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Pre-equilibrium effects in the formation of meta stable states

R UPADHYAY, CH V SASTRY, R K JAIN and J RAMA RAO
Department of Physics, Banaras Hindu University, Varanasi 221 005, India

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Abstract. Isomeric yield ratios have been measured for $^{93}Nb(\alpha, 2n)^{95m,g}Tc$ reaction in the energy range 25–60 MeV. The ratios were compared with theoretical values obtained by means of two models one based on compound nucleus mechanism only and the other including pre-equilibrium effects. The trend of experimental ratios is better reproduced by the latter model, although there remains some discrepancy as to the magnitude at higher energies.

Keywords. Isomeric yield ratios; pre-equilibrium effects; moment of inertia; stack foil activation; γ-spectroscopy.

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1. Introduction

Generally in nuclear reactions, the residual nucleus is formed in meta stable states, whenever, between a pair of its levels, the spin difference is large and energy difference small. The study of the cross-section ratio for the formation of the same pair of isomeric states of the residual nucleus, at different projectile energies is of great interest in understanding the reaction mechanism and in determining the spin distribution of nuclear level density [1]. The spin distribution of the compound system is determined by the angular momentum brought in by the projectile which changes with the energy of the projectile. This spin distribution is subsequently altered by particle emission and gamma de-excitation leading to the final spin distribution of the residual nucleus. With the increase in energy pre-equilibrium reaction mechanism dominates and the above picture changes drastically. The importance of this pre-equilibrium or pre-compound process has been emphasized by Blann [2]. The main result of such process is to enhance the emission of particles (nucleons or nuclear clusters) with high energy and predominantly in forward direction. The occurrence of pre-equilibrium reactions will undoubtedly affect the angular momentum distributions of the residual nuclei since high energy nucleons emitted in the forward direction will remove, on an average, much more spin than low energy nucleons evaporated isotropically from an excited compound nucleus in statistical equilibrium. Thus it is to be expected that pre-equilibrium processes would have a measurable influence on the yields of isomers with large difference in spins. For the above reasons it will be interesting to look at the variation of the isomeric yields and their ratio as a function of incident particle energy and to compare the observed trend of variation with those predicted by models based on compound nucleus mechanism only and others including pre-equilibrium effects also, to see the difference.

In literature, for the reaction $Nb(\alpha, 2n)Tc^{m,g}$, the individual cross-sections for isomeric and ground states as well as the isomeric ratio were reported (Gadioli *et al*

[3]; Ernst *et al* [4]; Branquinho *et al* [5]) and compared [5] with hybrid model, but only up to 48 MeV. The aim of this paper is to measure the isomer ratios for the reaction $^{93}Nb(\alpha, 2n)^{95m,g}Tc$ in the extended energy up to 60 MeV and to compare the results, on the one hand, with the predictions of Huizenga-Vandenbosch model based only on the compound nucleus mechanism, and on the other, with the latest STAPRE model [6] including the pre-equilibrium effects in the framework of exciton model. The standard stack foil activation technique [7] and 60 MeV alpha particle beam from the Variable Energy Cyclotron Centre were employed to obtain the excitation functions of the isomers in the energy range of 25–60 MeV.

2. Experimental details

To obtain the isomer ratio, it is necessary to determine the individual cross-sections for the formation of the meta stable state and the ground state separately. This was done in the present case by taking advantage of their different half-lives, 61*d* for isomeric state and 20 h for the ground state respectively. For the measurement of the individual cross-sections, the stack foil activation technique [7] and HPGe γ-counting method were used. 60 MeV alpha particle beam from Variable Energy Cyclotron Centre, Calcutta, India was used in the experiment. A stack of six spectroscopically pure niobium foils of weight 28 mg/cm^2 each were irradiated. Suitable aluminium degraders were used in between the foils to obtain intermediate energy points. The energy of alpha particles after they had traversed half the thickness of each niobium foil was determined by range energy relations given by Williamson *et al* [8]. Beam currents of the order of 150 nA were used. The energy and efficiency calibration of the detector was performed with a standard ^{152}Eu source. For the flux measurement, $^{27}Al(\alpha, \alpha 2pn)^{24}Na$ reaction was used as a secondary standard [9].

In the reaction $^{93}Nb(\alpha, 2n)^{95}Tc$ the two isomers formed have widely different spin-parities and half-lives. While ^{95m}Tc has a spin-parity of $(\frac{1}{2})^-$, ^{95g}Tc has an opposite spin parity $(\frac{9}{2})^+$. They almost decay independently of each other except for a weak 4% isomeric transition from 61 day isomer to 20 h ground state. Their cross reactions were, therefore, determined individually using their characteristic gamma rays (204 keV to identify ^{95m}Tc and 1074 keV for ^{95g}Tc) and the cross-section formula:

$$\sigma = \frac{A_i \cdot A_\gamma \cdot \lambda}{\phi \theta_\gamma P_\gamma W_i P_i N_{av}(1 - e^{-\lambda t_i}) e^{-\lambda t_w}(1 - e^{-\lambda \Delta})}$$

where, σ = reaction cross reaction; A_i = atomic weight of the target element; ϕ = incident flux; θ_γ = absolute abundance of the gamma ray; P_γ = detector efficiency of that gamma ray; W_i = weight per unit area of the foil; P_i = isotopic abundance; N_{av} = Avagadro number; λ = disintegration constant; t_i = time duration of irradiation; t_w = waiting time; Δ = data accumulation time.

Errors: The statistical error is about 2% while the error in the photopeak efficiency is 5%. Error in the uniformity of the thickness is about 2%. Error in the gamma abundances is 4%. The quoted error in the standard monitor reaction cross-section σ_{Al} for $^{27}Al(\alpha, \alpha 2pn)^{24}Na$ was taken to be 6% as given by Probst *et al*. Combining all these errors, the total error on the measured cross-section was estimated to be less than 10%.

3. Theory

Huizenga and Vandenbosch were the first to develop a detailed method for the calculation of the isomeric cross-section ratios based on the statistical compound nucleus theory, with some simplifying assumptions. The calculations are done in three parts: (1) the normalized initial compound nucleus spin distribution is computed, (2) if the compound system decays by particle emission, then the normalized spin distribution following particle emission is calculated and, finally (3) the spin distribution of the nucleus following dipole γ-emission is calculated. The ratio of the high spin state population to the low spin state population will give the corresponding isomeric ratio.

The statistical pre-equilibrium model STAPRE was developed by Uhl and Strohmaier to calculate the cross-sections for particle induced nuclear reactions with several emitted particles and gamma rays under the assumption of sequential evaporation. The evaporation step is treated within the framework of the statistical model with consideration of angular momentum and parity conservation. For the emission of first particle pre-equilibrium decay is taken into account via the exciton model [10]. The individual cross-sections for ground and isomeric states are given by the model from which the corresponding isomer ratio can be calculated.

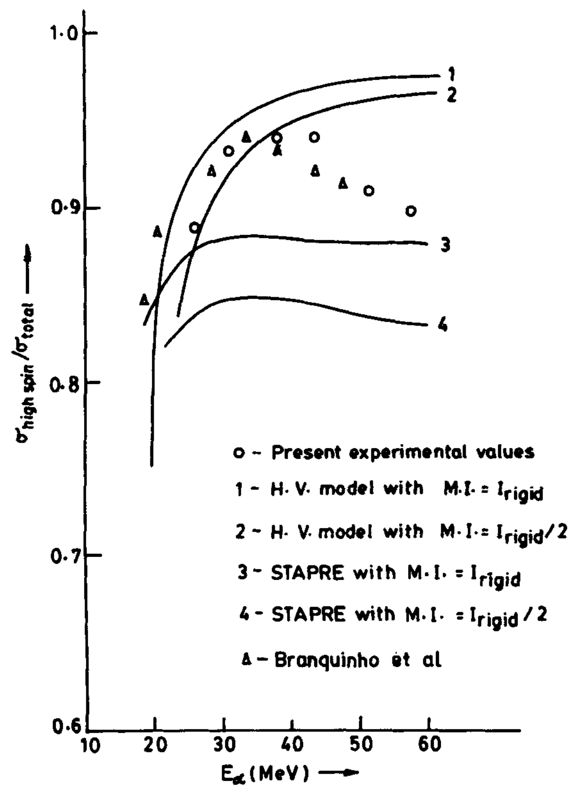

Figure 1. Isomeric cross-section ratio for the reaction ^{93}Nb(α, 2n)^{95m,g}Tc compared with two theoretical models alongwith previous results of Branquinho *et al* [5].

4. Results and discussion

Figure 1 shows the ratio σ high spin/(σ high spin + σ low spin) as a function of incident alpha particle energy, together with the previous experimental values of Branquinho *et al*, and with the theoretical predictions of Huizenga and Vandenbosch model and STAPRE model.

The individual isomeric cross-sections and their ratios are greatly influenced by the value chosen for the spin cut-off factor σ^2, occurring in the Fermi gas level density formula which determines the spin dependence of the nuclear level density. σ^2 depends on the nuclear temperature and the moment of inertia (MI) of the excited nucleus. It is customary to take rigid body moment of inertia, I_{rigid}. But a deviation of the moment of inertia from rigid body value possible at high excitations is likely to alter the relative populations of high and low spin states and hence the isomer ratio. Therefore, the measured isomeric ratios are compared with the theoretical values, treating the effective moment of inertia (MI) as a variable parameter. So, the experimentally observed values are compared with the theoretical values obtained from the two models, with the effective moment of inertia taken as the rigid body moment of inertia and also half that of a rigid body value, an shown in figure 1.

At the outset it can be seen that the measured ratio increases first with the incident energy up to about 35 MeV, and, later shows a definite decreasing trend up to 60 MeV. The overall trend can be understood quite clearly as the interplay between compound nucleus and pre-equilibrium reaction mechanisms, predominating at different regions of energy. This trend is also confirmed by the results of Branquinho *et al* up to 48 MeV as shown in figure 1. In the energy region up to 35 MeV, the trend can be understood as the tendency to produce residual nucleus at higher and higher spin values in the continuum with increasing bombarding energy, which is a characteristic in CN reactions. Afterwards, pre-equilibrium mechanism dominates. Here, since the pre-equilibrium particles are emitted with higher energy and angular momentum than before, the residual nucleus is left in a region of relatively lower spin in the continuum; hence the ratio decreases with increase in energy in 35–60 MeV region.

As the H–V model is only based on compound nuclear mechanism, it gives fairly good agreement with measured vlaues up to 35 MeV with the moment of inertia (MI) parameter half that of rigid body value but fails at higher energies showing a trend opposite to what is observed.

On the other hand, the theoretical values of the ratio based on the STAPRE model, which takes into account the pre-equilibrium effects in an approximate way, do show a decreasing trend towards higher energies, more so in the calculations with a moment of inertia value half that of the rigid body. However, there still remains a large discrepancy in the magnitude of the ratio between experiment and STAPRE model, indicating the need for further improvements in the model.

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