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# $^{106,110}$Pd (p,n$\gamma$)$^{106,110}$Ag reactions at $E_{\rm p} = 6.0 - 7.7$ MeV*

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This paper reports that the experimental excitation functions of reaction (p,n) are measured for $^{106}$Pd and $^{110}$Pd at proton energy $E_{\rm p} = 6.1 - 7.5$ MeV and $E_{\rm p} = 6.0 - 7.7$ MeV respectively. The off-resonance excitation functions were compared with calculation values of the statistical model. A new formula used to estimate the peak cross section of isobaric analogue resonance was tested and it was found that calculation values agree reasonably well with the present data within experimental error, which confirms that the excitation strength of isobaric analogue state in (p,n) reaction not only depends on its spin, but also proportionally increases with the projectile proton spatial transmission $T_{\rm p}$ and the spectroscopic factor $S$ for reaction (d,p) on the same target.

**Keywords:** isobaric analogue resonance, cross section, statistical model
**PACC:** 2430F, 2110H, 2460

## 1. Introduction

Nuclear reaction is an important tool to study the nuclear reaction mechanism, nuclear structure and nucleon–nucleon interaction.[1−3] Isobaric analogue states (IAS), observed as resonance in excitation function for (p,n) reaction, have been studied for decades and usually the relative cross sections were measured by measuring the emission neutron to understand the formation mechanism of isobaric analogue resonance (IAR) in the (p,n) reaction.[4,5] Previously, no work has focused on estimating the peak cross section of IAR although it can be significant when the experimental data are absent. Theoretical prediction of the peak cross section of IAR can help us understand the mechanism of IAR and obtain the full excitation function with IAR for (p,n) reaction. Although the experimental (p,n) cross section data have been measured for decades, some experimental data especially with small energy step and high quality are still absent. Further, most of the existent experiment (p,n) cross section data were obtained by measuring the emission neutron. So in recent years we have measured (p,n) reaction cross section by detecting the $\gamma$-ray from the residual nuclei and studying the possibility of predicting the peak cross section of IAR, and as a result successfully found a semi-empirical formula to estimate the peak cross section of IAR.[6,7] Some previous experiments have been reported for $^{106}$Pd at other energy ranges. But for $^{110}$Pd with energy step $< 15$ keV there are no absolute cross sections reported in the literature. The present work is a continuing study of IAR on target $^{106}$Pd and $^{110}$Pd.

## 2. The experimental method

The experiments were carried out at the MGC-20 cyclotron with diameter 103cm. Energy resolution of the beam is about $\Delta E/E \sim 1.1 \times 10^{-3}$. A proton beam with laboratory energy from $6.1 - 7.5$ MeV and $6.0 - 7.7$ MeV was used to bombard thin targets of enriched metallic $^{106}$Pd (0.3mg/cm$^2$ thick and 98.2% pure) and $^{110}$Pd (0.42mg/cm$^2$ thick and 98.5% pure) respectively. These targets were prepared at the PH 'Kyrkatovskii Institute' in Saint Petersburg.

During bombardment, a silicon-surface-barrier detector was used to monitor the elastically scattered proton at 21 degrees relative to the beam direction. Since at this angle the cross section for elastic scattering follows the Rutherford formula, knowing the solid angle of the monitor, we can easily obtain the absolute measurement of cross sections which is independent of target thickness and of integrated beam current. The time of irradiation was selected based on the lifetime of residual nuclei.

The beam current was about ∼100nA (electric) for $^{106}$Pd and ∼150nA for $^{110}$Pd. For $^{106}$Pd, the targets were removed from the scattering chamber after irradiation and placed in front of the Ge(Li)

$\gamma$-detector. For $^{110}$Pd, due to its short lifetime of residual nuclei $^{110}$Ag, we placed the Ge(Li) $\gamma$-detector just under the reaction chamber in order to count $\gamma$-rays from residual nuclei $^{110}$Ag almost immediately after irradiation. The $\gamma$-rays from activated foils were counted off line and the corresponding energy spectra were accumulated and recorded automatically at various times according to the lifetime of residual nuclei. The Ge(Li) detector achieved an energy resolution of 3.0 keV (FWHM) at 1332.5 keV. The absolute photo-peak efficiency of the gamma detector, which was obtained by using the calibrated source $^{152}$Eu, was determined with an accuracy of ∼1%. The lifetimes and absolute $\gamma$-ray intensities which were used in our experiment are shown in Table 1.

If lifetimes and absolute $\gamma$-ray intensities are known, it is possible to obtain the production rates of parent nuclei and, hence, the cross section. Taking into account the detector efficiency and extrapolating the decay curves at the end of bombardment, we determined the production rates from $\gamma$-ray peak areas. An absolute measurement of the cross section (p,n) was obtained by normalizing the Rutherford scattering.

**Table 1.** The information of $\gamma$-ray used in the present experiment.

| Targets | Residual nuclei | Lifetimes of residual nuclei | Energy of $\gamma$-rays for using/keV | Intensities/% | Ref. |
|---|---|---|---|---|---|
| $^{106}$Pd | $^{106m}$Ag | 8.46d | 451 | 28.3 | [8] |
| | $^{106g}$Ag | 23.96m | 616 | 0.142 | [8] |
| | | | 621 | 0.32 | [8] |
| $^{110}$Pd | $^{110m}$Ag | 252.2d | 658 | 94.4 | [9] |
| | | | 885 | 72.8 | [9] |
| | | | 937 | 34.3 | [9] |
| | $^{110g}$Ag | 24.6s | 658 | 4.5 | [9] |

In our experiment the total cross sections were obtained by adding the formation cross sections of ground and of isomeric states of residual nuclei ($\sigma_g$ and $\sigma_m$ respectively) together. The formation cross sections $\sigma_m$ were obtained with larger energy step (about ∼300 keV)[10] because of the long lifetimes of isomeric states. If isomeric ratio and $\sigma_g$ as a function of projectile proton energy are known, the total cross section at any energy can be obtained. Since $\sigma_m$ value is very small and its contribution to peak cross section of IAR is also small ($< 10\%$), the error from the unknowing effect in $\sigma_m$ at IAR is not significant. The effect of isomeric ratio at IAR was studied in Ref.[11].

There are several error sources which contribute to uncertainty in the cross section. Systematic errors arise from both the absolute Rutherford normalization (∼2%) and the $\gamma$-detector efficiency (∼1%). Uncertainties in absolute intensity of gamma transition of radioactive isotopes are $<\sim$ 1%. Pure statistical errors coming from determination of peak areas are $\sim$ 5%. The addition in quadrature of all kinds of errors yields an overall uncertainty of about $5\% - 6\%$ in the cross section.

## 3. Results and discussion

Measured cross sections for production $^{106}$Ag and $^{110}$Ag are shown in Figs.1 and 2 respectively, and some results from other works are also given. For $^{106}$Pd, the present results are consistent with those of Ref.[12], but our results and results of Ref.[12] are much larger than those of Ref.[13]. For $^{110}$Pd, our experimental excitation is in good agreement with the results of Ref.[13].

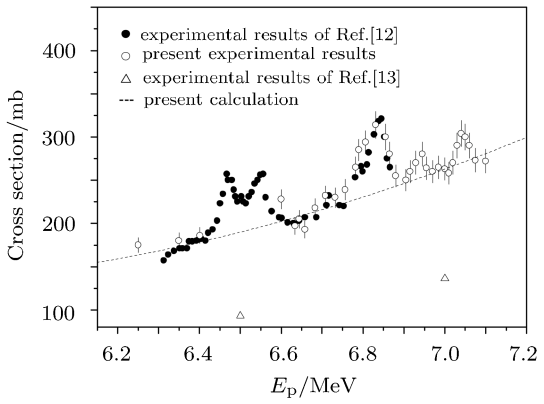



**Fig.1.** Excitation function with IAR on $^{106}$Pd plotted as a function of incident proton energy.

The experimental off-resonance excitation functions were compared with theoretical calculation of Hauser–Feshbach statistical theory. In our calculations, not only the (p,n) channel, but also emission channels (p,p), (p,$\gamma$) and (p,$\alpha$) were all taken into account. The calculation of (p,n) reaction cross sections was performed with the program in Ref.[14] by using

a standard optical model potential, whose parameters are taken from Ref.[15] for proton, from Ref.[16] for neutron and from Ref.[17] for alpha particle. The energy dependence of both real and imaginary parts of proton optical potential was taken from Ref.[18]. Parameter $a_v$ for proton channel was adjusted so that our experimental off-resonance excitation functions fitted the calculation results. And here we used the back-shifted Fermi gas model for the estimate of level density, whose parameter was taken or evaporated from Ref.[19]. The calculation results are shown in Figs.1 and 2.

The analogue of the state which can be strongly excited by (d,p) reaction is observed as a strong resonance in elastic scattering (p,p$_0$) and reaction (p,n) on the same target. So resonances in (p,n) reaction were identified as isobaric analogues, if the corresponding states were observed in (d,p) reaction on the same target. $E_{res}$, at which IAR on (p,p$_0$) and (p, n) reaction is observed, can be calculated with the formula given in Refs.[20,21].

The experimental peak cross section of IAR was obtained by the following calculation:

$$\sigma_{res}(p, n) = \sigma_{\text{on - res}}(E_{res}) - \sigma_{\text{off - res}}(E_{res}).$$

Here $\sigma_{\text{on - res}}(E_{res})$ is the experimental cross section and $\sigma_{\text{off - res}}(E_{res})$ the off-resonance cross section at $E_p = E_{res}$, respectively. Because the present off-resonance cross section calculation fits the experimental results, $\sigma_{off-res}$ is replaced by the calculated cross section at $E_p = E_{res}$.

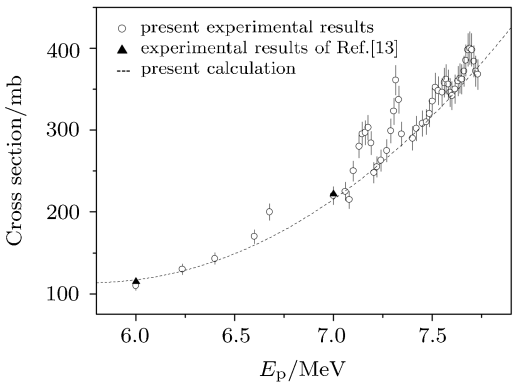



**Fig.2.** Excitation function with IAR on $^{110}$Pd plotted as a function of incident proton energy.

The peak cross section of IAR was theoretically estimated with the formula which was proposed by our group. The formula looks like the following:

$$\sigma_{res}(p, n) = 30 g \pi \lambda^2 T_p S W_{<>} .$$

where $g$ is the statistical factor, $S$ the spectroscopic factor for reaction (d,p) on the same target, $\lambda$ the wavelength for the bombarding proton, $T_p$ the spatial transmission coefficient of proton with the same $J$ as that of IAR, and $W_{<>}$ the parameter from known experimental data[7,12,22] and its value is given in Table 2.

**Table 2.** The dependence of parameter $W_{<>}$ on the spin of IAR.

| $J$ | 0 | 1 | 2 | 3 | 4 | 5 | 1/2 | 3/2 | 5/2 | 7/2 | 9/2 | 11/2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $W_{<>}$ | 1.15 | 3.09 | 4.13 | 4.13 | 3.41 | 2.40 | 2.21 | 3.75 | 4.25 | 3.85 | 2.91 | 1.98 |

$J$ is the spin of IAR.

The calculated peak cross sections are compared with experimental results in Tables 3 and 4. Spectroscopic factors $S$ for $^{106}$Pd and $^{110}$Pd and information about the levels of $^{107}$Pd and $^{111}$Pd are from Refs.[23] and [24] respectively. $T_p$ is calculated by using the same program as that for calculating cross section $\sigma_{pn}$. In Tables 3 and 4 only levels of $\sigma_{res} > 3$ mb are presented.

For $^{106}$Pd, the calculated peak cross sections are compared with the experimental results in Table 3. The third IAR corresponding to the levels of 303 keV and 313 keV should emerge at $E_p = \sim 6.8$ MeV according to our calculation, but it is too close to the strong fourth IAR to subtract its peak cross section. The fourth IAR (i.e. the first IAR of our experimental results) may correspond to the three levels of $^{107}$Pd: 367, 382 and 412 keV since IAR from them cannot be resolved experimentally.

As Table 4 indicates that the first two IARs in reaction (p,n) on $^{110}$Pd are very close, it is very likely that the wide resonance obtained at $E_p = 7.18$ MeV corresponds to the two levels of nuclei $^{111}$Pd with energy 0 and 72 keV. In the experiment, the IAR corresponding to the two levels of nuclei $^{110}$Pd cannot be resolved. Therefore, it is difficult to compare our experimental results with theoretical calculation shown in the table. But the experimental value of $\sigma_{res}$ at $E_p = 7.17$ MeV is close to the calculation value $\sigma_{res}$ for 72 keV level. The second experimental resonance at energy $E_p = 7.32$ MeV appears to

be associated with the three levels of $^{111}$Pd with energy 172, 192 and 231 keV. But the levels of 172 and 231 keV are absent in the table because the given $\sigma_{res}$ is very small (< 3mb) according to our calculation. In Ref.[25] the characteristic of level 192 keV is not given, but from Ref.[24] level 192 keV may be a doublet: $J^\pi = 1/2^+ + 3/2^+$. In the table, values $\sigma_{res}$ corresponding to $J^\pi = 1/2^+$ and $3/2^+$ are given and their sum is very close to our experimental result, which confirms the result of Ref.[24] but contradicts the result of Ref.[12]. Fig.2 shows that the third resonance corresponds to level 384 keV and the calculation values $\sigma_{res}$ by choosing $J^\pi$=$3/2^+$ and $5/2^+$ as the characteristic of this level are very close, so based on our work the spin of 384 keV cannot be determined. The fourth resonance at $E_p$ = 7.58 MeV may correspond to level 450 keV and in Ref.[23] the spin of the level is probably 7/2 or 3/2. If the level has $J^\pi$=$3/2^-$ the calculation peak cross section of IAR is very close to our experimental result.

**Table 3.** Information of IAR studied in the present work for $^{107}$Pd.

| $E_{lev}$ $^{107}$Pd /keV | $J^\pi$ | $E_p$(p,p$_0$) cal./MeV | $E_p$(p,n) cal./MeV | $\sigma_{res}$(p,n) cal./mb | $E_p$(p,n) exp./MeV | $\sigma_{res}$(p,n) exp./mb | $E_p$(p,n) exp./MeV[12] | $\sigma_{res}$(p,n) exp./mb[12] | $E_p$(p,p$_0$) exp./MeV[12] |
|---|---|---|---|---|---|---|---|---|---|
| 0 | $5/2^+$ | 6.49 | 6.47 | 48 | | | 6.47 | 65 | 6.48 |
| 116 | $1/2^+$ | 6.69 | 6.58 | 45 | | | 6.56 | 60 | 6.56 |
| 215 | $11/2^-$ | 6.7 | 6.7 | 4 | | | | | |
| 303 | $5/2^+$ | 6.79 | 6.79 | 35 | | | | | |
| 313 | $7/2^+$ | 6.8 | 6.8 | 4 | | | | | |
| 367 | $7/2^+$ | 6.86 | 6.86 | 9 | | | | | |
| 382 | $3/2^+$ | 6.87 | 6.86 | 48 | 6.84 | 75±25 | 6.85 | 80 | 6.88 |
| 412 | $1/2^+$ | 6.9 | 6.89 | 8 | | | | | 6.92 |
| 471 | $(3/2)^+$ | 6.96 | 6.95 | 27 | 6.94 | 24±15 | | | 6.98 |
| 568 | $5/2^+$ | 7.06 | 7.05 | 34 | 7.04 | 40±17 | | | 7.08 |
| 691 | $1/2^+$ | 7.19 | 7.18 | 16 | | | | | |
| 759 | $(3/2)^+$ | 7.25 | 7.25 | 13 | | | | | |

The errors of cross section used to get $\sigma_{res}$(p,n) in the table are than 6%.

**Table 4.** Information of IAR studied in the present work for $^{110}$Pd.

| $E_{lev}$ $^{111}$Pd /keV | $J^\pi$ | $E_p$(p,p$_0$) cal./MeV | $E_p$(p,n) cal./MeV | $\sigma_{res}$(p,n) cal./mb | $E_p$(p,n) exp./MeV | $\sigma_{res}$(p,n) exp./mb | $E_p$(p,p$_0$) exp./MeV[12] |
|---|---|---|---|---|---|---|---|
| 0 | $5/2^+$ | 7.14 | 7.14 | 36 | | | 7.136 |
| 72 | $1/2^+$ | 7.22 | 7.20 | 41 | 7.18 | 50±15 | 7.177 |
| 192 | $1/2^+ + 3/2^+$ | 7.34 | 7.33 | 54+18 | 7.32 | 80±18 | 7.311 |
| 384 | $3/2^+$ | 7.53 | 7.52 | 18 | 7.52 | 26±17 | 7.529 |
| | $5/2^+$ | 7.53 | 7.52 | 22 | | | |
| 450 | $7/2^-$ | 7.60 | 7.59 | 7 | 7.58 | 24±18 | 7.600 |
| | $3/2^-$ | 7.60 | 7.56 | 22 | | | |
| 508 | $1/2^+$ | 7.66 | 7.64 | 12 | | | |
| 534 | $7/2^-$ | 7.68 | 7.67 | 9 | | | |
| 587 | $3/2^-$ | 7.74 | 7.70 | 29 | 7.69 | 35±20 | 7.730 |
| 664 | $3/2^+$ | 7.81 | 7.80 | 13 | | | |
| | $5/2^+$ | 7.81 | 7.80 | 18 | | | |
| 715 | $3/2^+$ | 7.86 | 7.85 | 29 | | | 7.853 |
| | $5/2^+$ | 7.86 | 7.85 | 37 | | | |
| 740 | $3/2^+$ | 7.89 | 7.88 | 37 | | | |
| | $5/2^+$ | 7.89 | 7.88 | 50 | | | |

The errors of cross section used to get $\sigma_{res}$(p,n) in the table are than 6%.

To summarize the present paper, we can draw the following three conclusions:

1. The cross section (p,n$\gamma$ ) were measured on the target$^{106}$Pd and $^{110}$Pd.

2. The new formula, which can predict the peak cross section of IAR reasonably well, confirms that the excitation strength of IAS in (p,n) reaction not only depends on the spin of IAS, but also proportionally increases with the proton spatial transmission $T_p$ and the spectroscopic factor $S$ for reaction (d,p) on the same target.

3. According to the present study, level 192 keV of $^{111}$Pd could be a doublet with spin $J^\pi = 1/2^+ + 3/2^+$, and spin of level 450 keV very possibly is $3/2^-$.

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