PRODUCTION OF ISOMERIC STATES IN THE DEUTERON-INDUCED REACTION OF GOLD AT INCIDENT ENERGY 4.4 GEV

Elmira Melyan

Doctoral Degree Programme (1), FEEC BUT
E-mail: melyan@feec.vutbr.cz

Abstract: Gold targets were irradiated by 4.4GeV deuteron beam at Nuclotron in the Joint Institute for Nuclear Research in Dubna, Russia. Residual nuclei were formed at ground and isomeric states from the interaction of deuteron and gold target, which have been measured and investigated by the induced-activity method. Cross sections of ground and isomeric states were obtained with corresponding isomer ratios of nuclides formed by the reaction as a result of this study.

Keywords: nuclear reactions, residual nuclei, isomeric states, cross-sections

1 INTRODUCTION

The long-lived excited state of an atomic nucleus in which the decay to the nuclear ground state is inhibited by spin-parity combination of the excited and ground states is known as isomeric state, i.e. metastable state. The aim of the current experiment is to obtain a set of experimental cross-sections of formation of residuals in the reaction of deuterons with gold (^{197}Au). The particular interest in the deuteron-induced reactions on intermediate to heavy-mass targets is due to the fact that deuteron is considered to be the lightest weakly bound system, and thus during the interaction with a target nucleus, the characteristics of the interactions of the individual nucleons can be derived. Especially, the reaction induced by high-energy deuterons can proceed with the deuteron either as whole nucleus or as non-interacting nucleons.

Investigated data has major role in estimation of the contribution of different reaction channels, e.g. spallation, fission, multifragmentation processes. Spallation is the process, where one heavy fragment with mass close to the target mass is formed, fission on the other hand is the process in which a heavy nucleus splits into two or several daughter nuclei (elementary particles could be also produced), multifragmentation is the process leading to the formation of several fragments (more than two). Nuclear isomers play an important role in medical applications due to soft betta and gamma radiation and the absence of radioactive contamination after its decay. Isomers, which have suitable half-lives and radioactive properties, can be successfully used as radioactive sources for therapy of different types of cancer.

Induced-activity method [1] is used to study the production of nuclei in the isomer state from the interaction of 4.4 GeV deuteron beam with a gold target. This method in combination with appropriated nuclear properties allows us to identify, as well as determine the production cross-sections of the reaction products in isomeric states. The ground (σ_g) and metastable states (σ_m) of a nucleus depends on the angular momentum [2] of the entrance channel of the reaction, excitation energy of the residual nucleus and the type of particles emitted during its de-excitation. Study of the angular momenta of the reaction fragments can provide inside into an information about the configuration of the nuclear system at high excitation. The information about the primary angular momenta of the fragments can be obtained from the measurements of independent isomer ratios of the reaction products.

Usually, such measurements are based on the cross-section ratio of high-spin state (I_h) to low-spin state (I_l) called Isomer Ratio:

$$IR = \sigma(I_h)/\,\sigma(I_l) \quad (1)$$

The interpretation of the high spin states population maybe important for the understanding of the mechanism of the intermediate and high-energy particle interaction with nuclei. Gold target is attractive, since different interaction channels are present in the experimental data and are available for comparison. Nevertheless, the literature shows a lack of experimental data for the deuteron interaction with the gold target.

2 EXPERIMENTAL PROCEDURE

The experiment was conducted at Nuclotron of the Laboratory of High Energies (LHE), the Joint Institute for Nuclear Research (JINR), Dubna. Gold target with dimension of 20x20 mm^2 and thickness of 39.13 mg/cm^2 irradiated with 4.4 GeV energy deuteron beam during 28.6-hour time period. The total ion beam intensity was in the range of 6.43×10^{12} deuterons. The target consisted of a stack of 15 gold foils in order to enhance the statistics. Following reaction was used for monitoring $^{27}Al(d,3p2n)^{24}Na$. Induced-activity method was applied, where the γ-rays from the decay of the reaction residues formed in the target were measured in an off-line analysis. The characteristic γ-spectra of residual nuclei, generated in the target, were measured with high purity germanium (HPGe) detectors and evaluated by the code package DEIMOS32 [3] and the radioactive nuclei were identified by the energy and intensity of their characteristic γ lines, as well as by their respective half-lives. Cross-sections of residual nuclei were calculated by using the following equation:

$$\sigma = \frac{\Delta N\lambda}{N_n N_d k\varepsilon\eta\left(1-e^{-\lambda t_1}\right)e^{-\lambda t_2}\left(1-e^{-\lambda t_3}\right)}, \quad (2)$$

where (σ) is the cross-section of the reaction fragment production, (ΔN) is an area under the photopeak and (N_d) is the deuteron beam intensity, (N_n) is the number of target nuclei, t_1 is the irradiation time, (t_2) is the time of exposure between the end of the irradiation and the beginning of the measurement, (t_3) is the measurement time, (λ) is the decay constant, (η) is the intensity of gamma transitions, (k) is the total coefficient of gamma ray absorption in the target and detector materials, (ε) is the gamma ray detection efficiency.

3 RESULTS

The experimental cross-section of nuclides formed by the reaction of 4.4 GeV deuterons with ^{197}Au is presented in Table 1, where the types of cross-section (I-Independent and C-Cumulative) and the type of decay (β and EC) are also presented. Cross-sections calculated by DEIMOS code packages are provided in the last two columns and in the range of errors, their values are corresponding. In the case of $^{197\text{m}}Hg$ production, probably the neutron in the composition of deuteron doesn't interact, in contrast the proton has strong interaction with the neutron of gold. Thereby proton changes to neutron and the neutron of the target to proton, thus Hg nucleus originates with high spin. Production of isomer states of Hg proves the fact that, as much the number of emitted neutrons, as high the probability of production of spin states. The same is for Hf isomers.

The experimental cross-sections (independent (I) and cumulative (C)) for the reaction fragment production in the mass range of $44 \leq A \leq 198$ are presented in Table 1, as well as the decay type and the spin. The highest production cross-section for ^{196}Au explained by its ability to form by one neutron transfer reaction.

Nuclei	Type	Decay	I^P	σ, mb Deimos
^{44g}Sc	I	EC	2^+	1.76±0.7
^{44m}Sc	I	EC	6^+	0.45±0.16
^{92m}Nb	I	EC,β^-	2^+	0.38±0.2
^{95}Tc	C	EC	$9/2^+$	9.67±2.0
^{95m}Tc	C	EC	$1/2^-$	1.92±0.5
^{95}Nb	I	β^-	$9/2^+$	1.09±0.3
^{95m}Nb	C	β^-	$1/2^-$	0.35±0.01
^{102}Rh	I	EC,β^-	$1/2^-$	3.85±0.6
^{102m}Rh	I	EC,β^-	6^+	13.15±0.23
^{106m}Ag	I	EC,β^-	6^+	2.31±04
^{110m}Ag	I	EC,β^-	6^+	0.32±0.02
^{117m}Sn	C	IT	$11/2^-$	0.23±0.02
^{121g}Te	I	EC	$1/2^+$	11.34±0.91
^{121m}Te	I	β^+	$11/2^-$	0.67±0.34
^{148}Pm	I	β^-	1^-	3.76±0.52
^{148m}Pm	I	β^-	6^-	1.1±0.29
^{177m}Lu	C	β^-	$7/2^+$	1.36±0.3
^{177m}Hf	I	IT	$37/2^-$	2.45±0.3
^{179m}Hf	I	EC	$25/2^-$	1.03±0.1
^{184g}Re	I	EC	3^-	0.92±0.18
^{184m}Re	I	EC	8^+	4.09±0.25
^{185}Ir	C	Cβ^+	$5/2^-$	26.97±2.68
^{185}Os	I	Iβ^+	$1/2^-$	37.44±2.23
^{193}Hg	C	EC	$3/2^-$	3.39±1.1
^{193m}Hg	I	EC	$13/2^+$	7.19±0.8
^{194m}Ir	C	β^-	4^+	1.13±0.1
^{196}Au	I	EC,β^-	2^-	135.26±14.31
^{196m}Au	I	EC,β^-	12^-	5.56±0.3
^{197m}Hg	I	EC	$13/2^+$	2.63±0.2
^{197g}Hg	C	EC	$1/2^-$	14.73±4.0
^{198g}Au	I	β^-	2^-	1.56±0.25

Table 1: Cross-sections of residual nuclei

Table 2 lists cross-sections of several isomeric pairs, which were been detected. According to Table 2 for the isomers of ^{196}Au and ^{197}Hg nuclei has IR less than one, indicating that the mechanism of their formation is other than fission-like and/or spallation processes, such as direct interacted reaction. This is conditioned by high probability of origination of the low spin states, which decreases the isomer ratio value.

Nuclei	σ_m	State/Spin	σ_g	σ_m/σ_g
44Sc	0.45±0.16	m(6+) g(2+)	1.76±0.7	0.25±0.09
95Nb	0.35±0.01	m(1/2-) g(9/2+)	1.09±0.3	3.11±0.8
95Tc	1.92±0.5	m(1/2-) g(9/2+)	9.67±2.0	5.03±0.5
102Rh	13.15±0.23	m(6+) g(2-)	3.85±0.6	3.41±0.6
184Re	4.09±0.25	m(8+) g(3-)	0.92±0.18	4.44±1.1
193Hg	7.19±0.8	m(13/2+) g(3/2-)	3.39±1.1	2.12±0.7
196Au	5.56±0.3	m(12-) g(2-)	135.26±14.31	0.04±0.005
197Hg	2.63±0.2	m(13/2+) g(3/2-)	14.73±0.4	0.17±0.4

Table 2: Cross-sections of nuclei with ground and isomer states and the corresponding isomer ratios

4 CONCLUSION

As a result of this study the isomer ratio of eight nuclides produced by deuteron-induced reactions on gold target at intermediate energy is calculated. The cross-sections of 29 radioactive products formed in the reaction of deuterons with gold have been measured at bombarding energy of 4.4 GeV. The production cross-sections of the two isomer isotopes ^{193m}Hg and ^{197m}Hg are 7.19 ± 0.80 and 2.63 ± 0.20 respectively. The fact that production of cross-sections is higher for the ^{193m}Hg isotope indicates that when more neutrons are emitted from the composite remnant nucleus, high spin state isotopes are more likely to form in the final residue.

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