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Direct neutron decay of analogue resonances in ^{105}Rh

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A new method, while takes into account the contribution of direct neutron decay of analogue resonances to the isomeric ratio resulting from (p,n) reaction, is used to analyse the published experimental data for the reaction ^{104}Ru(p,n)^{104}Rh and also estimate a minimum probability of direct decay.

Keywords: neutron decay, reaction, isobaric analogue state, compound nuclei, isomeric ratio
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1. Introduction

The reaction (p,n), passing through the excitation of isobaric analogue states (IASs) that mix with the compound nuclei states having the same spin and parity as those of an analogue state, is a complicated process. In 1975 a new theory was presented, according to which the partial cross section for an IAR (p,n) reaction (here IAR stands for isomeric analogue resonance) resulted from contributions of not only the statistical decay of IAS but also the direct decay of IAS.[1] Since then, a lot of work has been done on this subject.[2,3] In Ref.[2] authors pointed out the limitation of statistical approach to the description of partial cross section for IAR (p,n) reaction and proposed a method of analysis, in which the possible contribution of direct neutron decay of IAR was taken into account. Application of the method to the IAR in the compound nuclei ^{118,120}Sb and ^{94}Nb revealed a number of cases of excessive resonance enhancement and determination of the indirect neutron decay widths compared with the purely statistical description. In Ref.[3] authors also paid attention to this problem when they studied the isomeric ratios arising from reaction (p,n) on target ^{94}Mo. It was found that the difference in isomeric ratio between in- and out-regions of IAR is doubled. In this work we point out that the enhancement maybe is due to the direct decay of IAR. The mechanism for the decay of isobaric analogue state (IAS) is difficult to study both theoretically and experimentally, so this problem has been still open up till now. In the present paper we use a new method to re-analyse the published isomeric ratio resulting from reaction ^{104}Ru (p,n)^{104}Rh[4] in hopes of obtaining some information on IAR decay mechanism.

2. Theory

In Ref.[5] the experimental data on the partial cross section for the IAR (p,n) reaction were analysed on the assumption that for purely statistical neutron decays of IAR each resonance with a given J^π has the same relationship between the observed cross section at the resonance and the sum of the optical-model transmission coefficients as fellows:

$$C_1 \cdot \sigma_{\mathrm{Rh}} = \sum_{lj} T_{\mathrm{n}lj}(E_{\mathrm{n}k}),$$

where the summation is carried out over all indices l (neutron orbital angular momentum) and $j = l \pm 1/2$, permissible according to the selection rules for the transition from the resonant J^π to the kth level of the final nucleus I^π.

In Ref.[2] the description of $\sigma_{\mathrm{R}k}$ was carried out on the basis of a more complete formula that took into account the contribution of the direct neutron decay of IAR:

$$\sigma_{\mathrm{R}k} = 4\pi\lambda^2 g \Gamma_{\mathrm{p}} \Gamma^{-2} (F_{\mathrm{n}k} \Gamma_{\mathrm{n}}^{\downarrow} + \Gamma_{\mathrm{n}k}^{\uparrow}) \qquad (1)$$

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with

$$F_{nk} = \frac{\sum\limits_{LJ} T_{LJ}(E_{nk})}{\sum\limits_{LJi} T_{LJi}(E_{ni})}, \qquad (2)$$

where Γ, Γ_p, $F_{nk}\Gamma_n^{\downarrow}$ and $\Gamma_{nk}^{\uparrow}$ are respectively the total, proton, neutron (statistical), and direct neutron widths of the IAR; the factor F_{nk} means the relative probability of statistical decay of IAR with J^{π}-to-the kth level of the final nucleus with I^{π}. The total cross section for the IAR (p,n) reaction is obtained by summing over all open neutron channels in Eq.(2) as follows:

$$\sigma_R = 4\pi\lambda^2 g\Gamma^{-2}\Gamma_p(\Gamma_n^{\uparrow} + \Gamma_n^{\downarrow}) \qquad (3)$$

with $\sum\limits_k F_{nk} = 1$ and $\sum\limits_k \Gamma_{kn}^{\uparrow} = \Gamma_n^{\uparrow}$,

From this equation, it is clearly seen that the partial cross section of IAR consists of two parts: statistical decay and direct decay. In Ref.[2] by analysing the decay of isobaric analogue state in reaction ^{93}Nb(p,n)^{93}Mo, the value $\Gamma_n^{\uparrow}/(\Gamma_n^{\uparrow} + \Gamma_n^{\downarrow}) \approx 0.33$–$0.46$ was obtained.

In the present work we study the isomeric ratios in the region of IAR in hopes of obtaining some information about the mechanism of IAR decay.

According to Eq.(3) we have the following formula:

$$\sigma_R = \sigma_R^{\downarrow} + \sigma_R^{\uparrow},$$

where $\sigma_R^{\downarrow} = 4\pi\lambda^2 g\Gamma_p\Gamma^{-2}\Gamma_n^{\downarrow}$, $\sigma_R^{\uparrow} = 4\pi\lambda^2 g\Gamma_p\Gamma^{-2}\Gamma_n^{\uparrow}$. Here $\sigma_R^{\downarrow}$ and $\sigma_R^{\uparrow}$ are just the partial cross sections resulting respectively from the statistical and direct decays of IAR. But there are many non-IASs mixed with IAS in the compound nuclei, so the total cross section at IAR is

$$\sigma_{total} = \sigma_R^{\downarrow} + \sigma_R^{\uparrow} + \sigma,$$

where the σ is the cross section resulting from decay of background non-IAS at IAR. Taking into account both decay processes, we can obtain the isomeric ratio at IAR in the following form:

$$\eta = (\sigma_m^{\downarrow} + \sigma_m^{\uparrow} + \sigma_m)/(\sigma_g^{\downarrow} + \sigma_g^{\uparrow} + \sigma_g). \qquad (4)$$

Here $\sigma_m^{\downarrow}$, $\sigma_g^{\downarrow}$, $\sigma_m^{\uparrow}$ and $\sigma_g^{\uparrow}$ are partial formation cross sections of isomeric and ground states as a result of statistical and direct decays of IAS respectively; σ_m and σ_g are formation cross sections of isomeric and ground states due to the decay of non-IAS and their ratio is denoted by $\eta_c = \sigma_m/\sigma_g$.

From Eq.(4) we can obtain the following formula:

$$\eta = \frac{\eta^{\downarrow}\sigma_R^{\downarrow}/(\eta^{\downarrow}+1) + \eta^{\uparrow}\sigma_R^{\uparrow}/(\eta^{\uparrow}+1) + \sigma_m}{\sigma_R^{\downarrow}/(\eta^{\downarrow}+1) + \sigma_R^{\uparrow}/(\eta^{\uparrow}+1) + \sigma_g}, \qquad (5)$$

where $\eta^{\uparrow} = \sigma_m^{\uparrow}/\sigma_g^{\uparrow}$, and $\eta^{\downarrow} = \sigma_m^{\downarrow}/\sigma_g^{\downarrow}$.

What we are interested in is the direct decay intensity (i.e. $\sigma_R^{\uparrow}/\sigma_R$), and if we denote it by a, then a value can be given by the following formula:

$$a = \frac{(\eta - \eta^{\downarrow})\sigma_R/(1+\eta^{\downarrow}) + \eta\sigma_g - \sigma_m}{(1+\eta)\sigma_R\{1/(1+\eta^{\downarrow}) - 1/(1+\eta^{\uparrow})\}}. \qquad (6)$$

In this expression η is the experimental isomeric ratio at IAR; σ_R the partial cross section of reaction (p,n) at IAR; σ_g and σ_m can be obtained by evaluating the off-resonance experimental isomeric ratios η_c and excitation function, and $\eta^{\downarrow}$ can be calculated by the statistical theory. What is still unknown on the right-hand side of the expression (6) is $\eta^{\uparrow}$. So in order to obtain the value a, $\eta^{\uparrow}$ must be known. But we can acquire a minimum value a_{min} by letting $\eta^{\uparrow} \to \infty$.

3. Experimental results and discussion

The excitation function and the experimental isomeric ratios are shown in Figs.1 and 2 respectively. It is clearly seen that a peak appears each in Fig.1 and Fig.2 at the same energy E_p=6.74MeV, corresponding to the level 160 keV of ^{105}Ru with spin and parity $1/2^{+1}$. Besides this one, there appear other two resonances, corresponding to the levels 21 and 332 keV of ^{105}Ru respectively, which were observed in the excitation function but not remarkably in the isomeric ratios. In Fig.2 an enhancement appears at the first IAR but not as remarkably as at the second one, and no enhancement exists at all at the third IAR. These IASs were also strongly excited in elastic scattering of proton.[6] It can be understood from Eq.4 that the enhancement in isomeric ratio can be large only at IAS with a big σ_R. So we can expect that the enhancement in isomeric ratio for the third IAS should be smaller than that for either of the first two. The off-resonance isomeric ratios and excitation function (energy step $\geq$ 0.5MeV) were studied in Ref.[7], and their corresponding isomeric ratios are in good agreement with those in Ref.[4] at E_p=7.0 MeV, but their corresponding cross sections are smaller than those in Ref.[4] (see Figs.1 and 2).

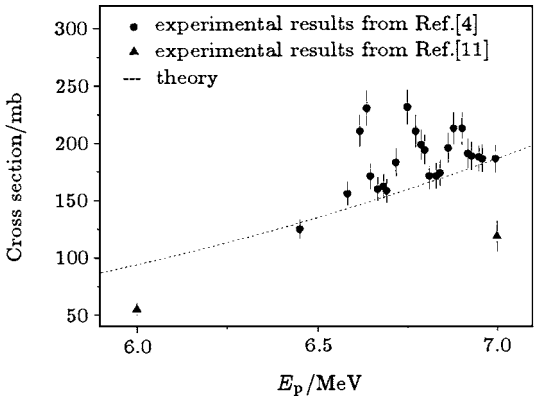


Fig.1. The excitation function on target ^{104}Ru from Ref.[4].

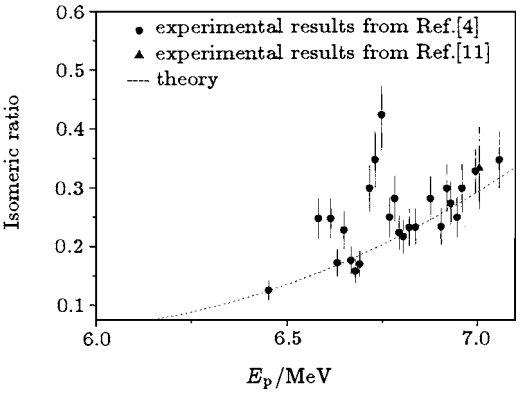


Fig.2. The isomeric ratio versus projectile proton energy (from Ref.[4]).

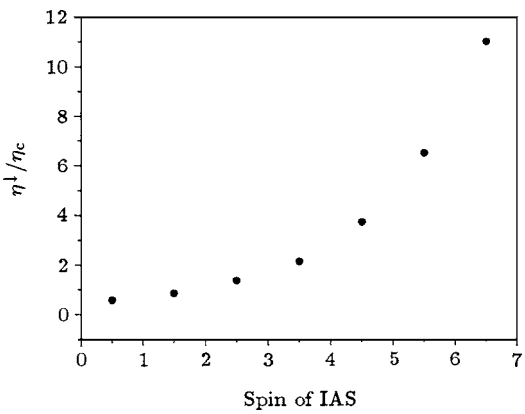


Fig.3. The ratio $\eta^{\downarrow}/\eta_c$ versus spin of IAS at E_p=6.74MeV.

The off-resonance isomeric ratio and excitation function were analysed by the statistical theory in Ref.[4] in which the optical potential was taken from Ref.[8] for proton, from Ref.[9] for neutron and from Ref.[10] for α in calculation. The energy dependence of both real and imaginary parts of optical potential for proton was taken from Ref.[11]. The isomeric ratios here were calculated in the same way as that in Refs.[4,12]. The excited states were described by use of the discrete level information as far as possible. Above the region of the discrete levels, all excited states were treated as a continuum described by the back-shifted Fermi gas model. According to the statistical model, the isomeric ratio depends not only on the spins of isomeric and ground states, but also on the cutoff parameter in the level density model. With the increase of the value of cut-off parameter and the difference in spin between isomeric and ground states, the calculated isomeric ratio increases.[13] The choice of parameters of level density was made according to the compilation in Ref.[14]. The parameters were verified by checking the reproduction of cumulative level densities. The branching ratios of transition: E1, E2, E3, M1 and M2 were estimated by Weisskopf model.[15] Dashed lines in Figs.1 and 2 and solid circles in Fig.3 are all for calculated results. In the present calculation, we exactly follow the same process and use the same parameters for optical potential and level density as those in Ref.[4].

The $\eta^{\downarrow}$ depends on resonant spin. The high spin excited state will most likely decay into high spin states of residual nuclei, as a result the $\eta^{\downarrow}$ increases as the spin of IAS increases. Figure 3 shows $\eta^{\downarrow}/\eta_c^{\rm theo}$ as a function of spin of IAS at E_p=6.74MeV, where $\eta_c^{\rm theo}$ is the calculated off-resonance isomeric ratio.

From Fig.3, we can see that when the spin of IAS is higher than 3/2, the ratio $\eta^{\downarrow}/\eta_c^{\rm theo}$ is bigger than 1. In this case, the contribution from the statistical decay of IAS can bring about an enhancement in isomeric ratio. So, the enhancement in isomeric ratio is caused not only by direct decay of IAR, but also by statistical decay of IAS. Because the theoretical $\eta_c^{\rm theo}$ is in good agreement with the experimental result in Ref.[4] (see Fig.2), in the present calculation of $a_{\rm min}$ the $\eta_c^{\rm theo}$ is replaced by the η_c.

For ^{104}Ru at E_p=6.74MeV the cross section and isomeric ratio without taking into account the contribution of IAR are σ_{pn}=160mb and η_c=0.23 (see Figs.1 and 2) respectively, the experimental cross section of IAR is σ_R=75mb, the experimental isomeric ratio at IAR is η=0.38, and according to our calculation we have $\eta^{\downarrow}$=0.6η_c (see Fig.3). Using these data we obtain $a_{\rm min}$=0.4, which implies that the direct IAS decay accounts for more than 40%, which confirms the results in Ref.[2]

In conclusion, we have derived a new formula which can be used to analyse the enhancement in iso-

meric ratio at IAR and thereby we can expect the isomeric ratio to be enhanced only at IAR with a big σ_{R}. According to our study, the enhancement in isomeric ratio at IAR possibly results not only from the direct neutron decay, but also from statistical decay. Analysing again the published experimental data in Ref.[4], we estimate the minimum direct decay intensity of IAS at E_{p}=6.74MeV in (p,n) reaction to be 0.4 in value. Although the new formula obtained in the present work can give us some important information about IAS decay, it cannot indicate how the direct neutron decay influences the isomeric ratio. Therefore, the further theoretical and experimental work is needed to solve this problem.

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