Ա.Ի. ԱԼԻԽԱՆՅԱՆԻ ԱՆՎԱՆ ԱԶԳԱՅԻՆ ԳԻՏԱԿԱՆ ԼԱԲՈՐԱՏՈՐԻԱ
(ԵՐԵՎԱՆԻ ՖԻԶԻԿԱՅԻ ԻՆՍՏԻՏՈՒՏ)

Ավետիսյան Ռոզա Վախտանգի

ՊՐՈՏՈՆ ԵՎ ՖՈՏՈՆ ՀԱՐՈՒՑՎԱԾ ՌԵԱԿՑԻԱՆԵՐԻ ԳՐԳՌՄԱՆ ՖՈՒՆԿՑԻԱՆԵՐԻ ԵՎ ԻԶՈՄԵՐ ՀԱՐԱԲԵՐՈՒԹՅՈՒՆՆԵՐԻ ՈՒՍՈՒՄՆԱՍԻՐՈՒՄԸ ՏԱՐԲԵՐ ՄԻՋՈՒԿՆԵՐԻ ՎՐԱ

Ա.04.16 - «Միջուկի, տարրական մասնիկների և տիեզերական ճառագայթների ֆիզիկա» մասնագիտությամբ ֆիզիկամաթեմատիկական գիտությունների թեկնածուի գիտական աստիճանի հայցման ատենախոսության

ՍԵՂՄԱԳԻՐ

ԵՐԵՎԱՆ – 2022

A.I. ALIKHANYAN NATIONAL SCIENCE LABORATORY

(YEREVAN PHYSICS INSTITUTE)

Roza Avetisyan

STUDY OF THE EXCITATION FUNCTIONS AND ISOMER RATIOS OF PROTON AND GAMMA INDUCED REACTIONS FOR DIFFERENT NUCLEI

SYNOPSIS

of Dissertation in 01.04.16 – “Nuclear, elementary particles and cosmic ray physics” presented for the degree of candidate of physical and mathematical sciences

YEREVAN - 2022

Ատենախոսության թեման հաստատվել է Ա.Ի. Ալիխանյանի անվան Ազգային Գիտական Լաբորատորիայի (ԵրՖի) գիտական խորհրդում:

Գիտական ղեկավար՝
Ֆիզմաթ. գիտ. թեկնածու Իվետտա Արտավազդի Քերոբյան (ԱԱԳԼ)

Պաշտոնական ընդդիմախոսներ՝
Ֆիզմաթ. գիտ. թեկնածու Գոհար Հովհաննեսի Հավհաննիսյան (ԵՊՀ)
Ֆիզմաթ. գիտ. դոկտոր Համլետ Գեղամի Մկրտչյան (ԱԱԳԼ)

Առաջատար կազմակերպություն՝
Երևանի պետական համալսարան (ԵՊՀ), Երևան, Հայաստան

Ատենախոսության պաշտպանությունը կայանալու է 2022 թ., Մայիսի 24-ին, ժամը՝ 14:00-ին, ԱԱԳԼ-ում գործող ԲՈԿ-ի 024 «Ֆիզիկայի» մասնագիտական խորհրդում (Ալիխանյան եղբայրների փ. 2, Երևան, 0036):
Ատենախոսությանը կարելի է ծանոթանալ ԱԱԳԼ-ի գրադարանում:
Սեղմագիրն առաքված է 2022թ. Ապրիլի 11-ին:
Մասնագիտական խորհրդի գիտական քարտուղար՝
Ֆիզմաթ. գիտ. դոկտոր Հրաչյա Հովհաննեսի Մարուքյան

The subject of the dissertation is approved by the scientific council of the A.I. Alikhanyan National Science Laboratory (YerPhI).

Scientific supervisor:
Candidate of ph-math sciences Ivetta Kerobyan (AANL)

Official opponents:
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Doctor of ph-math sciences Hamlet Mkrtchyan (AANL)

Leading organization:
Yerevan State University (YSU), Yerevan, Armenia

The defense will take place on 24th May, 14:00, during the “Physics” professional council’s session of SCC 024 of acting within AANL (2 Alikhanyan Brothers str., Yerevan - 0036).
The dissertation is available at the AANL library.
The synopsis is delivered on 11th April 2022.

Scientific secretary of the professional council
Doctor of ph-math sciences Hrachya Marukyan

Abstract

This thesis is dedicated to the experimental and theoretical investigations of excitation functions for proton induced reactions from natural tungsten, as well as the flux-weighted average cross sections for bremsstrahlung photon induced reactions from natural rhenium and natural niobium.

Our concern is focused on targets that can produce radionuclides of use in applications. During the experiments the high purity natural targets were used. For isomeric pairs the isomeric cross section ratios were determined.

The experiments were performed in the A.I. Alikhanyan National Science Laboratory (AANL) Yerevan, Armenia. For the gamma induced reactions the electron linear accelerator LUE-75 was used. The irradiations were carried out for 30 MeV and 40 MeV end-point bremsstrahlung energies. For the proton induced reactions the cyclotron C18/18 was used, covered the energy range from reactions threshold up to 18 MeV.

Experiments were carried out using the activation technique. The irradiated targets were measured by off-line gamma spectroscopy. The analyses were carried out on HPGe detector using the MAESTRO program.

The experimentally obtained data were compared with the available publications and the model calculations by the TALYS 1.9 and EMPIRE 3.2 codes. The comparison demonstrates the necessity for further improvements of the models and the codes. Phenomenological aspects of residual nuclides production and the capabilities of nuclear models to predict respective cross sections are described in this thesis.

Aim of the dissertation

The main focuses of this thesis are:

- Measurements of flux-weighted average cross section for ^{nat}Re(γ,xn) reactions;
- Measurements of flux-weighted average cross section for ^{nat}Nb(γ,xn) reactions;
- Measurements of excitation functions for $^{181;182;183;184;186}$Re residual nuclides by proton induced reactions on ^{nat}W;

- Measurements of isomeric cross section ratio for ^{182m,g}Re, ^{184m,g}Re and ^{186m,g}Re isomeric pairs;
- Determination and assessment of gamma and proton induced activity for ^{186g}Re.

Both photon and proton induced irradiations were performed at the AANL.

Novelty of the dissertation

Measurement of reaction cross sections is one of the main aims of many experimental nuclear physics groups due to the need of proven cross section data for the reactions. Moreover, the lack and discrepancies among the available data still exist. In order to improve the fundamental science, low energy nuclear reaction models, as well as the nuclear physics based applications the large amount of database is needed. Taking these conditions into account, the photon and proton induced reaction experiments were done. The new received data will make the significant contribution to the international database.

The current experimental results were compared with previously obtained experimental data available in the literature and with the theoretical calculation by TALYS and EMPIRE nuclear codes. Good agreement between current and other experimental data and the codes were obtained for residual nuclides. Still in some cases there are discrepancies between them which require further improvements.

The cross section values for ^{91m}Nb residual nuclide and the ICRs for ^{182m,g}Re, ^{184m,g}Re isomeric pairs are obtained for the first time.

All data from photon induced experiments are included to the international EXFOR database.

Practical value

The main part of this thesis has been the experimentally obtained data and its analysis, which were compared with the data available from the other research groups and the model calculations by the TALYS and EMPIRE codes. The comparison demonstrates the necessity for further improvements of the models and the codes. Phenomenological aspects of residual nuclides production and the capabilities of nuclear models to predict respective cross sections are described in this thesis. For the production of ^{186g}Re medical isotope the assessment of the specific activity are given and the production possibility in photon and proton induced reactions are considered.

Main points to defend

The main points to defend are experimental and theoretical investigations of proton and photon induced reactions for different nuclei in intermediate energy region. Particularly, for photon induced reactions the ^{nat}Nb and ^{nat}Re targets have been used. The flux-weighted average cross section measurements have been done for both. The data for the ^{91m}Nb residual nuclide obtained for the first time. The experimental and semi-empirical isomeric cross section ratios for the rhenium isomeric pairs are published for the first time.

The proton induced experiments were carried out on ^{nat}W targets. The stacked-foil technique has been used to get the excitation functions for residual nuclides. The experimental and semi-empirical isomeric cross section ratios for the ^{182m,g}Re; ^{184m,g}Re and ^{186m,g}Re isomeric pairs have been obtained. Due to the stacked-foil technique ICR values for ten different proton energies have been received.

The possibility of ^{186g}Re medical isotope production for both, LUE-75 linear accelerator and cyclotron C18/18 was discussed.

Structure of the dissertation

This dissertation is composed of:

- List of papers - published based on dissertation data
- List of figures
- List of tables
- Abbreviations
- Abstract
- Aims and objectives of work
- Introduction
- Five chapters
- Conclusion
- References

All figures and data tables are listed in the beginning of thesis. Five chapters are including theoretical and experimental activities and discoveries. Each one of five general chapters consists of several sections. In the final part of dissertation all results are summarized in "Conclusion". The abbreviations taking part in this work are presented.

Content of the dissertation

In the "**Aims and objectives of work"** part it is presented the main goal of defended subjects.

The **"Introduction"** of this dissertation is present the detailed description of nuclear reactions and mechanisms. Study of nuclear reaction mechanism is the fundamental tool to study the behavior of nuclear force between the nucleons inside the nucleus and to understand the nuclear structure. Most of the known nuclear reactions are produced by irradiating different materials to the beam of accelerated nuclear particles. In order to test these models, it is important to have extensive data on reaction cross sections, excitation functions, energy and angular distributions etc. of emitted particles. Nuclear reactions induced by proton and photon projectiles with neutron emission are of interest for fundamental and applied researches. These important tools are presented in this part shortly.

The **CHAPTER 1** "**Experimental facilities**" is dedicated to the experimental facilities. The LUE-75 and the cyclotron C18/18 are described in details. The main working parameters of accelerators are presented in Sections 1.1 and 1.2, respectively. Both, the linear accelerator and the cyclotron are located at the AANL, Yerevan, Armenia. The incident electron energies used for experiments at LUE-75 were 30 MeV and 40 MeV. The proton beam energy used for experiments at cyclotron was 18 MeV. In order to measure the flux-weighted average cross sections (gamma induced reactions) and excitation functions (proton induced reactions) for residual radionuclides the activation analysis was used. The gamma ray spectroscopy has been done by HPGe detector, which is available at the AANL as well. Detailed description of this facility is in Section 1.3.

In **CHAPTER 2 "Theoretical programs"** the theoretical programs related to this thesis are presented. The nuclear codes used for theoretical calculations and simulations are described in Sections 2.1-2.4. Apart from the experimentally accessible measurement of production cross sections, the theoretical modeling is necessary in order to understand the nuclear reactions. In addition, the theoretical modeling plays an important role to predict the cross sections for which measurements are either unavailable or have large discrepancies. In all experimental projects the theoretical calculations and simulations are needed, therefore different nuclear codes and the special written scripts were used.

CHAPTER 3 "Experiments and evaluation" is the largest section of the thesis. It is dedicated to the photon and proton induced experiments. There are presented both irradiation

conditions at LUE-75 linear accelerator (Section 3.1) and cyclotron C18/18 (Section 3.2), as well as the target preparations for the experiments. Both, for photon induced and proton induced experiments the target holders were made at the AANL (Subsections 3.1.1 and 3.2.1). In this part of thesis detailed parameters for each target is described separately (Subsections 3.1.2 and 3.2.2). The target materials are held in different target holders. A successful radionuclide production is crucially depends on the quality and composition of the target materials. The radionuclidic composition of the product is influenced by the isotopic composition of the target itself.

For the bremsstrahlung photon beam experiment the target holder was prepared manually, corresponding to the experiment conditions (Subsection 3.1.1). In Subsection 3.2.1 the Nirta target module for the cyclotron is presented. The targets descriptions and working parameters are described in details.

The flux-weighted average cross sections by gamma induced reactions (Subsections 3.1.4 and 3.1.5) are measured. The experiment has been done on the bremsstrahlung beam of the linear electron accelerator LUE-75 at 30 MeV and 40 MeV electron beam energies. The electron beam shape was elliptical with a 2 cm major and 1.4 cm minor axes. The photon flux determination has been realized by monitor reaction (Subsection 3.1.3). For the $^{nat}Re(\gamma,xn)$ reactions the calculated and measured flux-weighted average cross sections are presented in Table 1.

Taking into account that the monitor and studied reactions thresholds are different, the C_x flux conversion ratio is included. For $^{nat}Re(\gamma,xn)$ $^{182;183;184;186}Re$ reactions, the average flux obtained from the $^{65}Cu(\gamma,n)^{64}Cu$ monitor reaction is multiplied by a different conversion C_x factors, based on the monitor and studied reactions threshold difference.

The overall experimental uncertainties are coming from both statistical and systematic errors. The statistical errors are coming from counting statistics and mostly depend on the half-life of the radionuclides of interest. It is estimated to be about 3-7%. The systematic errors are due to uncertainties in the irradiation time - about 1%, the detection efficiency error - about 3%, the facility error about 10%. The overall uncertainties of the cross section measurements are in the range of 11-13% and the errors on the isomeric ratios and activity are the propagated errors from the reaction cross sections.

Table 1. The flux-weighted average cross sections for $^{nat}Re(\gamma,xn)^{182m,g;183;184m,g;186g}Re$ reactions based on the experimental data of Ref. [1] and calculations by TALYS 1.9 and EMPIRE 3.2

Residual nuclide	Bremsstrahlung end-point energy (MeV)	Flux conversion ratios (C_x)	Flux-weighted average cross section (mb)		
			Experimental	TALYS 1.9	EMPIRE 3.2
^{182g}Re	30	0.079	0.45±0.05	0.64	-
	40	0.224	0.93±0.09	1.34	-
^{182m}Re	30	0.079	2.27±0.23	1.19	-
	40	0.224	2.26±0.22	1.84	-
^{183}Re	30	0.518	16.56±1.98	30.3	40.02
	40	0.623	15.62±1.71	24.21	31.71
^{184g}Re	30	1.409	29.00±3.19	48.21	43.72
	40	1.305	24.06±2.52	42.94	39.13
^{184m}Re	30	1.366	0.78±0.09	1.26	0.47
	40	1.273	0.76±0.08	1.29	0.52
^{186g}Re	30	1.503	93.37±10.08	126.96	100.03
	40	1.374	92.12±9.48	110.45	87.01

The EMPIRE 3.2 does not perform the separation of metastable and ground states of $^{182m,g}Re$ isomeric pair, thus it is not given in Table 1. However, the TALYS 1.9 calculations are in good agreement with the measurements of current experiment for 30 MeV and 40 MeV bremsstrahlung end-point energies.

For ^{183}Re isotope, the experimental and theoretical results are different twice.

For ^{184g}Re isotope the calculations by both codes are in good agreement, while the experimental cross section is significantly lower from them.

In case of ^{184m}Re and ^{186g}Re the EMPIRE 3.2 calculations are closer to the experimental results. Following to obtained results, there is no significant description for all isotopes. In order to coordinate these disagreements between experiments and theoretical calculations, it is necessary to do more experiments in wide energy region.

For the $^{nat}Nb(\gamma,xn)$ processes the flux-weighted average cross sections are presented in Table 2. The comparison can be done taking into account the data from other data in literature.

It shows that for $^{93}Nb(\gamma,n)^{92m}Nb$ reaction, when the emission of one neutron takes place, there is good agreement between the experimental data based on the calculation of the number of photons performed by calculations using the TALYS 1.9 and EMPIRE 3.2 codes and the purely theoretical calculations using the same codes. It is notable that for all reactions the values of flux-weighted average cross sections calculated by EMPIRE 3.2 code are lower than the results from TALYS 1.9 code.

For reactions with a large number of emitted neutrons $^{93}Nb(\gamma,2n)^{91m}Nb$ and $^{93}Nb(\gamma,3n)^{90}Nb$, the experimental data based on the TALYS 1.9 and EMPIRE 3.2 codes are in good agreement, but they strongly differ from the theoretical calculations based on the same codes. In the case of the ^{90m}Nb isotope, due to the short lifetime ($T_{1/2}$=18.8 s), the total cross section of ^{90}Nb is measured, since ^{90m}Nb is converted into ^{90g}Nb by isomeric transition.

Table 2. Comparison of the experimental and theoretical data of the flux-weighted average cross sections with data from [2, 3]

Isotope	Energy (MeV)	Reference	Flux-weighted average cross section (mb)				
			Experimental results based on the calculated monitor reaction			Theoretical results	
			-	TALYS 1.9	EMPIRE 3.2	TALYS 1.9	EMPIRE 3.2
^{90}Nb	40	This work	-	2.88±0.033	2.62±0.031	2.25	1.56
	45	[2]	3.011±0.35	-	-	-	-
^{91m}Nb	30	This work	-	8.34±0.61	7.75±0.56	6.45	5.54
	40	This work	-	6.33±0.69	5.91±0.68	5.16	4.57
^{92m}Nb	12	[2]	8.73±0.196	-	-	-	-
	14	[2]	14.61±1.31	-	-	-	-
	16	[2]	20.37±1.65	-	-	-	-
	30	This work	-	36.79±0.38	34.19±0.35	31.06	26.20
	32	[3]	29.9±1.90	-	-	-	-
	40	This work	-	26.81±0.14	25.06±0.14	27.10	22.80
	45	[2]	23.94±1.89	-	-	-	-

The next part of this chapter deals to the measurement of excitation functions of proton induced reactions on ^{nat}W. The excitation functions for $^{nat}W(p,xn)^{181;182m,g,183;184g,186}Re$ reactions from the reaction thresholds up to the maximum energy provided by the cyclotron C18/18 have been obtained based on the external proton beam of cyclotron C18/18. In order to determine the excitation function, the stacked-foil technique has been used (Subsection 3.2.2). The measured cross sections and corresponding errors are summarized in Table 3.

The comparisons of the current experiment, theoretical calculations and available experimental data in literature have been done. For these comparisons the database after 2000 were taken. In order to increase the predictive power of theoretical models, it is necessary to use more new experimental data in RIPL (Reference Input Parameters Library).

Table 3. Measured cross sections and errors for ^{181}Re, ^{182m}Re, ^{182g}Re, ^{183}Re, ^{184g}Re, ^{186}Re radionuclides (* for the ^{186}Re the enriched target corrections have been done)

Proton energy (MeV)	Cross section (mb)					
	^{181}Re	^{182m}Re	^{182g}Re	^{183}Re	^{184g}Re	^{186}Re*
5.71±0.90	-	1.07±0.13	0.75±0.09	0.33±0.04	0.58±0.07	0.70±0.08
7.52±0.90	-	3.06±0.37	1.55±0.18	2.11±0.24	2.57±0.31	4.01±0.46
9.08±0.79	-	11.41±1.38	1.60±0.19	8.67±0.97	17.05±0.26	36.76±4.23
10.48±0.62	1.22±0.13	30.28±3.39	5.07±0.56	36.27±3.92	27.60±0.41	40.90±4.29
11.73±0.62	13.30±1.43	79.45±8.90	11.76±1.31	74.04±7.99	21.38±0.32	30.54±3.21
12.88±0.70	67.26±7.26	108.74±12.18	19.70±2.19	105.00±11.34	13.70±1.44	18.88±1.98
13.97±0.68	104.90±11.33	98.90±11.08	21.79±2.42	123.00±13.28	9.45±0.99	17.61±1.85
15.01±0.65	146.70±15.40	82.40±8.40	20.60±2.06	166.83±17.02	9.70±1.02	13.45±1.37
15.99±0.66	156.45±16.43	67.85±6.92	24.14±2.41	185.93±18.96	8.13±0.85	11.29±1.15
16.94±0.50	177.76±18.66	92.80±9.46	26.25±2.63	226.90±23.14	41.30±4.21	10.11±1.03

CHAPTER 4 "Isomeric cross section ratio" is dedicated to the measurement of ICRs of $^{182m,g}Re$, $^{184m,g}Re$ and $^{186m,g}Re$ isomeric pairs. ICRs for photon and proton reaction channels have been determined. The reaction channel dependence of ICR has been discussed and published earlier [4]. The empirical and semi-empirical results are obtained for both photon and proton induced reactions. The comparison of experimental and theoretical ICRs for the $^{182m,g}Re$ and $^{184m,g}Re$ isomeric pairs as well as the semi-empirical results for the $^{186m,g}Re$ isomeric pair for

the gamma induced reactions are presented in Table 4 and Table 5, respectively. The results for the ^{182m,g}Re and ^{184m,g}Re were obtained for the first time.

Table 4. The experimental and theoretical ICRs for ^{182m,g}Re and ^{184m,g}Re isomeric pairs

Isomeric pair	Bremsstrahlung end-point energy (MeV)	Isomeric Cross Section Ratio		
		Experimental	TALYS 1.9	EMPIRE 3.2
^{182m,g}Re	30	0.835±0.03	0.65	-
	40	0.709±0.01	0.58	-
^{184m,g}Re	30	0.026±0.002	0.025	0.011
	40	0.031±0.001	0.029	0.013

For ^{182m,g}Re isomeric pair EMPIRE 3.2 nuclear code does not distinguish metastable and ground states. Hence, only the TALYS 1.9 theoretical calculations have been done for this isomeric pair.

Table 5. The semi-empirical and theoretical ICRs for ^{186m,g}Re isomeric pairs

Isomeric pair	Bremsstrahlung end-point energy (MeV)	Isomeric Cross Section Ratio			
		Semi-empirical		Theoretical	
		TALYS 1.9	EMPIRE 3.2	TALYS 1.9	EMPIRE 3.2
^{186m,g}Re	30	0.03	0.018	0.023	0.017
	40	0.029	0.0166	0.024	0.0176

Due to the stack-foil technique, for the proton induced reaction ten values of ICRs have been obtained. Therefore, the experimental and semi-empirical results for ten values of proton energies altogether are presented in Table 6 - Table 8.

Table 6. ICR data for ^{182m,g}Re isomeric pair

Proton energy (MeV)	Isomeric Cross Section Ratio	
	Experimental	TALYS 1.9
5.71±0.90	0.59±0.069	0.95
7.52 ± 0.90	0.66±0.030	0.89
9.08±0.79	0.88±0.006	0.83
10.48±0.62	0.86±0.004	0.78
11.73±0.62	0.87±0.003	0.72
12.88±0.70	0.85±0.005	0.65
13.97±0.68	0.82±0.006	0.60
15.01±0.65	0.80±0.008	0.55
15.99±0.66	0.74±0.015	0.50
16.94±0.50	0.78±0.013	0.47

The situation is different in case of ^{184m,g}Re and ^{186m,g}Re isomeric pairs. Due to the long half lives of metastable states ^{184}Re ($T_{1/2}$=169 d) and ^{186}Re ($T_{1/2}=2\times10^5$ y) radioisotopes, only the semi-empirical results are available.

Table 7. Semi-empirical and theoretical ICR results for ^{184m,g}Re isomeric pair

Proton energy (MeV)	Isomeric Cross Section Ratio			
	Semi-empirical		TALYS 1.9	EMPIRE 3.2
	TALYS 1.9	EMPIRE 3.2		
5.71±0.90	0.007	0.001	0.010	0.002
7.52 ± 0.90	0.058	0.017	0.020	0.006
9.08±0.79	0.067	0.023	0.039	0.011
10.48±0.62	0.081	0.039	0.095	0.025
11.73±0.62	0.130	0.071	0.200	0.048
12.88±0.70	0.215	0.107	0.303	0.067
13.97±0.68	0.307	0.133	0.378	0.081
15.01±0.65	0.317	0.112	0.421	0.088
15.99±0.66	0.419	0.109	0.174	0.080
16.94±0.50	0.281	0.044	0.157	0.069

Table 8. Semi-empirical and theoretical ICR results for ^{186m,g}Re isomeric pair

Proton energy (MeV)	Isomeric Cross Section Ratio			
	Semi-empirical		TALYS 1.9	EMPIRE 3.2
	TALYS 1.9	EMPIRE 3.2		
5.71±0.90	0.024	0.007	0.013	0.005
7.52±0.90	0.138	0.065	0.025	0.012
9.08±0.79	0.070	0.046	0.068	0.032
10.48±0.62	0.120	0.078	0.166	0.070
11.73±0.62	0.215	0.117	0.284	0.115
12.88±0.70	0.364	0.158	0.373	0.150
13.97±0.68	0.421	0.132	0.427	0.166
15.01±0.65	0.512	0.120	0.454	0.169
15.99±0.66	0.571	0.100	0.467	0.164
16.94±0.50	0.610	0.081	0.480	0.161

In **CHAPTER 5 "Determination of activity"** the possibility of ^{186g}Re production in both gamma and proton induced reactions are discussed. ^{186g}Re is one of widely used radioisotope in nuclear medicine. The specific activity results for 30 MeV and 40 MeV end-point bremsstrahlung energies are presented in Table 9.

Table 9. Specific activity comparison for ^{186g}Re isotope from ^{187}Re(γ,n) reaction

Research center	Electron Beam energy (MeV)	Specific activity (μCi/μA·h·g)
A.I. Alikhanyan National Science Laboratory	30	71.75±6.96
	40	95.69±10.72
Kharkov Institute of Physics and Technology (KIPT) [5]	40	56.9

There is no other experimental result for the 30 MeV end-point bremsstrahlung beam energy. In case of end-point bremsstrahlung energy 40 MeV the result from the current experiment is exceeding the result from [5]. Based on received data, it can be concluded that the

isotope ^{186g}Re can be produced in the bremsstrahlung beam of photons at high current.

For the proton induced ^{186g}Re production the activity values were obtained for thin targets corresponding to each value of proton beam energy (Table 10).

Table 10. The proton induced activity of the ^{186g}Re radionuclide for thin target

Proton Energy (MeV)	Activity (μCi/μA·h·g)
5.71 ± 0.90	0.042 ± 0.049
7.52 ± 0.090	2.424 ± 0.279
9.08 ± 0.79	22.219 ±2.555
10.48 ± 0.62	24.722 ± 2.596
11.73 ± 0.62	18.462 ± 1.938
12.88 ± 0.70	11.412 ± 1.198
13.97 ± 0.68	10.644 ± 1.118
15.01 ± 0.65	8.136 ± 0.829
15.99 ± 0.66	6.824 ± 0.696
16.94 ± 0.5	6.111 ± 0.623

From the isotope production point of view the integral activity is of interest. The experimental value of the integral activity, obtained by integrating the activity of thin targets, is compared with the theoretically calculated values by TALYS 1.9 code and recommended data from IAEA (see Fig. 1).

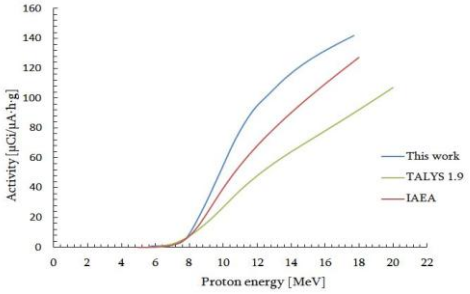

Fig. 1. The integral activity comparison for ^{186g}Re

In order to ensure in high specific activity of production, it is necessary to use the enriched target. In addition, to increase the radioactive purity of the final product and to avoid from accompanying reactions with high thresholds, it is necessary to limit the proton beam energy.

In **CONCLUSION**, the main results of the dissertation are summarized. For bremsstrahlung gamma induced reactions 30 MeV and 40 MeV electron beam energies were used. For proton induced reactions the energy range covered from reactions thresholds up to maximum energyprovided by C18/18. The irradiated targets were measured by off-line gamma spectroscopy. For all results the comparisons with available data from the other research groups have been done, while some of the results are obtained for the first time. Particularly, the data for the ^{91m}Nb radionuclide and ICRs for the ^{182m,g}Re, ^{184m,g}Re isomeric pairs are obtained for the first time.

The flux-weighted average cross sections for the ^{nat}Re(γ,xn)$^{182m,g;183;184m,g;186}$Re reactions have been measured. The separation of cross sections between metastable and ground states in case of ^{182}Re radionuclide is not performed by EMPIRE 3.2. However, the values based on TALYS 1.9 calculation are given, which are in good agreement with the current experiment for 30 MeV and 40 MeV bremsstrahlung end-point energies. For ^{183}Re isotope, the experimental and theoretical results are different twice for both the energies. For ^{184g}Re isotope the calculations by both codes are in good agreement, while the experimental cross section is significantly lower from them. In case of ^{184m}Re the EMPIRE 3.2 calculations are closer to the experimental results. For ^{186g}Re the experimental results are closer to the EMPIRE 3.2 calculations. Following to obtained results, there is no significant description for all isotopes. In order to coordinate these disagreements between experiments and theoretical calculations, it is necessary to do more experiments in wide energy region.

All data coming from photon induced experiment are included to the EXFOR database.

The results for the ^{93}Nb(γ,n)^{92m}Nb and ^{93}Nb(γ,3n)^{90}Nb reactions are compared with the available experimental data. There is a good agreement with the data of other authors. Comparison of the received experimental results, data available in literature and theoretical calculations of the flux-weighted average cross sections are summarized. It shows, when the emission of one neutron takes place (^{nat}Nb(γ,n)^{92m}Nb), there is a good agreement between the experimental data based on the calculation of the number of photons by codes and the purely theoretical calculations. It is important to mention, that the flux-weighted average cross sections

for all reactions calculated by EMPIRE 3.2 code are lower than the results from TALYS 1.9 code. For reactions with a large number of emitted neutrons (^{nat}Nb(γ,2n)^{91m}Nb; ^{nat}Nb(γ,3n)^{90}Nb), the experimental data based on both codes are in good agreement, but they strongly differ from the theoretical calculations based on same codes. Due to the short lifetime of ^{90m}Nb isotope ($T_{1/2}$=18.8 s), the total cross section for ^{90}Nb is measured, since ^{90m}Nb is converted into ^{90g}Nb by IT. The data for ^{90}Nb, ^{91m}Nb, ^{92m}Nb residual radionuclides are involved to the EXFOR database.

The next part of thesis is dedicated to the measurement of excitation functions of proton induced reactions on ^{nat}W. The excitation functions for ^{nat}W(p,xn)$^{181;182m,g,183;184g,186}$Re reactions from the reaction thresholds up to 16.94 MeV have been obtained based on the external proton beam of cyclotron C18/18. The measured cross sections and corresponding errors are summarized. The model calculations for these radionuclides have been done. In order to get higher accuracy results, it is necessary to do more experiments.

The upcoming part of thesis is dedicated to the ICR determination of ^{182m,g}Re, ^{184m,g}Re and ^{186m,g}Re isomeric pairs. The empirical and semi-empirical results are obtained for both gamma and proton induced reactions. The comparison of experimental and theoretical ICRs for the ^{182m,g}Re and ^{184m,g}Re isomeric pairs as well as the semi-empirical results for the ^{186m,g}Re isomeric pair for the gamma induced reactions have been determined. Due to the stack-foil technique, for the proton induced reaction ten values of ICRs have been obtained.

The possibility of ^{186g}Re production in both photon and proton induced reactions is discussed. ^{186g}Re is one of widely used radioisotope in nuclear medicine. Our research shows, that it is possible to produce ^{186g}Re radionuclide based on bremsstrahlung gamma beam with high beam current.

For the proton induced ^{186g}Re production activity it was obtained ten values, corresponding to the proton beam energy in each foil of stacked-target. The comparison with the experimental data from other research group shows, that it is possible to produce this radionuclide based on cyclotron C18/18 external proton beam. In order to get the clear product, the enriched tungsten target will be needed.

As a result, these experiments produce a new set of cross section data, which will extend cross section database and will contribute to develop new and improved simulation codes.

List of publiched papers

1. R. Avagyan, R. Avetisyan*, A. Gyurjinyan, V. Ivanyan, I. Kerobyan, “Study of high specific activity production of ^{186g}Re at cyclotron C18/18 by ^{186}W (p, n) reaction”. Armenian Journal of Physics. Vol. 11, pp. 101-106, 2018.
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4. A.E. Avetisyan, R.V. Avetisyan*, A.G. Barseghyan, Yu.A. Gharibyan, A.V. Gyurjinyan, R.K. Dallakyan, I.A. Kerobyan, H.A. Mkrtchyan. “Investigation of Flux-Weighted Average Cross Sections for Reactions on ^{93}Nb with Bremsstrahlung of LUE-75”. Physics of Atomic Nuclei, Vol. 84, pp. 245-249, 2021.
5. R.V. Avetisyan*, A.G. Barseghyan, Yu.A. Garibyan, A.V. Gyurdjinyan, I.A. Kerobyan, H.A. Mkrtchyan. “Production of ^{186g}Re Medical Isotope on the Proton Beam of Cyclotron C18/18”. Journal of Contemporary Physics, Vol. 56, pp. 1-5, 2021.

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5. N.P. Dikiy, V.A. Kushnir, Yu.V. Lyashko, V.V. Mitrochenko, S.A. Perezhogin, Yu.V. Rogov et. al. National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine, Pd and Re isotope production in the field of mixed x,n-radiation of electron accelerator.

Պրոտոն և ֆոտոն հարուցված ռեակցիաների գրգռման ֆունկցիաների և իզոմեր հարաբերությունների ուսումնասիրումը տարբեր միջուկների վրա

Ամփոփագիր

Պրոտոն և ֆոտոն հարուցված միջուկային ռեակցիաները մեծ նշանակություն ունեն ինչպես ֆունդամենտալ, այնպես էլ կիրառական գիտության մեջ: Այս ռեակցիաների հիման վրա ստացված տվյալները թույլ են տալիս մշակել և զարգացնել արդեն գոյություն ունեցող տեսությունները, ինչպես նաև մշակել նոր մոդելներ՝ ռեակցիաների մեխանիզմները ճշգրտելու համար:

Այս աշխատանքը նվիրված է վոլֆրամի, ռենիումի և նիոբիումի թիրախների վրա միջուկային ռեակցիաների փորձարարական և տեսական ուսումնասիրություններին: Գիտափոձերը կատարվել են պրոտոնային փնջի և արգելակային ճառագայթման միջոցով: Ընտրվել են այնպիսի ռեակցիաներ, որոնց արդյուքում ստացված նուկլիդներն ունեն նաև կիրառական նշանակություն: Գիտափորձերի ժամանակ օգտագործել են բարձր մաքրության բնական թիրախներ: Որոշ իզոմեր զույգերի համար կատարվել են իզոմեր հարաբերությունների չափումներ և հաշվարկներ:

Թեզի հիմնական նպատակն է՝

- միջին կտրվածքների չափումները $^{nat}Re(\gamma,xn)^{182;183;184;186}Re$ և ռեակցիաների համար;
- միջին կտրվածքների չափումները $^{nat}Nb(\gamma,xn)^{90;91;92}Nb$ ռեակցիաների համար;
- կտրվածքների չափումները $^{nat}W(p,xn)^{181;182;183;184;186}Re$ ռեակցիաների համար;
- իզոմեր հարաբերութունների չափումները $^{182m,g}Re$, $^{184m,g}Re$ և $^{186m,g}Re$ իզոմեր զույգերի համար;
- ֆոտոն և պրոտոն հարուցված ռեակցիաներում տեսակարար ակտիվության որոշումը բժշկական ^{186g}Re ռադիոնուկլիդի համար:

^{182m,g}Re և ^{184m,g}Re իզոմեր զույգերի համար իզոմեր հարաբերությունների կիսաէմպիրիկ արդյունքները և ^{91m}Nb իզոտոպի համար կտրվածքի տվյալները ստացվել են առաջին անգամ:

Գիտափորձերն իրականացվել են Ա.Ի. Ալիխանյանի անվան ազգային գիտական լաբորատորիայում (ԱԱԳԼ), Երևան, Հայաստան:

Ֆոտոն հարուցված ռեակցիաներն իրականացվել են ԼՈՒԵ-75 գծային էլեկտրոնային արագացուցչի արգելակային փնջի վրա: Ճառագայթումն իրականացվել է էլեկտրոնների 30 ՄէՎ և 40 ՄէՎ էներգիաների արգելակային ճառագայթման համար:

Պրոտոն հարուցված ռեակցիաներն իրականացվել են ցիկլոտրոն C18-ի դուրս բերված պրոտոնային փնջի վրա՝ ռեակցիաների շեմային էներգիաներից մինչև 18 ՄէՎ:

Գիտափորձերն իրականացվել են ակտիվացիոն մեթոդի կիրառմամբ: Ճառագայթված թիրախների համար գամմա սպեկտրները չափվել են բարձր մաքրության գերմանիում դետեկտորի միջոցով (HPGe detector)՝ օգտագործելով MAESTRO ծրագրային փաթեթը:

Փորձերի արդյունքում ստացված տվյալները համեմատվել են ինչպես տեսական հաշվարկների՝ այնպես էլ այլ գիտական խմբերի կողմից կատարված աշխատանքների հետ: Տեսական հաշվարկները կատարվել են TALYS 1.9 և EMPIRE 3.2 միջուկային կոդերով՝ տարբեր մոդելների համար: Վերոնշյալ համեմատությունը ցույց տվեց մոդելների հետագա կատարելագործման անհրաժեշտությունը:

ԼՈՒԷ-75-ի վրա կատարված գիտափորձերից ստացված բոլոր արդյունքները տեղ են գտել EXFOR միջազգային փորձարարական տվյալների բազայում: Գիտափորձերի արդյունքում ստացված տվյալները տպագրվել են տեղական և միջազգային ամսագրերում:

Изучение функций возбуждений и изомерных отношений для разных ядер в протон и гамма индуцированных реакциях

Резюме

Протон и фотон индуцированные ядерные реакции имеют огромное значение как в фундаментальной, так и в прикладной областях науки. Данные, полученные на основании исследований этих реакций, предоставляют возможность улучшить и развить как уже существующие теоретические модели, так и разработать новые модели с целью уточнения механизмов реакций.

Данная работа посвящена экспериментальному и теоретическому исследованию ядерных реакций на мишенях вольфрама, рения и ниобия. Эксперименты были выполнены с использованием протонного пучка и тормозного излучения. Для эксперимента были выбраны такие реакции, в результате которых получаются нуклиды, имеющие прикладное значение. В качестве мишеней были использованы натуральные мишени высокой чистоты. Для некоторых изомерных пар выполнены измерения и вычисления изомерных отношений.

Основной целью диссертации является:

- измерение средне-взвешенных сечений для реакций $^{nat}Re(\gamma,xn)^{182;183;184;186}Re$;
- измерение средне-взвешенных сечений для реакций $^{nat}Nb(\gamma,xn)^{90;91;92}Nb$;
- измерение сечений для реакций $^{nat}W(p,xn)^{181;182;183;184;186}Re$;
- измерение изомерных отношений для изомерных пар $^{182m,g}Re$, $^{184m,g}Re$ и $^{186m,g}Re$;
- определение удельной активности для используемого в медицине изотопа ^{186g}Re в протон и фотон индуцированных реакциях.

Для $^{182m,g}Re$ и $^{184m,g}Re$ изомерных пар впервые получены полуэмпирические результаты изомерных отношений.

Экспериментальные данные для средне-взвешенных сечений для изотопа ^{91m}Nb получены впервые.

Эксперименты были выполнены в Национальной Научной Лаборатории имени А.И. Алиханяна, Ереван, Армения.

Эксперименты с фотон индуцированными реакциями были осуществлены на тормозном пучке электронного линейного ускорителя ЛУЭ-75. Облучения проводились при энергиях электронов 30 МэВ и 40 МэВ.

Эксперименты с протон индуцированными реакциями были выполнены на выведенном протонном пучке циклотрона С18/18 при пороге исследуемых реакций до 18 МэВ.

Эксперименты проводились с использованием активационного метода. Спектроскопические измерения облученных мишеней были выполнены посредством сверхчистого германиевого детектора (HPGe detector) с последующей обработкой программным пакетом MAESTRO.

Полученные в результате выполненных экспериментов данные были сравнены как с теоретическими вычислениями, так и с данными других авторов. Теоретические вычисления проводились посредством ядерных кодов TALYS 1.9 и EMPIRE 3.2 с использованием различных моделей. Проведенные сравнения свидетельствуют о необходимости дальнейшего развития существующих моделей.

Экспериментальные результаты, полученные на ЛУЭ-75, занесены в международную базу экспериментальных данных EXFOR.

Результаты экспериментов опубликованы в международных и местных журналах.