-2005/39 Version 6.2.4, Oak Ridge National Laboratory (2020).
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Poster / **32**

Nondestructive Determination of Water Content in Concrete Using Am-Be Neutron Source - Experimental Verification -

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A new nondestructive measurement technique has been developed to evaluate the amount of water in concrete. A concrete wall is irradiated with fast neutrons to activate a gold foil set on the concrete. By evaluating in advance the relation of the gold activity and water content by calculations, we can determine the water content in the concrete, the water content of which is not known. In this study, to validate the present technique experiments were performed with concrete samples having different water contents, which were made from only cement and water. It was confirmed from the experiments that water content could be estimated by the present nondestructive measurement technique though the system is still simple with cement and water. Now we are examining the validity for concretes made from cement, water and sand.

Poster / **33**

Development of Absolute Epi-thermal and Fast Neutron Flux Intensity Detectors for BNCT

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BNCT is a promising cancer therapy which kills tumor cells while suppressing exposure dose to normal tissues. Normally, the neutron field of BNCT, which is produced by a nuclear reactor or an accelerator-based neutron source, has an energy distribution spreading within thermal, epi-thermal and fast neutron regions. Because epi-thermal neutrons are generally used for BNCT, we must measure the epi-thermal neutron flux intensity to evaluate the therapeutic effect and patient's exposure dose. In addition, we also have to measure the fast neutron flux intensity to evaluate the exposure dose that may be harmful to the human body. However, it is quite difficult to measure such intensities directly and accurately because there is no suitable neutron spectrometer and no activation material covering epi-thermal or fast neutrons separately. The objective of this work is hence to develop new detectors to precisely measure the absolute integral flux intensities of epi-thermal and fast neutrons.
An epi-thermal neutron detector we develop controls its sensitivity by using cadmium and polyethylene. A fast neutron detector controls by using cadmium, B4C and polyethylene. The shape of the epi-thermal neutron detector is a cube, each side of which is 5.52 cm covered with a cadmium sheet. However, the epi-thermal neutron detector is a little sensitive to fast neutrons. To clarify the fast neutron contribution, we develop the fast neutron detector. To extract only fast neutrons, the fast neutron detector consists of two sub-detectors, and the fast neutron intensity is estimated by making difference of the two sub-detectors. The shape of one of them is a cube covered with polyethylene with a side of 4.4 cm and that of the other is a cube covered with B4C with a side of 4.6 cm. Moderated neutrons are measured by activation reaction of 71Ga (n, γ) 72Ga of a GaN foil positioned at the center of the detector. Design calculations were carried out by MCNP5.
After fabricating the detectors, in order to test the performance of the epi-thermal and fast neutron detectors, verification experiments were conducted at KUR, Kyoto University and FNL facility, Tohoku University, respectively.
As the result, the epi-thermal neutron flux intensity could be measured with an error of 3.9 % by correcting the high energy neutron contribution with the calculated value. The fast neutron flux intensity could be measured accurately, that is, the experimental and calculated values agree well within the error range.

Poster / **34**

Study on characteristics of neutron and γ-ray fields at compact neutron source RANS-II facility by simulation by the PHITS code

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RIKEN Accelerator driven compact Neutron Source-II (RANS-II) based on the ^{7}Li(p, n)^{7}Be reaction for neutron production with 2.49 MeV proton beam, has been under beam commissioning to demonstrate specific performance of the system. RIKEN has a prospect of realizing novel non-destructive

neutron inspection for infrastructures with the use of RANS. As prominent characteristics, RANS-II has the maximum neutron energy of 0.8 MeV, which is lower than that of 5 MeV at RANS based on the ^{9}Be(p, n)^{9}B reaction with 7 MeV proton injection, and gives extremely forward favored angular distribution with respect to the proton beam direction. Also, it should be emphasized that RANS-II system is installed in a relatively small space isolated by concrete shield with boron containment. Accordingly, there should be quite large differences in neutronic performances between RANS-II and RANS in terms of neutron spectrum and angular distributions. In preparation of experiments at RANS-II, the simulation of radiation fields for neutron and γ-ray in RANS-II experimental hall plays a critical important role for designing experimental set-up in low background.

Then, we have performed simulations to characterize radiation fields of RANS-II The cross section libraries implemented in PHITS are utilized in neutron and γ-ray transportations. Several important conditions of RANS-II modeling are as follows:
□ The lithium (Li) target is made by depositing thin Li layer of about 100 μm on a 5 mm thick Cu substrate cooled by water in the target station.
□ The target station with about 90 cm side cubic shape, configures five layers; polyethylene, lead, borated polyethylene, lead and iron, to reduce the radiation leakage.
□ There is a hole with a 15 $\times$ 15 cm^2 cross section in the forward direction.
□ The experimental hall has dimensions of 14 $\times$ 5.5 $\times$ 3.0 m^3 surrounded by floor and wall made of concrete (partly the borated concrete) and polyethylene ceiling.

As a result, the neutron and γ-ray distribution spreads widely in the experimental hall due to the wide openings in the target station. The scattered radiation could be the major contributor to the background of experiments. On the other hand, primary neutrons produced at the target are shielded reasonably by the target station. To design effective collimators for high quality beam extraction, we have calculated neutron beam profiles with parameters of collimator diameters and materials. It is shown that there is an optimized collimator configuration to extract suitable beam.

Poster / **35**

Neutron Filtering System for Fast Neutron Cross-Section Measurement at ANNRI

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The Accurate Neutron-Nucleus Reaction Measurement Instrument (ANNRI) beamline in the Materials and Life Science (MLF) experimental facility of the Japan Proton Accelerator Research Complex (J-PARC) provides the most intense neutron beam available in the world and was carefully designed to precisely measure neutron-induced reactions using the time-of-flight (TOF) method. Currently, the J-PARC accelerator is operated in double-bunch mode in which two 0.1 μs wide proton
bunches are shot into a spallation target with a time difference of 0.6 μs. Because of this, events detected with a specific time-of-flight (TOF) have two different energies as they could have been originated from each of the two different proton pulses. This is particularly important in the continuum
region (keV region) where the cross section can be expressed as a smooth averaged function. In this region, it is impossible to separate the contribution from each proton pulse and, hence, this mode introduces serious ambiguities into the cross-section measurements.

A neutron filtering system has been designed in order to bypass the double-bunched structure of the neutron beam as part of the "Study on accuracy improvement of fast-neutron capture reaction data of long-lived MAs for development of nuclear transmutation systems" project. Filter materials were introduced into the ANNRI beamline in order to produce quasi-monoenergetic neutron filtered beams. The materials suitable to be used as filters present sharp minima in the total cross-section due to the interference between the potential and s-wave resonance scattering. Neutrons having that energy can be transmitted through the filters and, therefore, produce a quasi-monoenergetic beam. Filter assemblies consisting of Fe with a thickness of 20 cm, and Si with thicknesses of 20 cm and 30 cm of Si were used separately to produce filtered neutron peaks with energies of 24 keV (Fe) and of 54 and 144 keV (Si).

In this study, the characteristics and performance of the neutron filtering system at ANNRI using Fe and Si determined from both measurements and simulations are presented. The incident neutron flux was analyzed by means of transmission experiments using Li-glass detectors and capture experiments using a boron sample which was measured with a NaI(Tl) spectrometer. Moreover, simulations using the PHITS code were performed in order to determine the energy distribution of the integrated filtered peaks and assess the reliability of experimental results. Finally, preliminary results of the capture cross section of ^{197}Au are presented using the NaI(Tl) spectrometer alongside the neutron filtering system.

Poster / **36**

The origin of correlation between mass and angle in quasi-fission

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Mass-angle distribution (MAD) measurement of heavy and superheavy element fragmentation reactions is one of the powerful tools for investigating the mechanism of fission and fusion process. MAD shows a strong correlation between mass and angle when the quasi-fission event is dominant. It has characteristic that appears diagonal correlation as long as the quasi-fission event is dominant. This diagonal correlation could not be reproduced in previous our model before the introduction of the parameters.
In this study, we systematically evaluate the uncertainty model parameters contained in our model and clarify those model parameters to reproduce the diagonal correlation that appears in MAD. Using a dynamical model based on the fluctuation diffraction theorem that employs Langevin equations, we calculate the mass angle distribution and mass distribution of the four reaction systems 48Ti + 186W, 34S + 232Th, 48Ti + 208Pb, and 28S + 238U, which are dominated by quasi-fission. We were able to clarify the effects of uncertain model parameters on the mass angle distribution and mass distribution. In addition, we identified the values of model parameters that can reproduce the correlation between mass and angle. As a result, it found that the balance of tangential friction and moment of inertia values is important for the correlation between mass and angle.

NuclearPhysics2 / **37**

Isotope production in spallation reaction of 93Zr and 93Nb induced by proton and deuteron / 93Zr□□93Nb□□□□□□□□□□□□□□□□□□□□□□□

Author: Kieta / □□ Nakano / □□[1]

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Nuclear transmutation technology has been attracting attention as a method for treating high-level radioactive waste. One of the candidates is the spallation reaction using high-energy particles, especially for the nuclides with relatively small neutron-capture cross sections such as long-lived fission

product (LLFP) ^{93}Zr. The accumulation of nuclear reaction data and the development of nuclear reaction models based on the data are indispensable for the accurate prediction of the amount of conversion of ^{93}Zr to stable nuclides and/or short-lived nuclides and residual long-lived nuclides after the transmutation. Therefore, under the ImPACT program (Period: 2014 – 2018), we have measured isotope-production cross sections in proton- and deuteron-induced spallation reactions on LLFP ^{93}Zr and adjacent nuclide ^{93}Nb at RIKEN RIBF.

In the experiment, a ^{93}Zr beam at 50 MeV/nucleon and a ^{93}Nb beam at 113 MeV/nucleon were produced by inflight-fission of ^{238}U. These beams were irradiated to secondary targets containing hydrogen and deuterium to induce spallation reactions, and the product yields were analyzed by ZeroDegree Spectrometer to determine the product cross sections. The results are compared with the nuclear reaction models.

Poster / **38**

Experimental program of nuclear data for accelerator-driven nuclear transmutation system using FFAG accelerator – First subprogram: spallation neutron measurement

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For accurate prediction of neutronic characteristics for accelerator-driven system (ADS) and a source term of spallation neutrons for reactor physics experiments for the ADS at Kyoto University Critical Assembly (KUCA), we have launched an experimental program to measure nuclear data on ADS using the Fixed Field Alternating Gradient (FFAG) accelerator at Kyoto University (Period: October 2019 – March 2023). This program is composed of two subprograms, focusing on two nuclear reaction mechanisms, (1) spallation reactions and (2) high-energy fission, for incident proton energies from several tens of MeV to 100 MeV. In the first subprogram, we will measure neutron energy spectra of double-differential cross-sections (DDXs) and thick-target neutron-yields (TTNYs) for several targets (i.e. Pb, Bi, Fe, etc.); in the second subprogram, fission fragment mass number induced from heavy targets (i.e. Pb, Bi) will be measured. In this poster session, the present status of the first subprogram will be presented.

Poster / **39**

Estimation of Flux and Residual Radioactivity for the COMET Phase-I Experiment

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COherent Muon to Electron Transition (COMET) is an experiment at J-PARC, which will search for coherent neutrino-less conversion of a muon to an electron in muonic atoms. The experiment will be carried out in two steps: Phase-I and Phase-II. In the Phase-I experiment, 3.2 kW 8 GeV proton beam irradiates a 70-cm long graphite target to produce negative pions. The negative pions are captured in the magnetic field and delivered to pion-decay and muon-transport sections. The Phase-I experiment aims to detect the $\mu^{-}e$ conversion events and measure the beam-related background events for the Phase-II experiment. Now, it has been planned that the maintenance by radiation workers would be conducted after the 150-day operation and the following 180-day cooling. It is necessary to evaluate the residual radiation dose for the safety of the workers during the maintenance. On this study, we calculated fluxes of neutron, photon, proton and other charged particles in the beam room during the beam operation and the residual activity after the cooling time by using Monte Carlo simulation code PHITS version 3.22 and DCHAIN-PHITS version 3.21. The calculation results show that the design of components around the target and beam dump needs to be improved to reduce the radioactivities after the cooling time.

Poster / **40**

Neutron emission during fission process by dynamical model/

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Through joint research by the Japan Atomic Energy Agency (JAEA) and Kindai University, it has become clear that the yield distribution of fission products (fission fragments) changes significantly depending on the neutrons emitted from the compound nucleus. In the so-called multichance fission (MCF) concept, fission takes place after emitting several neutrons. This revives the shell structure of a nucleus responsible for mass-asymmetric fission, thus change the fission-fragment mass distribution. The effect of MCF is particularly important to treat high energy fissions, such as ADS system which transmute long lived minor actinide nucleus by fission. Until now, the calculation was performed by combining the fission model calculation (Langevin equation) and a statistical model using a code such as GEF [1,2]. However, this method does not introduce neutron emission during the fission process.
In the present work, we have introduced the neutron evaporation during fission process in the Langevin model. For this, a change of potential energy in each neutron evaporation step is treated. Fission fragment mass distribution of $^{236-238}$U,$^{238-240}$Np, and $^{240-242}$Pu were calculated in the initial excitation energy range of E*=15-55MeV. The results show that the double-peak structure is maintained even at the highest excitation energies, and successfully reproduced the experimental data taken at the JAEA tandem facility [3-5].

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NuclearMedicine / **41**

Production and Applications of Radioisotopes at RIKEN RI Beam Factory - Search for New Elements through Diagnosis and Therapy of Cancer -

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At RIKEN RI Beam Factory (RIBF), we have been developing production technologies of radioisotopes (RIs) and conducting RI application studies in the fields of physics, chemistry, biology, engineering, medicine, pharmaceutical and environmental sciences [1]. With light- to heavy-ion beams from the AVF cyclotron, we produce more than 100 RIs from 7Be (atomic number Z = 4) to 262Db (Z = 105). Recently, we often produce 211At in the 209Bi(α,2n)211At reaction for nuclear medicine [2]. RIs of a large number of elements (multitracer) are simultaneously produced from metallic targets such as natAg, 197Au, and 232Th irradiated with a 135-MeV nucl.−1 14N beam from RIKEN Ring Cyclotron [3]. The multitracer is useful to trace the behavior of many elements simultaneously under an identical experimental condition. We installed a gas-jet transport system to the GAs-filled Recoil Ion Separator (GARIS) as a novel technique for superheavy element chemistry [4]. Long-lived isotopes of 261Rfa,b, 262Db, 265Sga,b (Z = 106), and 266Bh (Z = 107) useful for chemistry studies were produced in the heavy-ion induced reactions on a 248Cm target and their decay properties were investigated in detail using a rotating wheel apparatus for α and spontaneous fission spectrometry [5–8]. Thanks to the pre-separation of Sg atoms with GARIS, chemical synthesis and gas-chromatographic analysis of the first organometallic compound of SHEs, Sg(CO)6 were conducted under a large international collaboration lead by the Univ. Mainz and GSI groups [9].

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Poster / 42

Optimization of Activation Detector for Benchmark Experiment of Large-angle Elastic Scattering Reaction Cross Section by 14MeV Neutrons

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<span> The elastic scattering reaction cross section data commonly show smaller in backward angles compared to those of forward angles when the energy of the incident neutron is high. However, in high neutron flux field, such as fusion reactor, the back-scattering reaction cross section is becoming not negligible on the calculation result. Until now, there were differences reported between experimental and calculated values of neutron benchmark experiments using a DT neutron source, which focused on back-scattering phenomena like a gap streaming experiment. For this problem, the author's group developed a benchmark method for large-angle scattering cross sections and has carried out experiments with an iron sample for the last few years. The benchmark method was

successfully established based on the activation of Nb foil having a large activation cross section at around 14 MeV.

<span> We are now planning to carry out benchmark experiments for other fusion structural materials such as tungsten, lead, F82H and so on. And in the next step, we aim to consider benchmark experiments for lighter materials like Li, Be, B, C, N and O. In this case, the energy of neutrons generated by backscattering is low. Especially for Li, being one of the most important materials in fusion reactor, back-scattering neutrons cannot be captured by Nb foil due to the high threshold energy of ⁹³Nb(n,2n) reaction.

<span> In this study, to solve this problem, we examined possible nuclides having a low activation reaction threshold energy, so that it can react with low energy neutrons generated by the backscattering of Li, and simultaneously having not too low threshold energy, so that the influence of room-return neutrons can be eliminated properly. The optimization was achieved by calculating and comparing the number of counts for all the possible reactions of all the existing stable nuclides considering appropriate irradiation and measuring times. The activation reaction cross section data were taken from JENDL/AD-2017.

<span> As a result, we have found that ¹⁸¹Ta(n,2n) was the most suitable reaction giving us the largest number of counts in an acceptable short experimental time. Then experiments were carried out to confirm whether ¹⁸¹Ta(n,2n)<sup> cross section was consistent with the nuclear data.

Poster / **43**

Production cross sections of 175Hf in the natLu(p,xn) and natLu(d,xn) reactions

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A long-lived isotope of Hf, 175Hf (T1/2 = 70 d), is useful for basic studies for rutherfordium (Rf, Z = 104). This isotope is producible in no-carrier-added form in the proton- and deuteron-induced reactions on natLu. However, excitation functions of these nuclear reactions have been scarcely studied. In this work, we measured the excitation functions of the natLu(p,xn)175Hf and natLu(d,xn)175Hf reactions up to 18-MeV proton and 24-MeV deuteron energies using a stack-foil technique and a γ-ray spectrometry. We performed these experiments at RIKEN and Institute for Nuclear Research (ATOMKI). The target stacks of Ta/Lu/Ti and Lu/Ti foils were irradiated for 2 h with proton or deuteron beams of approximately 180–240 nA. After the irradiation, each foil was subjected to γ-ray spectrometry with Ge detectors. We noticed that the half-life of 173Hf is slightly longer than that adopted in the current nuclear database. Therefore, we measured a precision half-life of 173Hf in a separate experiment. In this work, we could measure the excitation functions of the natLu(p,xn)173,175Hf and natLu(d,x)173,175Hf, 173,174m,174g,176m,177m,177gLu reactions. Thick-target yields of 175Hf were also deduced from the measured excitation functions. The yields are 0.47 MBq/μA·h at 17.2-MeV proton and 2.0 MBq/μA·h at 24.0 MeV deuteron. We determined the half-life of 173Hf to be 24.176 ± 0.012 h which is 0.58 ± 0.10 h longer than that in the database.

Tutorial / **44**

Introduction to Nuclear Reactor Theory

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In this tutorial, I would like to briefly introduce the nuclear reactor theory.
Please keep in mind that the whole nuclear fission power plant is a too complicated system, thus it is not easy to understand the multi-physics in the nuclear power plant. From the overall view of the nuclear power plant, thermal energy via fission in the nuclear reactor core is utilized to finally generate electricity.

To appropriately design and control the nuclear reactor, we must understand and predict the behavior of neutrons and nuclear reactions. For this purpose, reactor physics has been developing as an engineering science to systematize the relevant knowledge.
The effective neutron multiplication factor k_{eff} is an important core-characteristics parameter to judge whether the nuclear reactor core is subcritical, critical, or supercritical. The k_{eff} value indicates the ratio of fission-induced neutron-production to neutron loss (absorption or leakage). In the nuclear reactor, fission power is constantly maintained at the "critical state" of the fission chain reaction.
To roughly predict the neutron multiplicity by the fission chain reaction, the point kinetics equation is simple and useful. If we think of a point kinetic equation without delayed neutrons, this equation is similar to that of the Susceptible-Infected-Removed (SIR) model, which is used in the epidemiology. However, if there were no delayed neutrons in the fission event, we could never control the fission chain power reaction. In other words, the delayed neutron plays an important role to control the fission power in the actual nuclear reactor core by humans.

In order to predict the macroscopic and average behavior of neutrons, the Boltzmann neutron transport equation is utilized as the master equation. Note that the rigorous Boltzmann equation is too complicated to obtain the solution. At the dawn of the nuclear age, scientists and engineers simplified the prediction model based on ingenious approximations such as diffusion and Fermi-age theories. Recently, as computing performance and computational science improve, we can accurately solve the numerical solution of the Boltzmann equations as much as possible. At the end of this tutorial, I will briefly explain unique numerical analysis methods, which have been developed and utilized in the field of reactor physics. Through this tutorial, I would like to promote understanding that the nuclear data such as microscopic nuclear cross section are essential input data for the reactor physics analysis.

Poster / 45

Development of Evaluation Method of Uncertainty of Radioactivity by Propagating Nuclear Data Covariance for Clearance Verification in Decommissioning of Nuclear Power Plants

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To optimize disposal of low-level radioactive waste originating from decommissioning of nuclear facilities, required are 1) reliable assessment of radioactivity level by calculation and measurement and 2) a good estimate of the uncertainty of those results for the classification of radioactive waste. In order to improve the reliability of the calculations in clearance verification, we established a procedure of estimating the uncertainty of radioactivity concentration due to that of nuclear data. For that, we estimated covariance of neutron cross sections of important nuclides that account for over 90 % in ΣD/C of concrete material and carbon steel by employing a propagation of uncertainties

in the resonance parameters and statistical model parameters with nuclear data code group T6. Here, D stands for radioactivity concentration, and C stands for clearance level. Then, we developed a new method to calculate uncertainty of radioactivity with Total Monte Carlo method by connecting randomly perturbed endf-format files generated by the T6 calculation to a cross section processing code NJOY and an activation calculation code ORIGEN2 using ORLIBJ40, a set of cross section library based on JENDL-4.0. It was concluded that the uncertainty of the radioactivity due to that of nuclear data for nuclides which dominate the ΣD/C is sufficiently small, and the main factor of uncertainty of radioactivity comes from that of the neutron flux.

Poster / **47**

Development of a neutron detector for nuclear data measurement using high-intensity neutron beam

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Highly precise neutron nuclear data is required in nuclear transmutation research of long-lived minor actinides (MA) in nuclear waste. In neutron capture cross section measurement, monitoring the number of the incident neutrons is necessary. However, in measurement with J-PARC/ANNRI, direct neutron monitoring system has not been employed. To make measurement with ANNRI more robust, an additional neutron beam monitor is required. Conventional neutron detectors cannot be used as a beam monitor at ANNRI because of two reasons, high counting rate environment and gamma-flash. The neutron flux at ANNRI is one of the highest in the world. Gamma-flash, an intense gamma-ray burst produced when the proton beam pulse bombards the spallation target, can paralyze a detector generally used in nuclear data measurement. In general, a semiconductor detector or an inorganic scintillator, which is adopted for a neutron detector, has relatively longer response time and is unsuitable for beam monitoring at ANNRI.
Therefore, a combination of a thin plastic scintillator and a ^{6}LiF foil was selected as a detection system, whose fast response enabled detecting neutrons at a high counting rate. Low gamma ray sensitivity of a thin plastic scintillator allows measuring fast TOF region without count loss or detector paralysis. The geometry of the ^{6}LiF foil, the plastic scintillator, and photomultiplier tube (PMT) was designed. The optimal thickness of the ^{6}LiF foil was determined with simulation codes, SRIM and PHITS. A ^{6}LiF foil was made by vacuum deposition method. A test detector system was built to study the feasibility of the method.
The detector system was tested under the high neutron irradiation condition at J-PARC /ANNRI. A neutron TOF spectrum was successfully measured without significant count loss or detector paralysis. A neutron energy spectrum was driven from difference of TOF spectrum with and without ^{6}LiF. The neutron spectrum was compared with a past neutron spectrum and good agreement was obtained. Statistic error was 0.68 % at 6.0 meV even though measurement times in this study was pretty short (~11 min).

Poster / **48**

Study of the fission path energy of U-236 using microscopic mean-field model

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Microscopic mean-field model is one of strong methods for providing and improving fission-related nuclear data.
It needs appropriate effective interaction, but there is no effective interaction designed for fission path.
In order to tackle this problem, we calculate the U-236 potential energy surface with respect to the elongation of a nucleus and the mass asymmetry with existing Skyrme effective interactions.
We report the energy characteristics of potential energy surface and important parts for correcting the fission barrier.

Tutorial / **49**

Roles and Current Status on Reactor Physics Experiment in Research Reactors

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Nuclear reactors are mainly categorized as two parts: a commercial power reactor; a test and research reactor for generating electric power and conducting research of radiation utilization, respectively. Of two reactors, main roles of the test and research reactor are to conduct the research and development of nuclear engineering and radiation detection fields with the use of radiation, including neutron, alpha-ray, beta-ray, gamma-ray, and so on, and to contribute to the education of young generation. Many research reactors are importantly equipped with experimental facilities to research objectives, including irradiation holes, neutron beams and spectrum shift changers, although the commercial reactors insufficiently meet the items. An index of classification of research reactors is to provide a wide range of neutron spectrum and thermal reactor power, with the combined use of nuclear fuel, moderators, reflectors and coolant materials by varying the kinds, the geometries, the configurations and the utilization purposes.
Another part of the presentation is to contain the feasibility study on the accelerator-driven system (ADS) conducted for nuclear transmutation analyses with the combined use of the solid-moderated and solid-reflected core and the fixed-field alternating gradient (FFAG) accelerator, in the Institute for Integrated Radiation and Nuclear Science, Kyoto University. Through the experimental analyses by MCNP with major nuclear data libraries (JENDL-4.0. ENDF/B-VII.1, JENDL/HE-2007 and JENDL/D-99), static and kinetic parameters of reactor physics are interestingly revealed for nuclear transmutation of minor actinides (Np-237 and Am-241) and uncertainty quantification of a coolant material (lead and bismuth), with respect to ADS. Additionally, experimental education programs for domestic and overseas students conducted at the Kyoto University Critical Assembly are introduced in the presentation.

Poster / **50**

The fission fragments of neutron-rich nuclei by the Langevin method toward application to r-process calculations

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Nuclear fission plays an essential role in nucleosynthesis by the rapid-neutron-capture process (r-process), which is a cosmic origin of heavy elements beyond iron. For very neutron-rich environments in neutron star mergers, the strong r-process can be achieved, and the nucleosynthesis path goes into the trans-uranium region. In such conditions, fission is important to shape the r-process abundances due to fission recycling, which determined the termination of the r-process in the heavy nuclei region. Besides abundance prediction, fission is also a key role as the main heating source of kilonovae, which are electromagnetic transients of neutron star mergers. A sign of fission heating may have been observed in the light curve of the kilonova associated with the gravitational wave, GW170817. The precise understanding of fission becomes much crucial in the era of gravitational astronomy.

In this study, we calculate the fission-fragment mass distributions of very neutron-rich nuclei, which are important for the nucleosynthesis calculations of the r-process, but experimental nuclear data is not available. We adopt the Langevin method [1], widely adopted in the study of low-energy fission in the past few years. We found that the calculated mass distributions for uranium, of which Z distribution is calculated with UCD (unchanged charge distribution assumption), well reproduce experimental data in JENDL (^{232}U to ^{238}U) [2]. We also found that the fission distribution changes from the two peak feature (asymmetric fission) to the one-peak (symmetric fission) as the neutron number increases. The confirmation by future experiments would be desirable for these theoretical predictions to develop a complete theory set of fission distributions applicable to r-process nucleosynthesis simulations.

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Poster / 51

Comparison of photon spectra emitted from fuel debris using different decay data libraries

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We require reliable nuclear data that can appropriately evaluate the radiation characteristics of fuel debris for the purpose such as development of new sensors, non-destructive assay technologies and optimization of radiation shielding. In the past, even if different results were obtained depending on calculation codes, it was difficult to clarify what caused the differences. To overcome it, we have developed a new reliable code to calculate radiation decay and radioactive source spectra that can accurately treats with large amounts of nuclides and all decay modes in the decay data file.
As the first step, we compared the photon spectra of fuel debris by using the recent decay data files: JENDL/DDF-2015, decay sub-libraries of ENDF/B-VIII.0 and JEFF-3.3. As shown in Fig.1, the result of JENDL/DDF-2015 is smaller than those of ENDF/B-VIII.0 and JEFF-3.3. This is mainly caused by the following reasons:
(1) X-ray data of 137mBa (T1/2 =2.6 min.) in JENDL/DDF-2015 is missing. The 137mBa is generated from β- decay from large amount of 137Cs (T1/2 = 30 years) and it will remain for a long time by radiation equilibrium.
(2) Gamma ray data of 241Am in 60 keV is missing in JENDL/DDF-2015.
(3) Gamma ray data of 106Rh (T1/2 = 2 hour) is missing in JENDL/DDF-2015 in the energy range from 3.0 to 3.4 MeV. The 106Rh is in the radiation equilibrium with 106Ru (T1/2=1.0 year)
In the presentation, we will report requests for the modifications on the decay schemes and branching ratios of decay modes for the next JENDL decay data file.

Poster / **52**

Nuclide production cross sections of natLu target irradiated with 0.4-, 1.3-, 2.2-, 3.0-GeV protons

Authors: Hayato Takeshita[1]; Shin-ichiro Meigo[2]; Hiroki Matsuda[3]; Hiroki Iwamoto[4]; Keita Nakano[5]; Yukinobu Watanabe[1]; Fujio Maekawa[6]

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Reliable assessment of radioactivity in target and structural materials for high-energy accelerator facilities such as accelerator-driven systems and spallation neutron sources requires detailed information on nuclide production cross sections by spallation reactions. To obtain the systematic cross section data for nuclide productions by spallation reactions, we have conducted irradiation experiments at Japan Proton Accelerator Research Complex (J-PARC). So far, we have measured nuclide production cross sections for light to medium-heavy target elements (Z≤47) with proton energies ranging from 0.4 to 3.0 GeV. To investigate heavier target elements, we conducted an experiment for target elements with atomic number around Z=70, including $^{\mathrm{nat}}\mathrm{Lu}$ (Z=71) target.
Four sets of Ho ($90\mathrm{mg/cm}^2$), Lu ($100\mathrm{mg/cm}^2$), and Re ($210\mathrm{mg/cm}^2$) foils were packed in aluminum containers together with 0.1-mm-thick aluminum catchers to avoid recoil contamination. Each set of targets was irradiated with 0.4-, 1.3-, 2.2-, and 3.0-GeV protons accelerated by 3-GeV Rapid Cycling Synchrotron (RCS). The beam current was monitored by a current transformer installed in front of the irradiation position. After the irradiation, gamma-rays emitted from the samples were detected by two high-purity Germanium detectors (relative efficiency 20%, Canberra Co., Ltd.).
The measured cross sections were compared with theoretical predictions by Particle and Heavy Ion Transport code System (PHITS) [1], and INCL++/ABLA[2,3]. The figure shows experimental and calculated $^{\mathrm{nat}}\mathrm{Lu}(p,X)^{\mathrm{nat}}\mathrm{Be}$ reaction cross sections. INCL/GEM model implemented in PHITS underestimated the experimental cross sections by a factor of about 2.
In the presentation, we will report our experimental results for the natLu target, and more detailed discussion on reaction mechanics will be given.
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Poster / **53**

A New Method to Reduce Systematic Uncertainties of Capture Cross Section Measurement Using a Sample Rotation System

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Precise nuclear data for neutron-induced reactions are necessary for the design of nuclear transmutation system. Nevertheless, current uncertainties of nuclear data for minor actinide (MA) does not achieve requirements for the design of transmutation facilities. Measurements of the neutron capture cross section are ongoing at the Accurate Neutron Nucleus Reaction measurement Instrument (ANNRI) in the Materials and Life science experiment Facility (MLF) of the Japan Proton Accelerator Research Complex (J-PARC). The determination of an incident neutron flux for measurements of neutron capture cross section is one of the main causes that affect the final uncertainty of the cross section results.
In the present work, we suggest a new method to reduce systematic uncertainties of capture cross section measurements. The method employs change of the self-shielding effect with sample rotation angle. In the new technique, a sample area density of a boron sample which is used for measurements of the incident neutron spectrum. In capture cross section measurements in ANNRI, a boron sample is placed to determine the incident neutron spectrum by counting 478 keV γ-ray from the ^{10}B(n,$\alpha\gamma$)^{7}Li reaction. The uncertainty of the boron sample area density that is usually calculated from the mass and the area introduces the uncertainty of the incident neutron spectrum. In this method, the boron sample is tilted with respect to the neutron beam direction, thereby changing the effective area. The neutron self-shielding effect increases with the effective area density. This results in change of the shapes of time-of-flight(TOF) spectrum of 478 keV γ-ray counts form the ^{10}B(n,$\alpha\gamma$)^{7}Li reaction with the tilted angle. Comparing the difference of the TOF spectra at different angles and assuming the 1/v energy dependence of cross section of the ^{10}B(n,$\alpha\gamma$)^{7}Li reaction, the area density of the boron sample can be determined without using the sample mass and area.
Theoretical and experimental studies on the new method are ongoing. Calculation using Monte Carlo simulation code PHITS were carried out to study the feasibility of the present method. Test experiments using a sample rotation system at ANNRI were also performed. Preliminary results will be given in this poster session.

Poster / **54**

Measurement of neutron total cross sections of Sn-Pb alloys in solid and liquid states

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Recently, a small modular reactor (SMR) with inherent and passive safety has been receiving attention all over the world. In Japan, a very small modular reactor, namely, MoveluX^{TM}(Mobile-Very-Small reactor for Local Utility in X-mark) has been developing by Toshiba Energy SystemsSolutions Corporation. MoveluX^{TM} is a thermal reactor that uses a calcium hydride as a neutron moderator. The use of a Sn-Pb alloy as an in-core heat transport medium is being considered. The Sn-Pb alloy is in a solid state when the reactor is started, and becomes liquid since the core temperature reaches 660℃ during operation. Therefore, the total cross section data of the Sn-Pb alloy is important for evaluating the effect of the change in the total cross section depending on the state of Sn-Pb alloy on the reactor characteristics. However, there are no reports on experimental data for total cross section of Sn-Pb alloys in both solid and liquid states in spite of the fact that it is important data for nuclear engineering. In the present study, the neutron total cross section was obtained from neutron transmission measurements by the time-of-flight (TOF) method using the Kyoto University Institute for Institute for Integrated Radiation and Nuclear Science – Linear Accelerator (KURNS-LINAC). The sample temperature was changed from room temperature (solid) up to 300℃ (liquid). The total cross sections of solid and liquid states were compared and the change in Bragg edge due to the difference of crystal structure was observed in the energy region below 0.01 eV. Comparing the total cross sections of the solid and the solid resolidificated after melting, it was confirmed that some Bragg edges, which are thought to be due to the crystal structure of Pb, disappeared by the resolidification. At the poster presentation, the detail of the total cross section measurement experiment and the results obtained so far will be discussed.

Poster / **55**

Comparison of double-differential cross sections between JENDL/PD-2016.1 and experimental data for photo-neutron production of medium-heavy nuclei at 16.6 MeV

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The double differential cross-section (DDX) of the photoneutron is an important quantity for radiation shielding and shielding calculation of the electron accelerator design. Shielding calculation is usually carried out by Monte Carlo simulation codes, which use the nuclear data library in the calculation. We measured the DDXs of the (γ, xn) reaction using 16.6 MeV polarized photon on $^{\mathrm{nat.}}\mathrm{Pb}$, $^{197}\mathrm{Au}$, $^{\mathrm{nat.}}\mathrm{Sn}$, $^{\mathrm{nat.}}\mathrm{Cu}$, $^{\mathrm{nat.}}\mathrm{Fe}$, and $^{\mathrm{nat.}}\mathrm{Ti}$ targets [1], and showed the neutron spectra including the evaporation and direct components. In this presentation, we compared the DDXs from the photonuclear data JENDL/PD-2016.1 and the experiment to check their consistency. The DDXs were extracted from the JENDL/PD-2016.1 library by our python-based software. The abundances of each target's isotopes were considered in calculating the DDXs from the JENDL/PD-2016.1 library. This comparison showed the differences in the photoneutron's energy distributions, and the differences were mostly in the direct component. The evaporation components were found in both JENDL/PD-2016.1 and the experimental data; however, they were not totally consistent. This result can be the first comparison of the DDXs from JENDL/PD-2016.1 and the experiment. The quantitative comparison and discussion will be presented at the symposium.

Keywords: differential double cross-section photoneutron, 16.6 MeV polarized photon, JENDL/PS-2016.1.

[1] T.K. Tuyet et al., "Double differential cross section of the (γ, xn) reaction on medium-heavy nuclei for 16.6 MeV polarized photons. 2020 Fall meeting of AESJ, Sep. 16th – 18th.

Facility / **56**

Nuclear data study for Accelerator Driven System at J-PARC

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In order to decrease the toxic waste produced at the nuclear reactor, a study of the Accelerator Driven System (ADS) is going around the world. Since the neutron production target at ADS is designed to be irradiated by protons in the kinetic energy of several GeV, a study with the high-energy particles in the kinetic energy region around GeV is essential for the research and development of ADS. However, many accelerator facilities using several GeV-protons, which were built 1970's, are going to shut

down due to their lifetime. Eventually, the facilities to be able to use protons with several GeV are scarce in the world. In Japan, J-PARC can only apply for the sake of ADS using the hadron including proton. At the 3-GeV proton synchrotron (RCS) facility and the beam transport line, some studies are going at J-PARC aimed for nuclear data of ADS.
In this session, some results of the experiment related to nuclear data for ADS are introduced, such as nuclide production cross-section induced by proton and displacement cross-section.

NuclearMedicine / 57

Development of Radioisotopes Production Method by Accelerator-based Neutron: Activity at Kyushu University 2020

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Radioisotopes (RIs) production using deuteron accelerator-based neutrons has been studying at Kyushu University. We especially focus on neutrons generated via the C or Be(d, n) reactions in a target whose thickness is thicker than the deuteron range. These reactions are selected because, (1) high intense neutrons having high kinetic energy are possible to be generated by the elastic and non-elastic break-up reaction of deuterons, and (2) neutron energy spectrum has maximum around a half incident deuteron energy, i.e. the spectrum shape can be adjusted by varying deuteron energy. The study has been conducted by the two approaches: proposal of new production routes or new RIs with the accelerator-based neutron method and systematic measurements of double-differential thick-target neutron yields (DDTTNYs) up to 40 MeV. Present paper shows some example of past works (high purity 64Cu production starting from [illegible]Zn which includes multiple stable isotopes), present status (chemistry, systematic DDTTNY measurement results), and future prospects (covariance application for neutron spectrum unfolding to take nuclear data uncertainty into account) of our project.

NuclearMedicine / 58

Measurements of production cross sections of medical radioisotopes via charged-particle induced reactions / [illegible]RI[illegible]

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Radioisotopes can be used for a variety of applications, e.g., radiotherapy and diagnostics in nuclear medicine. There are basically several reactions to produce each radioisotope. Investigations of such reactions are necessary to find better reactions with less byproducts and with higher cost effectiveness. Production cross sections of the radioisotopes are thus important nuclear data. However, there still exist a lack of data and data with large errors. It is necessary to obtain more accurate and reliable data for the application. Recent technical development of accelerators and detectors enables us to reach such data.
We focus on charged-particle-induced reactions among the possible reactions for the production. The charged-particle-induced reactions have an advantage to be able to produce radioisotopes with atomic numbers different from those of targets. We can expect to chemically separate the reaction products from the targets and to obtain the radioisotopes with high specific activity.
Experiments to measure the production cross sections are performed at RIKEN, Japan and ATOMKI, Hungary. The well-developed methods, stacked foil activation technique and high-resolution gamma-ray spectrometry, are adopted. The targets consisted of thin foils were irradiated with the charged-particles beams. Gamma-rays emitted from the irradiated foils without chemical separation were measured by HPGe detectors. Nuclear data required for deduction of cross sections were obtained

from online databases. The cross sections of the monitor reactions were compared with the IAEA recommended values to assess the beam parameters and target thicknesses.
The production cross sections can be derived and compared with previous studies and theoretical model calculation in the TENDL-2019 library. Thick target yields of the products for practical use can also be derived from the measured cross sections. The results are expected to contribute nuclear medicine.
We report our research activity on the experiments for the production cross sections of several medical radioisotopes.

Poster / 60

Research for nuclear transmutation of high-radiotoxic nuclide ^{90}Sr via proton- and deuteron-induced reactions

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Processing of spent fuel from nuclear power plants is a worldwide problem. The high-level radioactive waste is the product after the reprocessing of spent fuel, which includes minor actinides and fission products of radioactive waste. Especially, ^{90}Sr ($T_{1/2}$ = 28.8 years) is the highest radiotoxic nuclide in the fission products. It is highly desired to develop nuclear transmutation technology using accelerator facilities to reduce these harmful nuclides. The simplest way can be to irradiate a neutron beam on the radioactive waste. However, it is not well known that ^{90}Sr is transmuted into how much and which nuclide in this reaction. Therefore, it is essential to study, in advance, the reaction-cross-sections to each nuclide from ^{90}Sr. From this point of view, the inverse kinematics, i.e. including the ^{90}Sr beam incident on light-particle targets, is an effective method the reaction products can be identified at the forward directions.
To realize this purpose, we have planned the proton- and deuteron-induced reaction-cross-section measurements in inverse kinematics and performed the experiment using the BigRIPS separator [1] and the ZeroDegree spectrometer [1] at the RIKEN Radioactive Isotope Beam Factory. The radioactive ^{90}Sr beam with 104 MeV/u, produced and separated in the BigRIPS, incident on the C, CH_2, and CD_2 targets. The reaction products in the forward directions were transferred to the ZeroDegree and identified using the detectors at the focal plane. The reaction-cross-sections were obtained from the measured yields of each reaction channel. At this time, the contributions from carbon and beam-line materials were subtracted as a background. The obtained reaction-cross-sections were compared to the PHITS calculation [2] and the data with different energy of 185 MeV/u [3].

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Poster / 61

Theoretical evaluation of non-resonant background strength in binary breakup reaction

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Inelastic scattering is useful tool to explore the nuclear structure in the excited states. In particular, the inelastic excitation to the continuum energy states above the particle decay threshold, which is often called breakup reaction, is very important because we can pin down a specific nuclear structure by controlling the exit channels, which are the combination of the emitted fragments.
A typical and good example about the inelastic scattering to the continuum can be seen in the breakup reaction of ^{12}Be into the α + ^{8}He and ^{6}He + ^{6}He channels. In this experiment, the careful multi-pole decomposition analysis (MDA) was performed, and the MDA analysis elucidates that many resonant states with a sharp width exist in the spins from $J^{\pi} = 0^{+}$ to 8^{+}. The 0^{+} resonances in the α + ^{8}He channel appear in a close energy spacing of 0.5 MeV in the lower energy region below $E_{e.x.} \leq 15$ MeV, which is quite consistent to the energy scheme expected from the cluster resonances.
Basic and important quantities in the analysis of the resonance enhancement embedded in the continuum strength are the resonance parameters, such as the resonance energy and the decay width. In determining the resonance parameters, the evaluation of the non-resonant background strength is indispensable because the resonant enhancement, which has the strong energy dependence, are embedded in the non-resonant background contribution with a broad structure. Since the background strength is structure-less and must have the weak energy dependence, the shape of the non-resonant background strength is often assumed by the simple analytic function or evaluated from the simple reaction mechanism, such as the direct breakup without the final state interaction between the decaying fragments.
In this report, we investigate the structure of the non-resonant background continuum, which is generated by the binary breakup reaction, and explore the prescription to evaluate the background contribution by extending the Migdal-Watson formula for the s-wave breakup in the charge neutral system. In the calculation of the strength function for the binary breakup, we employ the complex scaling method (CSM), which is a powerful tool to describe the few-body continuum states. We handle the breakup reaction of ^{20}Ne into α + ^{16}O and ^{12}Be into α + ^{8}He. From the CSM calculation and the Migdal-Watoson theory, we propose the analytic function, which is appropriate to evaluate the background contribution for the binary breakup.

Facility / 62

Proposal of 1 A class deuteron single cell linac / ⌧⌧⌧⌧⌧⌧⌧⌧⌧ImPACT2017⌧⌧⌧

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A 1-ampere-class high-intensity deuteron linac (ImPACT2017 model) is proposed for mitigating long-lived fission products (LLFPs) by nuclear transmutation. This accelerator consists of single-cell rf cavities with magnetic focusing elements to accelerate deuterons beyond 1A up to 200MeV/u.

63

Conference Photo