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Isomeric cross-section ratios resulted from reaction (p,n) on targets ^{100}Ru and ^{104,106,110}Pd

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Abstract. The isomeric cross section ratios for production ^{100mg}Rh and ^{104mg,106mg,110mg}Ag in reaction (p,n) were measured over energy range from ∼6 MeV to ∼9 MeV. Statistical model calculations were performed for analyzing the experimental isomeric ratios and it was found that the theoretically calculated ratios agree well with our experimental results. In the present work the tendency that theoretical values will be larger than experimental results for energy above 9 MeV was indicated and the influence of the optical model parameters and the level density model was discussed.

PACS. 24.60.Dr Statistical Compound-nucleus reactions – 24.90.+d Other topics in nuclear reactions: general – 25.40.Ep Inelastic proton scattering

1 Introduction

Studies of excitation functions of proton threshold reactions on medium mass nuclei are of considerable significance for testing nuclear models. Furthermore, isomeric cross section ratios are of great interest for studying the spin dependence of formation isomeric state. However, the available information on the latter, especially as a function of incident proton energy, is often unsatisfactory. So in this work we chose to investigate the isomeric pairs ^{100mg}Rh and ^{104mg,106mg,110mg}Ag found in (p,n) reaction on ^{100}Ru and ^{104,106,110}Pd, respectively. To our knowledge, the isomeric ratios as results of reaction (p,n) on targets ^{100}Ru and ^{106}Pd are absent in literature.

A description of the experimental procedure is presented in Sect. 2. Section 3 is a discussion of the isomeric ratio calculation. In Sect. 4, the experimental results are compared with calculations and the conclusions are summarized.

2 Experimental method

The experiments were carried out at the MGC-20 cyclotron with diameter 103 cm. Energetic resolution of beam is about $\Delta E/E \sim 1.1 \times 10^{-3}$. Beams of proton with laboratory energy from ∼6 to ∼9 MeV were used to bombard thin targets of enriched metallic ^{100}Ru and ^{104,106,110}Pd respectively. These targets were prepared in PH “Kyrkatovskii Institute” in Saint Petersburg. Information about them is given in the following table.

Table 1.

	^{100}Ru	^{104}Pd	^{106}Pd	^{110}Pd
Thickness (mg/cm^2)	1.3	0.56	0.3	0.42
Purity (%)	92.9	99.6	91.2	98.2

During bombarding, a silicon-barrier detector was used to monitor the elastic scattering proton and placed at 21 degrees relative to the beam direction. The intensity of irradiation was about ∼100 nA. Each irradiated sample was counted on a Ge(Li) detector, which achieved an energy resolution of 3.0 keV (full width of half maximum) at 1332.5 keV. The absolute photopeak efficiency of the gamma detector, which was obtained by using the calibrated source ^{152}Eu, was determined with an accuracy of ∼1% (statistical error). In measuring γ-rays from ^{152}Eu and irradiated foils there was always a γ-resource ^{60}Co with its location fixed near the γ-detector. The photopeak counts of ^{60}Co per time unit depended on the activity of the measured γ-resources. Therefore, the effect of the differences of dead time resulted from the differences of activities between ^{152}Eu and irradiated foils was corrected automatically if considering the relative changes of photopeak counts of ^{60}Co per time unit. The half-life and intensities used in our experiments are given in Table 2.

The time of irradiation and recording the γ-rays from residual nuclei, even the time interval between each recording of γ-rays and irradiation were selected according to half-lives of isomeric or ground state of the residual nu-

Table 2.

Residual nuclei	Half-life	Spin of isomeric or ground state	Energy of γ-rays (keV)	Intensity (%)	Ref.
^{100m}Rh	4.6m	(5^+)	540	1.68	[1]
			687	1.01	[1]
^{100g}Rh	20.8h	1^-	446	11.2	[1]
			540	78.4	[1]
			823	20.1	[1]
			1107	13.3	[1]
^{104m}Ag	37.6m	2^+	556	61	[2]
			768	0.61	[2]
			1239	2.59	[2]
^{104g}Ag	69.2m	5^+	556	92.8	[2]
			768	65.9	[2]
			1239	25.1	[2]
^{106m}Ag	8.46d	6^+	451	28.3	[3]
^{106g}Ag	23.96m	1^+	616	0.142	[3]
			621	0.32	[3]
^{110m}Ag	252.2d	6^+	658	94.4	[4]
			885	72.8	[4]
			937	34.3	[4]
^{110g}Ag	24.62s	1^+	658	4.5	[4]

clei. In this way the product rates of isomeric and ground states were got respectively, hence the isomeric ratio.

3 Calculation results

Calculation was performed in the frame of statistical model. We generated the particle transmission coefficients in the standard optical model using the potential of [5, 6] for the protons (see Tables 3 and 4) and of [7] for neutrons (see Table 5). In order to investigate the influence of optical potential on calculated isomeric ratios we used two sets of proton potential (see Tables 3 and 4). The energy dependence of both real and imaginary parts of proton optical potentials was taken from [8]. The present calculation is analogous to that of [9]. In our calculation all probable γ-decay of each excited level of product nuclei, which formulate the isomeric or ground states, were taken into account. In the product nuclei, the excited states were described by means of the discrete level information as far as possible. The branching ratios for γ-transitions between the discrete levels were got from literature [1–4]. Above the region of discrete levels, all excited states were treated as a continuum described by the Gilbert-Cameron level density model or the back-shifted Fermi gas model. The choice of level density parameters was guided by the compilation of Gilbert A. et al. [10] and Dig et al. [11]. The parameters were verified by checking the reproduction of cumulative level densities. The branching ratios of transitions E1, E2, E3, M1 and M2 were estimated using Weisskopf model [12].

Calculation results depend on the selection of the parameters of optical model and of level density model. In order to investigate the influence of optical potential, two sets of optical parameter for proton (see Tables 3 and 4) were used and the calculation results are shown in Fig. 1. These obviously show that the selection of optical parameter influences the calculation isomeric ratios. This can be understood if it is noticed that various optical parameters generate different partial transmission coefficients which influence the cross section formation of the isomeric and ground states. The distribution function of the angular momentum of the compound nucleus J_c depends on the transmission coefficients of proton. This function is given in [13, 14]

$$\sigma(J_c, E_p) = \pi\lambda^2 \sum_{S=|I-s|}^{I+s} \sum_{I=|J_c-S|}^{J_c+S} \frac{2J_c+1}{(2s+1)(2I+1)} T_1(E_p) \tag{1}$$

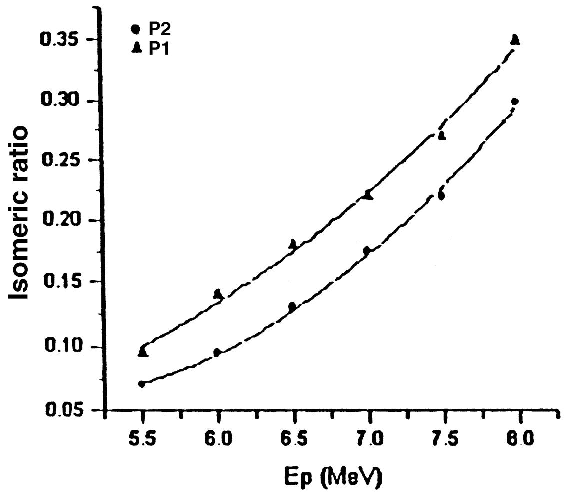

Fig. 1. The isomeric ratio calculated by using proton optical potential P1 and P2 for target ^{100}Ru

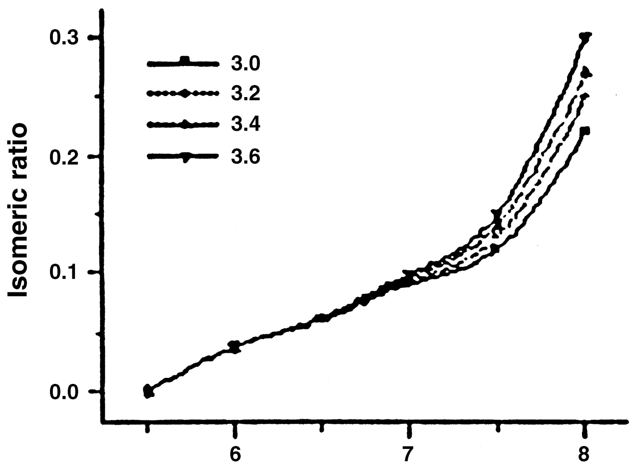

Fig. 2. The calculated isomeric ratios by using various spin-cutoff parameters σ: 3.0, 3.2, 3.4 and 3.6 for target ^{104}Pd

Table 3. First set of parameters of proton potential P1

Targets	V (MeV)	r_v (fm)	a_v (fm)	W_s (MeV)	r_w (fm)	a_w (fm)	V_{so} (MeV)	r_{so} (fm)	a_{so} (fm)
^{100}Ru	60.9	1.23	0.65	9.1	1.28	0.5	7.5	1.23	0.65
^{104}Pd	64.79	1.25	0.65	4.93	1.25	0.47	7.5	1.25	0.65
^{106}Pd	64.53	1.25	0.64	1.79	1.26	0.47	7.5	1.25	0.65
^{110}Pd	62.33	1.25	0.65	3.12	1.17	0.51	7.5	1.25	0.65

Table 4. Second set of parameters of proton potential P2

Targets	V (MeV)	r_v (fm)	a_v (fm)	W_s (MeV)	r_w (fm)	a_w (fm)	V_{so} (MeV)	r_{so} (fm)	a_{so} (fm)
^{100}Ru	66.9	1.22	0.69	2.68	1.22	0.26	7.5	1.22	0.69
^{104}Pd	61.93	1.29	0.65	7.61	1.22	0.64	7.5	1.25	0.65
^{106}Pd	58.43	1.26	0.65	10.84	1.37	0.22	7.5	1.25	0.65
^{110}Pd	59.43	1.25	0.65	23.17	1.24	0.30	7.5	1.25	0.65

Table 5. Optical parameters of neutron potential

$V = 48.7 - 0.33\text{En}$ (MeV)	$\text{Ws} = 7.2 + 0.68\text{En}$ (MeV)
$r_v = 1.25$ (fm)	$r_w = 1.25$ (fm)
$a_v = 0.65$ (fm)	$a_w = 0.43$ (fm)

where λ is the deBroglie wavelength of the incoming projectile, s the spin of the projectile, I the spin of the target nucleus and $T_1(E_p)$ the transmission coefficient of proton with orbital angular momentum 1 and energy E_p. This $\sigma(J_c, E_p)$ is distributed among the final states of residual nuclei by emission neutron. A compound state with angular momentum J_c emits a neutron with orbital angular momentum I, which leads to a final state with angular momentum J_f. The relative probability of formation of this final state is given by:

$$P(J_f) \propto \rho(J_f) \sum_{S=|J_f-1/2|}^{J_f+1/2} \sum_{I=|J_c-S|}^{J_c+S} T_I(E_n) \qquad (2)$$

where $T_I(E_n)$ is the transmission coefficient for emission neutron with orbital angular momentum I and energy E_n. The probability of populating a final state with spin J_f by neutron emission from a compound state of spin J_c depends on the level density $p(J_f)$. The formation cross section of final state of residual nuclei is given by the following formula:

$$\sigma_{\text{final}}(J_f) = P(J_f) \cdot \sigma(J_c, E_p) \qquad (3)$$

Further, the final excited state decays γ-ray, which leads to the formulation of isomeric and ground states. Therefore, the optical parameters of proton and neutron can considerably influence the calculation ratios. To obtain available ratios, a right optical potential is important.

It is well known that the parameters of level density model influence the calculation isomeric ratios (see (2)).

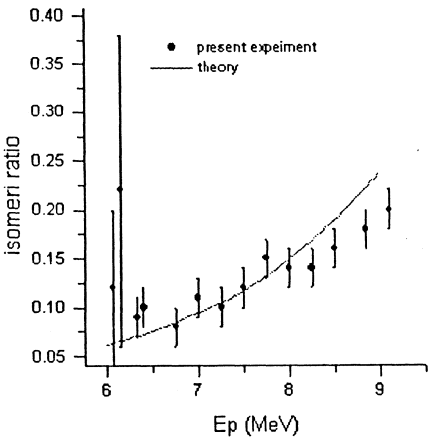

Fig. 3. The isomeric ratios plotted as the function of proton energy on target ^{100}Ru

These influences were also observed in our calculation. In the present work the isomeric ratios were calculated using three kinds of empirical formulae to describe level density: the constant temperature formula, the Gilbert-Cameron formula and the back-shifted Fermi gas model. The constant temperature formula is just the first part of composed four-parameter formula introduced by Gilbert-Cameron. Calculation isomeric ratios by using the first two level density models are near, although the level densities given by the first two formulae are very different for higher energy. Furthermore, it is found that the two models have the same σ. For the third level density model, the σ is not constant but depends on the excited energy. The calculation isomeric ratios of the last model are smaller than that of the other two (see Fig. 5) because of its smaller σ value. As the projectile energy increases, the angular momentum in the compound nucleus also increases, and the maximum of the distribution function $\sigma(J_c, E_p)$

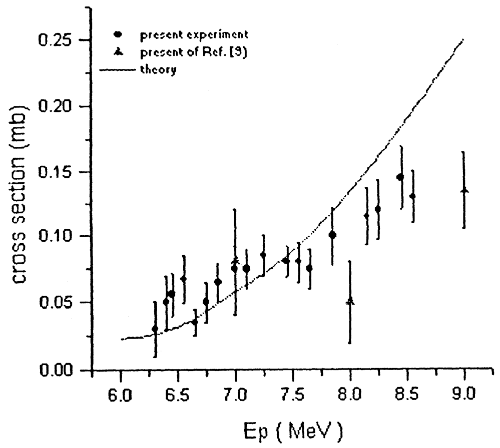

Fig. 4. The isomeric ratio plotted as the function of proton energy on target ^{104}Pd

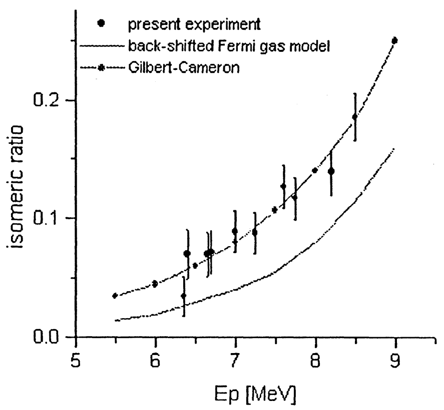

Fig. 5. The isomeric ratio plotted as the function of proton energy on ^{106}Pd

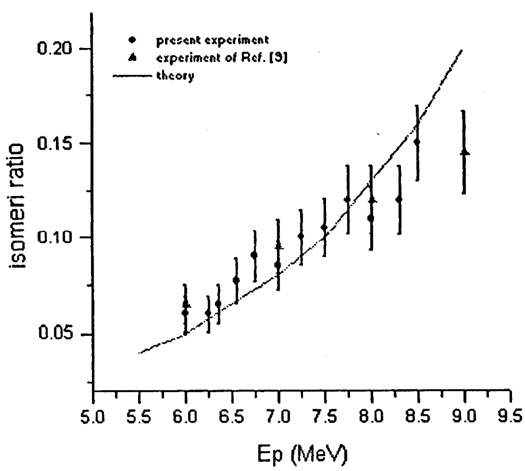

Fig. 6. The isomeric ratio plotted as the function of proton energy on ^{110}Pd

for the angular momentum J_c of the compound nucleus will move to the high spin J_c (see Fig. 4 of [15]). And the calculated isomeric ratios are much more sensitive to the parameter σ for reactions induced by energetic particles which produce compound nuclei of higher angular momentum or for reaction in which neutrons (which can carry more angular momentum) are emitted. So, as the projectile energy increases, the calculated isomeric ratios resulted from reaction (p, n) are more sensitive to the parameter σ [15, 16] (see Fig. 2).

4 Results and discussion

The results of measurement are presented in Figs. 3–6. The total error in the isomeric ratios amounts to 15%–20% (statistical error) and it can be larger in lower energy. For ^{100}Ru and ^{106}Pd, there are no experimental results in literature. For ^{104,110}Pd, the isomeric ratios were studied in [9] and their results are consistent with the present results (see Figs. 4, 6). The solid line in these figures is theoretical values got by using the proton optical parameter P1 and back-shifted Fermi gas model. The reason using the optical parameter P1 is that it gives us the calculation ratios close to the experiment results. As seen in these figures, the theory is in good agreement with the experiment except for ^{106}Pd. For ^{106}Pd, the fit will be better if we use Gilbert-Cameron model to estimate the level density (see Fig. 5). And for ^{100}Ru, we chose $J^{\pi} = 5^{+}$ as the quantum characteristic of isomeric state in our calculation. For all targets investigated here, as seen in Figs. 3, 4 and 6, the theoretically calculated ratios will be larger experimental ratios for energy above 9 MeV. This discrepancy is also observed in [17]. In this work the authors found that their theoretical ratios are much larger than their experimental results for energy above 10 MeV and this problem can not be resolved by varying the branching ratios of the discrete levels and the absolute normalization of the γ-ray strength functions and the relative M1/E1 normalization. However, our experiment and analyzing technology limit further conclusion.

To conclude, we measured the isomeric ratios resulted from reaction (p, n) on targets ^{100}Ru and ^{104,106,110}Pd. Experimental results were compared with the theoretically calculated values and a good agreement was found.

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