Neutron inelastic cross section measurements for ^{nat}Ti

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Abstract. A neutron inelastic scattering experiment was performed at the GELINA (Geel Electron LINear Accelerator) neutron source of the European Commission Joint Research Centre Geel (EC-JRC Geel) with the aim of determining the reaction cross sections for the stable isotopes of natural titanium. A ^{235}U fission chamber was used to monitor neutrons with energies up to 20 MeV. The GAINS (Gamma Array for Inelastic Neutron Scattering) spectrometer was employed to detect the γ rays resulting from the decay of the excited nuclei. We determined the γ-ray production cross sections of the first transitions in the ^{46,48,49,50}Ti isotopes. The experimental values were compared with previous reported results and also with theoretical calculations performed with the TALYS 1.8 code using the default input parameters. Uncertainties of around 5% were obtained for the strongest observed transitions.

1. Introduction

The results of neutron inelastic scattering experiments are very important for the development of the new generation of nuclear reactors (Gen IV) [1] due to the fact that during this reaction the incident neutron flux is altered. The scientists in charge with the design of the reactors require neutron inelastic cross section data with very low uncertainty (usually less than 5% for the strongest γ-ray transition) [2] because this affects directly the criticality coefficient uncertainty [3]. These data are relevant also for other applications and fields of physics. In general, the experimental cross section data can be also used as a tool for a better understanding of nuclear reaction mechanisms.

In particular, the neutron inelastic scattering cross sections on the stable isotopes of natural titanium are important due to the fact that titanium is a material used extensively in the construction of the new generation of nuclear reactors. Another motivation comes from the fact that the first transition in ^{48}Ti ($E_\gamma = 983.5$ keV) is investigated in order to establish a possible γ-ray reference cross section for neutron-induced reactions [4–6]. Looking in the experimental nuclear reaction database EXFOR [7] we observe that most of the neutron inelastic scattering experiments on the titanium isotopes were performed between 1960 and 1980 in a limited energy range. The energy range was extended by Dashdorj et al. [8] in 2007 when they determined the γ-production cross sections of the transitions observed from the inelastic scattering of the neutrons on ^{48}Ti up to $E_n = 200$ MeV.

Our goal was to measure the γ-production cross sections for the most important transitions in all of the stable Ti isotopes. Cross section data from the present experiment have already been reported in [9, 10] and a full publication is in preparation.

2. Experimental setup

This experiment was performed using the GELINA neutron source [11–13] operated by EC-JRC Geel. This is a facility especially designed for performing neutron-induced measurements with very high precision. A Linac is used to accelerate electrons to energies between 70 and 140 MeV with a repetition rate up to 800 Hz (corresponding to a period of 1.25 ms between pulses) and the FWHM of the pulse of less than 1 ns. These characteristics make GELINA one of the best white neutron sources available in the world. The highly energetic electrons hit a mercury-cooled depleted uranium target producing via bremsstrahlung a strong γ-flash. A small part of this γ-flash interacts with the uranium target [13] and, via U(γ, xn) and U(γ, f) reactions, neutrons are produced with energies in the range spreading from thermal up to 18 MeV. 12 flight paths are distributed at various angles around the uranium target with several measurement cabins located at various distances (10–400 m).

The neutron inelastic scattering experiments were usualy performed on flight path 3 in the measurement cabin located at 200 m and 90° with respect to the electron beam. Two ^{nat}U filters (36.8 g/cm^2 thickness each) were placed at 100 m inside the flight path beam line to reduce the intensity of the γ-flash. The inelastic excitation is followed by γ-ray emission and γ-rays are detected using GAINS [14, 15]. It consists of maximum 12 HPGe detectors (100% relative efficiency and 2.8 keV energy resolution at 1.33 MeV) placed at 3 different angles (110°, 125° and 150° relative to the neutron beam direction)

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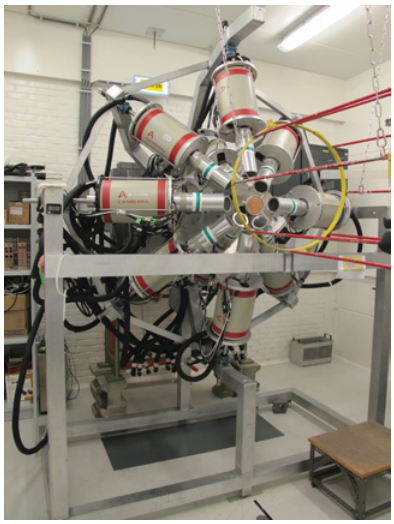

Figure 1. The Gamma Array for Inelastic Neutron Scattering (GAINS) spectrometer placed on flight path 3, at 200 m from the neutron source.

chosen to precisely integrate the differential cross sections over the entire solid angle. The detectors are placed at backward angles with respect to the sample in order to reduce the impact of the γ-flash.

In order to normalize the data, the neutron flux was monitored using a ^{235}U fission chamber (FC) centered on the flux at about 146.8 cm upstream the sample. It contains 8 uranium layers of 70 mm diameter on five Al foils of 20 μm thickness supported by 84 mm diameter ring [16]. The FC uses as a counting gas a P10 mixture at atmospheric pressure. The neutrons produce fission reactions in the uranium layers. The main working principle of the FC consists of applying a hight voltage in order to collect the charge generated by the fission fragments moving through the P10 mixture. For extensive descriptions of the FC see Refs. [16, 17].

The acquisition of the data is digital for the HPGe detectors and analoque for the FC. The digital acquisition uses Acqiris DC440 digitizers running at 420 $\times$ 10^6 samples/s (2.38 ns/sample), with 12-bit amplitude resolution (4096 channels full range) [18]. The acquired data is transfered to a PC and for each signal the time and the amplitude is computed and recorded. The energy of the incident neutron is determined from the time information, while the γ energy is determined from the amplitude of the corresponding event. The time is calculated as the difference between the moment when the neutrons produce the inelastic reaction in the sample and the γ ray is emitted and detected and the moment when the neutrons are created.

3. Experimental particularities

During this measurement, GELINA was running at 800 Hz, and GAINS was operated with only 10 HPGe detectors (2 detectors from 150° were missing). The sample, a natural titanium disk with a diameter of 8.000(1) cm, 0.45 cm thickness and 99.995% purity, was irradiated for $\approx$ 430 h in order to get good statistics. From the measured mass and area of the sample we computed an areal density of 2.139 g/cm^2, which, in turn, was exploited together with the isotopic abundance to determine the areal

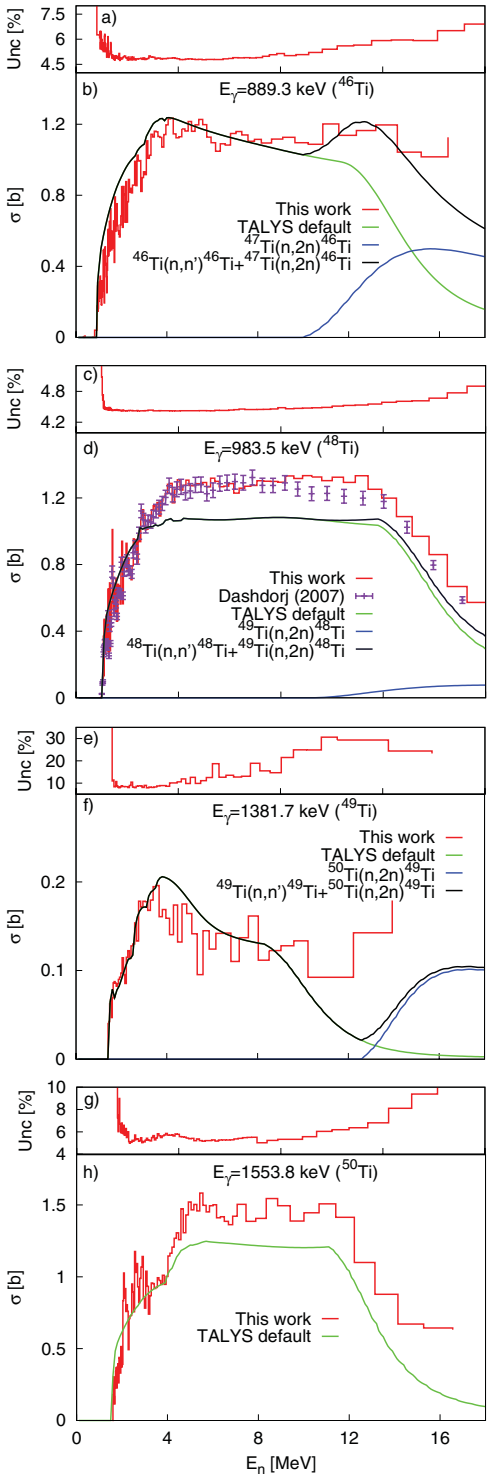

Figure 2. The γ-ray production cross sections for the first transitions in ^{46,48,49,50}Ti. Panels b), d), f), h) display the γ production cross sections while panels a), c), e), g) show the corresponding total relative uncertainties.

density corresponding to each isotope. The efficiency of the FC was calculated to be 85.5(4)%. For the calibration measurements we used an ^{152}Eu point-like source with an activity of 18.6(6) kBq. In order to take into consideration the geometric and the attenuation effects in the extended sample we performed also Monte Carlo simulations. We should note that in this experiment we observed several transitions coming from each stable isotope of natural

Table 1. The isotopic abundance of each stable isotope of ^{nat}Ti [19] and the corresponding areal density.

Isotopes	^{46}Ti	^{47}Ti	^{48}Ti	^{49}Ti	^{50}Ti
Isotopic composition (%)	8.25(3)	7.44(2)	73.72(3)	5.41(2)	5.18(2)
Corresponding areal density (g/cm^2)	0.176(1)	0.159(1)	1.576(1)	0.115(1)	0.110(1)

Table 2. The threshold energies for (n, 2nγ) reactions relevant for the present experiment.

Reaction	^{47}Ti(n,2nγ)^{46}Ti	^{48}Ti(n,2nγ)^{47}Ti	^{49}Ti(n,2nγ)^{48}Ti	^{50}Ti(n,2nγ)^{49}T
Q value (MeV)	9.0710(5)	11.8710(5)	8.3100(5)	11.1600(5)

titanium, except the first transition in ^{47}Ti with $E_\gamma = 159.4$ keV. This was due to the fact that the thresholds in the acquisition system were set higher than it was needed in order to observe it.

Perhaps the most important experimental particularity comes from the combination between the fact that natural titanium has five stable isotopes, with consecutive mass number, and the fact that the incident neutron energies were higher that the threshold energy for the $^{47-50}$Ti(*n, 2n*) reactions (see Table 2). Following the latest reactions the same nucleus is left excited as in the $^{46-49}$Ti(n, n') reactions. Because it was not possible to distinguish between the (n, n') and the (*n, 2n*) contribution, our experimental results will be also compared with the sum of the two contributions as predicted by TALYS [20], scaled with the abundance of each isotope in natural titanium.

4. Theoretical considerations

Our experimental results are compared with theoretical calculations performed with the TALYS 1.8 code using the default input parameters. These calculations use the semi-empirical model and parameters that were obtained from global optimizations. For calculating the level densities it uses the approach of Gilbert and Cameron [21] together with the constant temperature model at lower energies and the back shifted Fermi gas model with one energy dependent level density parameter which accounts for the damped shell effect at higher energies. The γ-ray strength functions are described using the generalized Lorentzian form by Kopecky and Uhl [22] for E1 transitions. For the other type of transitions it uses the Brink-Axel option [23, 24]. The Reference Input Parameter Library [25] is employed to derive the nuclear structure and the decay table used in the modeling of de-excitation of the nuclei.

5. Results and discussion

Figure 2 displays the results of the γ-production cross sections for the first transitions in ^{46,48,49,50}Ti and the corresponding total relative uncertainties. Our experimental results are in a fairly good agreement with the TALYS 1.8 default calculations which implies that the theoretical modeling of the reactions is well performed. In panel b) we can observe clearly the contribution coming from the ^{47}Ti(*n, 2n*γ)^{46} reaction on top of the ^{46}Ti$(n, n'\gamma)$ cross section. This corresponds to an increase in the value of the γ-production cross section around 10 MeV neutron incident energy which is the sum between the Q-value of the reaction and the threshold energy to excite the first level in ^{46}Ti. The same contribution can be also observed in panel d) where we can see an increase in the value of the cross section around 9 MeV. This is also the main difference between our experimental results and the results of Dashdorj et al. [8] and it comes from the fact that they used an enriched ^{48}Ti sample. All the cross sections reported here have maximum values above 1.2 b and total relative uncertainties around 5% except the one for ^{49}Ti where the cross section is around 0.2 b. This results in a larger total uncertainty (10%) due to the fact that the statistical uncertainties dominate.

6. Conclusions

Using the neutrons provided by the GELINA neutron source and the GAINS spectrometer in combination with a fission chamber we performed an inelastic scattering experiment in which we studied the γ-ray transitions corresponding to the five stable isotopes of a natural titanium sample. We reported here the γ-production cross sections for the first transitions in ^{46,48,49,50}Ti and comparison with the theoretical calculations performed with the TALYS 1.8 code and previous experimental results if available. For most of the transitions discussed here the total relative uncertainty was around 5%.

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References

[1] The Generation IV International Forum, online: `http://www.gen-4.org/`
[2] Nuclear Energy Agency, OECD, Nuclear Data High Priority Request List, online: `http://www.nea.fr/dbdata/hprl/`
[3] M. Salvatores, G. Aliberti, G. Palmiotti, D. Rochman, P. Oblozinsky, M. Herman, P. Talou, T. Kawano, L. Leal, A. Koning and I. Kodeli, Nuclear data needs for advanced reactor systems: a NEA Nuclear Science Committee initiative, Proceedings of the International Conference on Nuclear Data for Science and Technology, April 22-27, 2007, Nice, France, EDP Sciences (2008), 879
[4] A.D. Carlson, V.G. Pronyaev, R. Capote, F.-J. Hambsch, F. Kåppeler, C. Lederer, W. Mannhart, A. Mengoni, R.O. Nelson, A.J.M. Plompen, P. Schillebeeckx, S. Simakov, P. Talou, S. Tagesen, H. Vonach, A. Vorobyev, and A. Wallner, Nucl. Data Sheets **118**, 126 (2014)

[5] A.D. Carlson, V.G. Pronyaev, R. Capote, G.M. Hale, F.-J. Hambsch, T. Kawano, S. Kuneida, W. Mannhart, R.O. Nelson, D. Neudecker, P. Schillebeeckx, S. Simakov, D.L. Smith, P. Talou, X. Tao, A. Wallner, and W. Wang, Nucl. Data Sheets **123**, 27 (2015)
[6] A.D. Carlson, V.G. Pronyaev, R. Capote, G.M. Hale, F.-J. Hambsch, T. Kawano, S. Kuneida, W. Mannhart, R.O. Nelson, D. Neudecker, P. Schillebeeckx, S. Simakov, D.L. Smith, P. Talou, X. Tao, A. Wallner, and W. Wang, Eur. Phys. J. Web of Conferences **106**, 04002 (2016)
[7] N. Otuka et al., Nucl. Data Sheets **120**, 272 (2014)
[8] D. Dashdorj, G.E. Mitchell, J.A. Becker, U. Agvaanluvsan, L.A. Bernstein, W. Younes, P.E. Garrett, M.B. Chadwick, M. Devlin, N. Fotiades, T. Kawano, R.O. Nelson, Nucl. Sci. Eng., **157**, 65 (2007)
[9] A. Olacel, F. Belloni, C. Borcea, A. Negret, N. Nyman, E. Pirovano, A.J.M. Plompen, JRC Technical report, JRC data for the Ti-48 standard, Luxembourg: Publications Office of the European Union (2015)
[10] A. Olacel, Ph.D. thesis, Faculty of Physics, University of Bucharest (2015)
[11] A. Bensussan, J.M. Salome, Nucl. Instrum. Methods **155**, 11 (1978)
[12] M. Flaška, Ph.D. thesis, Slovak University of Technology in Bratislava, Published by IOS Press under the imprint Delft University Press, 2006
[13] D. Ene, C. Borcea, S. Kopecky, W. Mondelaers, A. Negret, A.J.M. Plompen, Nucl. Instrum. Methods Phys. Res. A **618**, 54 (2010)
[14] D. Deleanu, C. Borcea, Ph. Dessagne, M. Kerveno, A. Negret, A.J.M. Plompen, and J.C. Thiry, Nucl. Instrum. Methods Phys. Res. **624**, 130 (2010)
[15] A. Negret, C. Borcea, Ph. Dessagne, M. Kerveno, N. Nankov, A. Olacel, A.J.M. Plompen, and C. Rouki, Nucl. Data Sheets **119**, 179 (2014)
[16] L.C. Mihailescu, L. Olah, C. Borcea, and A.J.M. PLompen, Nucl. Instrum. Methods Phys. Res. A **531**, 375 (2004)
[17] C. Rouki, P. Archier, C. Borcea, C. De Saint Jean, J.C. Drohé, S. Kopecky, A. Moens, N. Nankov, A. Negret, G. Noguère, A.J.M. Plompen, and M. Stanoiu, Nucl. Instrum. Phys. Res. A **672**, 82 (2012)
[18] A. Negret, C. Borcea, J.C. Drohé, L.C. Mihailescu, A.J.M. Plompen, and R. Wynants, International Conference on Nuclear Data for Science and Technology, April 22-27, 2007, Nice, France, editors O.Bersillon, F.Gunsing, E.Bauge, R.Jacqmin, and S. Leray, EDP Sciences (2007), p. 1015-1018
[19] National Institute of Standards and Technology, `http://www.nist.gov`
[20] A.J. Koning, S. Hilaire and M.C. Duijvestijn, International Conference on Nuclear Data for Science and Technology, April 22-27, 2007, Nice, France, editors O. Bersillon, F. Gunsing, E. Bauge, R. Jacqmin, and S. Leray, EDP Sciences (2007), p. 211–214
[21] A. Gilbert and A.G. W Cameron, Can. J. Phys. **43**, 1446 (1965)
[22] J. Kopecky and M. Uhl, Phys. Rev. C **41**, 1941 (1990)
[23] D.M. Brink, Ph.D. thesis, Oxford University, 1955
[24] P. Axel, Phys. Rev. **126**, 671 (1962)
[25] R. Capote, M. Herman, P. Obložinský, P.G. Young, S. Goriely, T. Belgya, A.V. Ignatyuk, A.J. Koning, S. Hilaire, V.A. Plujko, M. Avrigeanu, O. Bersillon, M.B. Chadwick, T. Fukahori, Zhigang Ge, Yinlu Han, S. Kailas, J. Kopecky, V.M. Maslov, G. Reffo, M. Sin, E.Sh. Soukhovitskii, P. Talou, Nucl. Data Sheets **110**, 3107 (2009)