Activation of Mn, Li$_2$O and LiF in the JSI TRIGA reactor to study potential tritium production monitors for fusion applications

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Received 7 January 2019, revised 29 April 2019
Accepted for publication 17 May 2019
Published 5 July 2019

Abstract

Two series of measurements were performed in the JSI TRIGA research reactor in 2014 and 2017 to validate the $^{55}$Mn(n,$\gamma$)$^{56}$Mn cross-sections and experimentally investigate the relationship between the $^{55}$Mn(n,$\gamma$)$^{56}$Mn reaction and the rate of tritium production through the $^6$Li(n,t)$^4$He reaction. Indeed, previously observed similarities between the sensitivity profiles of the neutron reaction of tritium production on lithium, $^6$Li(n,t)$^4$He, and those of the $^{55}$Mn(n,$\gamma$)$^{56}$Mn reaction in tritium breeder modules indicated that the latter reaction could be used as an effective monitor of tritium production, at least for short-term monitoring (the half-life of $^{56}$Mn being 2.579 h). However, experimental verification, improvements and validation of the $^{55}$Mn(n,$\gamma$)$^{56}$Mn reaction in tritium breeder modules indicated that the latter reaction could be used as an effective monitor of tritium production, at least for short-term monitoring (the half-life of $^{56}$Mn being 2.579 h). However, experimental verification, improvements and validation of the $^{55}$Mn(n,$\gamma$)$^{56}$Mn cross-sections are needed in order to meet the required accuracy. Foils of certified reference material Al–1% Mn, as well as LiF thermoluminescent detectors and Li$_2$O samples were irradiated, both bare and under cadmium, to study the potential use of the $^{55}$Mn(n,$\gamma$)$^{56}$Mn reaction for monitoring tritium production in fusion devices. Additionally, Al–0.1% Au was also irradiated for comparison, the $^{197}$Au(n,$\gamma$)$^{198}$Au reaction cross-section being a standard. In order to obtain complementary information for data validation purposes, the irradiations were performed in positions within the JSI TRIGA reactor with different neutron spectra, i.e. in the central channel, the pneumatic tube and the F19 position, both in the outer ‘F’ ring of the reactor core and in the IC-40 irradiation channel located in the graphite reflector surrounding the reactor core. Bare and cadmium-covered irradiations were needed to subtract the contribution of epithermal neutrons to the $^{55}$Mn(n,$\gamma$)$^{56}$Mn reaction. Calculations of the reaction rates were performed using the Monte Carlo code MCNP6.1 with a detailed model of the JSI TRIGA reactor, with the samples, the irradiation capsules and covers being modelled explicitly. The uncertainties involved in the measurements and the calculations were carefully evaluated. The principal objective was to study the energy response and correlations between the $^{55}$Mn(n,$\gamma$)$^{56}$Mn reaction in irradiated Al–1% Mn and the $^6$Li(n,t)$^4$He reaction in irradiated LiF and Li$_2$O. Good consistency between the measured and calculated $^{55}$Mn(n,$\gamma$)$^{56}$Mn and $^{197}$Au(n,$\gamma$)$^{198}$Au reaction rates, in most cases within the uncertainty bars, was observed.

Keywords: tritium production rate, Mn activation foils, TRIGA reactor measurements

(Some figures may appear in colour only in the online journal)
1. Introduction

In future fusion reactors, such as ITER or DEMO, based on the fusion reaction of deuterium and tritium nuclei (the D–T reaction), the required quantities of tritium fuel will be produced by bombardment of lithium nuclei with neutrons. Several types of special tritium breeder modules (TBMs) will be installed in the ITER reactor to demonstrate self-sufficiency of tritium production. Experiments will be necessary to confirm adequate rate of tritium production in the reactor. A direct method of measuring the rate of neutron-induced tritium production consists of the irradiation of LiF and subsequent determination of the tritium concentration in the material.

LiF pellets commercially produced as thermoluminescent detectors (TLDs) can be used to measure tritium production. In the scope of the fusion for energy (F4E) project of the European Commission we proposed to investigate, as an alternative, the potential use of manganese as a detector for monitoring tritium production in fusion machines. Important similarities between the sensitivity profiles of the tritium production reaction in $^6\text{Li}$ and those of the $^{55}\text{Mn}(n,\gamma)^{56}\text{Mn}$ reaction in the TBMs were observed [1–4], suggesting that the latter reaction could be used to monitor tritium production, at least in the short term (the half-life of $^{56}\text{Mn}$ being 2.579 h). However, validation and, possibly, improvements of the $^{55}\text{Mn}(n,\gamma)^{56}\text{Mn}$ reaction rates are needed in order to meet the required accuracy in some energy ranges. The target accuracy in determination of the tritium production rate that is relevant for ITER is 5% ($1 – \sigma$). Figure 1 displays reaction cross-sections for the $^6\text{Li}(n,t)^4\text{He}$, $^{55}\text{Mn}(n,\gamma)^{56}\text{Mn}$ and $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ reactions. Figure 1 also suggests that the epi-thermal contribution to the $^{55}\text{Mn}(n,\gamma)^{56}\text{Mn}$ reaction has to be excluded, and this can be done by comparing the measurements with/without Cd.

Differences in the cross-section evaluations for the $^{55}\text{Mn}(n,\gamma)^{56}\text{Mn}$ reaction were observed, which resulted in differences in the calculated reaction rates. Calculated-to-experimental (C/E) ratios for the Frascati Neutron Generator (FNG)-bulk shield [5], FNG-tungsten (W) [6, 7] and FNG-helium cooled lithium–lead (HCLL) [3] benchmarks demonstrate that the differences between the results using IRDFF [8] and IRDF-2002 [9] dosimetry nuclear data libraries are up to 5%, up to 10% and around 18%, respectively. Relatively good C/E agreement was found in the FNG-bulk shield experiment which is most sensitive in the 100–1000 eV energy range. On the other hand, large discrepancies between the measured and calculated reaction rates were found for the FNG-W [6, 7] benchmark, in which the $^{55}\text{Mn}(n,\gamma)^{56}\text{Mn}$ reaction rates are highly sensitive to the response function above 1 keV, and in the FNG-HCLL benchmark. However, some systematic errors may be present in the last two benchmarks. In the FNG-W benchmark, the exact Mn content in the foils needs to be verified and in the FNG-HCLL benchmark, heterogeneity of $^6\text{Li}$ enrichment in the Li–Pb block was observed. Although the better consistency observed between the $^{55}\text{Mn}(n,\gamma)^{56}\text{Mn}$ and $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ results seems to indicate better performance of the new data, it is at present still difficult to confirm with certainty the progress achieved.

In the scope of the fusion for energy (F4E) project of the European Commission, a first series of measurements was performed at the JSI TRIGA [10] reactor in 2014 [11]. Aluminium foils containing 1% manganese (Al–1%Mn) or 0.1% gold (Al–0.1%Au) were irradiated in the JSI TRIGA thermal reactor, together with LiF (TLD) and LiPb samples, with the principal objective of studying the energy response of the $^{55}\text{Mn}(n,\gamma)^{56}\text{Mn}$ reaction as well as the correlation between the $^{55}\text{Mn}(n,\gamma)^{56}\text{Mn}$ reaction rates and the tritium production rates in LiF and LiPb. Some inconsistencies were observed between the measured and calculated tritium activity for LiF (TLD) and LiPb samples which were encapsulated in Pyrex glass vials; these were probably caused by the presence of boron in the glass [11].

2. Experimental campaign

In 2017, a better defined set of experiments was performed at the JSI TRIGA reactor in which foils of certified reference materials Al–1%Mn and Al–0.1%Au and LiF and Li$_2$O samples were irradiated. The samples were irradiated in different TRIGA irradiation channels, i.e. in the central channel (CC), the pneumatic tube (PT) in the core periphery (F24 position in the outer ‘F’ ring of the reactor core), in position F19 and in the IC40 irradiation channel in the graphite reflector. Irradiations with different neutron spectra provide complementary information for data validation. All the irradiations were performed at a reactor power of 25 kW. Figure 2 displays the JSI TRIGA reactor core configuration used for the experiments (core no. 220).

Reaction rates for the $^{55}\text{Mn}(n,\gamma)^{56}\text{Mn}$ and $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ reactions were measured using Al–1%Mn and Al–0.1%Au foils, respectively. The Al–1%Mn foils were prepared by pressing Al–1%Mn material in wire form; the foil masses were approximately 10 mg and their diameter was approximately 5 mm. The Al–0.1%Au foils were punched out of Al–0.1%Au material in foil form; the foil masses were approximately 6 mg and their diameter approximately 5 mm. Tritium production measurements were performed using two different types of sample, LiF and Li$_2$O, developed and produced in the Institute of Nuclear Physics of the Polish Academy of Science in Krakow.

LiF samples consisted of three TLD pellets wrapped in Al foil. The masses of the single pellets were approximately 34 mg. The Li$_2$O samples were in powder form, encapsulated in specially designed Al cylindrical containers and closed with a screw cap. The masses of the Li$_2$O samples were approximately 120 mg each.

A set of one LiF sample (consisting of three TLD pellets), one Al container with Li$_2$O, one Al–1%Mn foil and one Al–0.1%Au foil were packed together into a cylindrical container, 10 mm in diameter and 22 mm high, with a wall thickness of 1 mm. The containers were either made from Al for bare irradiations or from Cd for Cd-covered irradiations. The containers were inserted into dedicated 3D-printed tubes made from polyethylene. Eight such sets of samples were irradiated in the TRIGA reactor. Figure 3 displays a schematic
2.1. Activation rate measurements in Al–1%Mn and Al–0.1%Au

After irradiation and appropriate cooling times, the induced activities in the Al–1%Mn and Al–0.1%Au foils were measured using two high-purity germanium (HPGe) detectors manufactured by Ortec (model GEM40P4-PLUS-S, model GEM-C5060P4-B), both operated by an Ortec DSpec 50 data acquisition system. The saturation activities per target atom (which correspond to the reaction rates) were calculated from the determined peak areas in the recorded gamma spectra, the measured sample masses and the quoted concentrations for the reference materials used, the irradiation, cooling and measurement times and the calibrated detection efficiency, using Figure 1.

**Figure 1.** Reaction cross-sections for the $^6$Li(n,t), $^{55}$Mn(n,γ) and $^{197}$Au(n,γ) reactions. Data were retrieved from the ENDF/B-VII.1 nuclear data library.

**Figure 2.** (Left) Photograph of the JSI TRIGA Mark II reactor core in operation. (Right) Core configuration (no. 220) during the experimental campaign, with the irradiation locations CC, F19, PT and IC40 indicated.

drawing of one set of samples packaged in the containers and a 3D-printed tube, and photographs of the samples, containers and tubes.
the JSI-developed SPCACT code. In addition to the saturation activity values, the SPCACT code computes their associated uncertainties, which are combined from the uncertainties in the determined peak areas, the sample masses, the irradiation, cooling and measurement times and the uncertainty in the detection efficiency.

2.2. Measurements of tritium production in LiF and Li₂O

Tritium activity measurements in irradiated LiF (TLD) and Li₂O materials were performed using the liquid scintillation counting (LSC) technique at the Tritium Laboratory of the Faculty of Physics and Applied Computer Science, UST, Krakow, Poland. Direct LSC measurement of tritium activity in LiF (TLD) or Li₂O requires conversion of the sample to liquid form through chemical dissolution in an aqueous solution of HNO₃ for LiF, and dissolution in distilled water for Li₂O [12, 13]. Dissolved sample solutions (or fractions thereof) were mixed with the scintillation cocktail Ultima Gold µLLT (Perkin Elmer) in 20 ml polyethylene vials (Packard). Measurements were performed using scintillation spectrometers: TRI-CARB model 2550-TR/AB LSC (Packard) and Quantulus model 1220 (Perkin Elmer). Each single vial was measured for 1000 min in 10 cycles of 100 min each. The measurement yield was no lower than 24% in the tritium channel, which corresponds, for the measurement conditions, to a detection limit no lower than 0.01 Bq per sample (vial). Standardization was performed for each set of samples by use of a dissolved NIST tritium standard, SRM 4926 E B, which we additionally verified in the 9th International Tritium Inter-comparison Exercise (TRIC 2012, IAEA, Vienna). The C/E values with estimated errors are shown in figure 9.

3. Monte Carlo calculations

Calculations of the $^{55}$Mn($n,\gamma$)$^{56}$Mn, $^{197}$Au($n,\gamma$)$^{198}$Au and $^6$Li($n,t$)$^4$He reaction rates were performed using the Monte Carlo particle transport code MCNP6.1 [14] in conjunction with the ENDF/B-VII.1 nuclear data library [15] and a detailed computational model of the JSI TRIGA reactor. In the calculations, the core configuration and the control rod positions were reproduced and the irradiation capsules, covers and samples themselves were modelled explicitly. Figure 4 displays the calculated neutron spectra in the Li₂O material in the capsules located in the irradiation channels.

The reactor power and control rod positions were kept constant during the irradiations; however, some small perturbation of the neutron flux and the reactor power due to the insertion of Cd covering the capsules was recorded. These detailed power variations have not yet been taken into account in the present calculations. The MCNP calculations resulted in a considerable overestimation of the effective multiplication factor (around 1.05). This is because we did not take temperature feedback and fuel burnup effects explicitly into account; this should be investigated further. However, this overestimation is compensated for in the normalization of the calculated values with regard to the reactor power level [16] according to equation (1):

$$R_{abs} = R_{MCNP} \frac{P_{\nu} \nu w}{w k_{eff}} ,$$

where $R_{abs}$ is the absolute reaction rate value, $R_{MCNP}$ is the raw calculated result, $P$ is the reactor power level during the irradiation, $\nu$ is the average number of neutrons emitted per fission, $w$ is the recoverable energy per fission and $k_{eff}$
is the calculated effective multiplication factor. The MCNP statistical uncertainties were in general of the order of a few per cent, and up to around 10% for the Cd-covered results. Spectral effects due to fuel burnup were seen as a probable cause for the reduction in the thermal flux of the order of about 10% in the central channel and the first fuel element ring \[17\].

4. Results and discussion

The results of the comparison between the calculated and the measured $^{55}\text{Mn}(n,\gamma)^{56}\text{Mn}$ and $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ activities are presented in figures 5–8 for the positions CC, PT, F19 and IC40, respectively. The reaction rates per target atom were computed from measurements using both HPGe detectors (denoted as ‘D1’ and ‘D2’ in figures 5–8), for the measured peak areas of the 846.8 keV, and 1810.7 keV gamma rays for the $^{55}\text{Mn}(n,\gamma)^{56}\text{Mn}$ reaction and 411.8 keV gamma rays for the $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ reaction.

The displayed C/E uncertainty bars include the experimental uncertainties (most importantly due to uncertainties in the detection efficiency and counting statistics) and computational uncertainties (statistical uncertainties, 5% power normalization uncertainty). For the Al–1%Mn and Al–0.1%Au foils the agreement between the measurements and the calculations is reasonably good, in most cases within the uncertainty bars. Slightly larger differences were observed for the IC-40 location (in the graphite reflector surrounding the reactor core), which are probably due to deficiencies of the computational model (e.g. uncertainties in the graphite reflector composition).
Figure 6. C/E comparison for the $^{55}\text{Mn}(n,\gamma)^{56}\text{Mn}$, $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ reaction rates, PT location.

Figure 7. C/E comparison for the $^{55}\text{Mn}(n,\gamma)^{56}\text{Mn}$, $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ reaction rates, F19 location.

Figure 8. C/E comparison for the $^{55}\text{Mn}(n,\gamma)^{56}\text{Mn}$, $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ reaction rates, IC40 location.
A comparison of the calculated and measured tritium activities expressed as C/E ratios is shown in figure 9. The abscissa denotes the irradiation position and cover. The results indicate a systematic overestimation of the calculations for the LiF (TLD) and Li2O samples by roughly 20%, and 40%, respectively.

Several reasons for the observed overestimation were identified. Preliminary analysis of measured values for LiF (TLD) indicated differences occurring within a single package of three LiF samples. Typically, the TLD pellet in the middle of the package shows systematically smaller activity (around two standard deviations), most likely due to neutron absorption in the outer pellets. However, this effect does not represent an important source of uncertainty or bias in the comparison between the experimental and calculated values since (a) the experimental tritium production rates in LiF are in fact averages over the three LiF samples and (b) in the calculations, tallies for the 6Li(n,t)4He reaction were defined in the region comprising all three LiF samples.

For the Li2O samples, the measured 3H activities are subject to an additional systematic error coming from the chemical preparation, and caused by the incomplete recovery of the irradiated Li2O samples (up to 10% of the initial mass). This explains the outlying measurement points and irregular C/E values for Li2O (figure 9). Another source of the observed differences in tritium activity in LiF and Li2O samples is the abundance of 6Li in the compounds used, which is known with an uncertainty no better than ±2%. Deviations from the certified Li abundances are not uncommon and have already been experienced in some previous studies (e.g. [3]). A possibly lower 6Li abundance than assumed for natural Li may also contribute to the observed difference. The effects of tritium self-absorption in the irradiated material and tritium escape were not taken into account.

Table 1 summarizes the main sources of uncertainty in the experimental and calculated 55Mn(n,γ)56Mn, 197Au(n,γ)198Au and 6Li(n,t)4He reaction rates.

| Source | Al–1%Mn/Al–0.1%Au | TLD/Li2O |
|--------|-------------------|----------|
| Detection efficiency (expt.) | ~2% | <2% |
| Counting statistics (expt.) | ~1% | 1% |
| γ self-absorption (expt.) | ~1% | – |
| Decay correction (expt.) | Negligible | Negligible |
| Mass uncertainty (expt.) | 1–2% | 3% |
| Li2O recovery (expt.) | – | Up to 10% |
| 6Li abundance and/or inhomogeneity (expt.) | – | 2% or higher [18–20] |
| Reactor power (calc.) | 5% | 5% |
| MCNP calculation statistics (calc.) | Up to 4%/11% | <1% |
| Burnup spectral effect in MCNP model (calc.) | Up to 10% | Up to 10% |

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5. Conclusions

In order to study the potential use of the 55Mn(n,γ)56Mn reaction as a tritium production monitor, a series of foils of certified reference materials Al–1%Mn and Al–0.1%Au as well as LiF (TLD) and Li2O samples were irradiated in different irradiation channels in the JSI TRIGA research reactor, both bare and under Cd. The irradiations were performed in different neutron spectra, i.e. in the CC, the PT in position F24 in the outer ‘F’ ring of the reactor core, in position F19 and in the IC-40 irradiation channel in the graphite reflector. A detailed MCNP6.1 computational model was prepared including the irradiated samples, containers, covers and tubes modelled explicitly.

The experimental and calculated results and their associated uncertainties were studied. Good consistency between
the experimental and calculated values was observed for the $^{55}$Mn (n,$\gamma$)$^{56}$Mn and $^{197}$Au (n,$\gamma$)$^{198}$Au reaction rates, in most cases within their respective $1 - \sigma$ uncertainties. The experimental and calculated values agreed to within 10% for the CC, PT and F19 locations (except $^{197}$Au (n,$\gamma$)$^{198}$Au in the F19 location) and to within 20% for the IC40 location.

In the case of LiF (TLD) and Li$_2$O samples, the model calculations overestimate the measurements results of tritium activity by roughly 20%, and 40%, respectively. Systematically lower experimental results obtained for both materials can be attributed in part to incomplete recovery of the irradiated material from the capsule (up to ~10%), abundance and/or isotopic inhomogeneity of $^6$Li.

The difficulty of sufficiently accurate radiometric assessment of tritium activity produced in the reaction with $^6$Li is a major reason for the search for monitors that can measure tritium production by easier procedures. Gamma spectrometric measurements present a promising alternative, and the $^{55}$Mn (n,$\gamma$)$^{56}$Mn reaction is a suitable candidate for monitoring neutron flux at the energies relevant for tritium production. It was demonstrated in this paper that, although not originally planned, Mn foil irradiation can serve to verify and validate other direct measurements of tritium production.

Further studies and laboratory experiments leading to improved assessment of correlation (with reduced uncertainty) between induced tritium activity in $^6$Li and neutron flux measured by use of the $^{55}$Mn (n,$\gamma$)$^{56}$Mn reaction can deliver a practical and easy-to-use tool for measuring tritium in the TBM (ITER) project.

Acknowledgments

The work leading to this publication has been funded partially by Fusion for Energy under the specific grant agreement F4E-FPA-395-01. This publication reflects the views only of the authors, and Fusion for Energy cannot be held responsible for any use which may be made of the information contained therein.

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References

[1] Kodeli I. et al 2011 Sensitivity and uncertainty analysis of the HCLL breeder blanket experiment in the frame of the EU fusion technology programme Nucl. Eng. Des. 241 1243–7
[2] Kodeli I., Radulovic V., Kavšek D., Pohorecki W. and Kuc T. 2014 TRIGA irradiations of Mn foils and TLD as potential tritium production monitors for fusion applications 23rd Int. Conf. Nuclear Energy for New Europe (Portorož, Slovenia, 8–11 September 2014) (https://www.djs.si/proc/nene2014/pdf/NENE2014_1102.pdf)
[3] Batistoni P. et al 2012 Neutronics experiments for uncertainty assessment of tritium breeding in HCBP and HCLL blanket mock-ups irradiated with 14 MeV neutrons Nucl. Fusion 52 083014
[4] Kodeli I. 2015 Validation of IRDFF-v1.04 (&v1.05) dosimetry library using SINBAD shielding benchmark experiments IAEA Nuclear Data Section INDC-2641, INDC(SLO)-0002 Vienna (https://doi.org/10.68.46.107/publications/indc/indc-slo-0002/)
[5] Kodeli I., Petrizzi L. and Batistoni P. 2000 Transport, sensitivity and uncertainty analysis of FNG 14 MeV neutron bulk shield experiment J. Nucl. Sci. Technol. Suppl. 1 713–7
[6] Batistoni P. et al 2006 Neutronics design and supporting experimental activities in the EU Fusion Eng. Des. 81 1169–81
[7] Kodeli I. 2004 Cross section sensitivity analysis of 14 MeV neutron benchmark experiment on tungsten J. Nucl. Mater. 329–33 717–20
[8] Capote R., Zolotarev K.I., Prunyaev V.G. and Trkov A. 2012 Updating and extending the IRDF-2002 dosimetry library J. ASTM Int. 9 1–9
[9] International Reactor Dosimetry File 2002 (IRDFF-2002) 2006 IAEA Technical Report Series 452 (Vienna: International Atomic Energy Agency)
[10] Kodeli I., Radulovic V., Veniger G., Kavšek D., Kuc T., Ciechanowski M. and Pohorecki W. 2017 26th Int. conf. Nuclear Energy for New Europe (Portorož, Slovenia, 11–14 September 2017)
[11] Pohorecki W., Kuc T., Ostachowicz B. and Bilski P. 2011 Novel methods of tritium production rate measurements in HCLL TBM mock-up experiment with liquid scintillation technique Fusion Eng. Des. 86 2429–32
[12] Kuc T., Pohorecki W. and Ostachowicz B. 2014 Direct measurement of tritium production rate in LiPb with removed parasitic activities: preliminary experiments Fusion Eng. Des. 89 1491–4
[13] Copić M., Dimić V., Ilić R., Lipic L. and Rant J. 1974 Experience with TRIGA aluminum-clad fuel elements 3rd European Conf. of TRIGA Users (Germany, 29 Oct 1974) ed F.R. Neuberger (San Diego, CA: General Atomic Co.) pp 4.1–4.20 (https://mis.iaea.org/search/search.aspx?orig_q=RN:6215643)
[14] Goorley J.T. et al 2013 Initial MCNP6 release overview—MCNP6 version 1.0, LA-UR-13-29234
[15] Chadwick M.B. et al 2011 ENDF/B-VII.1 nuclear data for science and technology: cross sections, covariances, fission product yields and decay data Nucl. Data Sheets 112 2887–996
[16] Žerovnik G., Podvratač M. and Snoj L. 2014 On normalization of fluxes and reaction rates in MCNP criticality calculations Ann. Nucl. Energy 63 126–8
[17] Štancar Ž. et al 2017 Reaction rate distribution experiments at the Slovenian JSI TRIGA Mark II research reactor, TRIGA-FUND-RESR-002 International Handbook of Evaluated Reactor Physics Benchmark Experiments (DVD) (Paris: OECD Nuclear Energy Agency) p 251
[18] Coplen T.B. et al 2002 Compilation of minimum and maximum isotope ratios of selected elements in naturally occurring terrestrial materials and reagents Water-Resources Investigations Report 01–4222 (Reston, VA: US Geological Survey)
[19] Coplen T.B. et al 2012 Isotope-abundance variations of selected elements Pure Appl. Chem. 74 1987–2017
[20] Qi H.P., Coplen T.B., Wang Q.Z.H. and Wang Y.H. 1997 Unnatural isotopic composition of lithium reagents Anal. Chem. 69 4076–8