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STUDIES OF ISOMERIC RATIOS IN THE PHOTONUCLEAR REACTIONS, INDUCED BY BREMSSTRAHLUNG IN THE ENERGY RANGE FROM 15 TO 20.5 MeV

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1. Introduction

In nuclear reactions, the isomeric ratios are usually expressed as the ratios of the cross-sections for the production of high spin state relative to that of low spin state. They furnish valuable information about the energy level structure of nuclei and about the nuclear reaction mechanism involved. The isomeric cross-section ratios are more crucial test since, because of the large difference in angular momentum, usually associated with the isomer pair, they are sensitive to the angular momentum variations in the reactions. Fitting the calculated isomeric ratios to the experimental ones it is possible to obtain information about the spin dependence of the nuclear level density, in particular, about the spin cut-off parameter (SCOP) σ and the level density parameter a. So the experimentally measured isomer ratio can be used as a criterion for assessing the role of the nuclear reaction mechanism.

Up to now few works have been doveted to the experimental determination and the theoretical calculation of isomeric ratios in photonuclear reactions, especially in the low energy range. Therefore, our data could contribute to the knowledge of photonuclear reactions at low excitation energies. The purpose of the present work is to test the applicability of the Huizenga-Vandenbosch method /1,2/ to the analysis of (γ,n) photonuclear reactions.

2. Experimental method

Our experiments were carried out using the bremsstrahlung beam from two electron cyclic accelerators, namely the MT-17 microtron of the Centre of Nuclear Physics, Hanoi, Vietnam (the maximum bremsstrahlung energy is 15 MeV) and the MT-22 microtron of the Joint Institute for Nuclear Research, Dubna, USSR (the maximum bremsstrahlung energy can be varied stepwise from 15 MeV to about 20.5 MeV). The isomeric ratios were determined by γ-spectroscopy.

We used two measuring systems.

At the Centre of Nuclear Physics, Hanoi, samples were measured by a spectroscopic system consisting of a 62 cm^3 coaxial high-purity Ge (HP) detector (ORTEC) with a resolution of 2.1 keV at the 1332 keV gamma line of ^{60}Co, a spectroscopic amplifier (CANBERRA model 2021) and a 4096-channel analyzer (model ND-66B, Nucl. Dta, Inc.) coupled with a PDP11/23 computer for data processing.

At the Joint Institute for Nuclear Research, Dubna, the measuring system consisted of a 45 cm^3 Ge(Li) detector (or a 2.8 cm^3 Ge(HP) detector for low-energy gamma rays), a NOKIA spectroscopy amplifier, a 4096-channel analyzer (NOKIA, model LP-4096).

The samples were transported from the measuring site to the irradiation site and vice versa by a pneumatic transfer system (minimum transfer time $\sim$ 2s).

3. Statistical model calculations

The method of Huizenga and Vandenbosch is based on the following assumptions:

1) The isomeric and ground states are populated only during the final stage of the gamma cascade.

2) At the final stage, transitions with small changes in the J values are predominant.

3) The number of the gamma rays emitted should be kept as a free parameter.

4) Only dipole transitions are to be considered.

5) The level density is independent of energy.

6) Only discrete levels due to the isomeric and ground states are to be considered.

7) Only the dominant decay modes are to be considered.

The distribution of the angular momentum Jc in compound nuclei, formed by interaction between the target nuclei with spin Jo and the projectile particle with the orbital angular momentum ℓ, spin S and energy Ep is expressed as:

$$\sigma(J_c,E_p)=\pi\lambda^2\sum_{S=|J_o-s|}^{J_o+s}\sum_{\ell=|J_c-S|}^{J_c+S}\frac{2J_c+1}{(2s+1)(2J_o+1)} \cdot \qquad (1)$$

In the special case of photonuclear reactions, the relative occupation probability for compound nuclei is proportional to the number of magnetic substates:

$$P(J_c)\sim 2J_c+1 \cdot \qquad (2)$$

The emission of one neutron from the compound nuclei leads to forming new nuclei and the relative probability for forming such nuclei with spin J is

$$P(J_c,J)\sim \rho(J)\sum_{S=|J-s'|}^{J+s'}\sum_{\ell'=|J_c-S|}^{J_c+S}T_{\ell'}(E_n) \cdot \qquad (3)$$

where $T_{\ell'}(E_n)$ are the penetrability coefficients for a neutron with angular momentum ℓ' and kinetic energy E_n. The evaporation energy E_n is replaced by an average $\bar{E}_n$, assumed to be: $\bar{E}_n = t$

with t calculated according to /3/

$$U = at^2 - t. \quad (4)$$

where U is the excitation energy and t is the thermodynamic temperature.

The level density of excited nuclei as a function of spin J is expressed by the known level density formulae /4,5/.

$$\rho(J) \sim \rho(0)(2J+1)\exp[-(J+\tfrac{1}{2})^2/2\sigma^2], \quad (5)$$

where the SCOP, σ is related to the moment of inertia θ and the thermodynamic temperature t by:

$$\sigma^2 = \frac{\theta t}{\hbar^2}. \quad (6)$$

If the remaining excitation energy of residual nuclei, obtained from the compound nuclei after emission of one neutron is below the particle threshold, it is supposed that the residual nuclei deexcite predominantly by E1 γ-ray emission with the average energy:

$$\bar{E}_\gamma = 4\left(\frac{U}{a} - \frac{5}{a^2}\right)^{1/2}, \quad (7)$$

where U is the residual excitation energy. The γ-ray transition probability to states with spin J is assumed to be

$$P(J_f) \sim \sum_{J_i} P(J_i)\rho(J_f). \quad (8)$$

The γ-cascade continues until the residual energy becomes smaller than the "γ-ray cut-off energy" /6/, a deciding gamma ray is emitted to isomeric or ground states. If the residual energy remains within the "γ-ray cut-off region", partly a further E1 γ-ray and partly the deciding gamma ray are emitted.

The relative probability for the population of the isomeric pair is calculated using the procedure of ref./7/. So the following formulae were used to calculate the isomeric ratio

$$R = \frac{\sum_{J_f = M}^{\infty} P(J_f)}{\sum_{J_f = 0}^{M} P(J_f)}, \quad (9)$$

where $M = \frac{S_h + S_l}{2}$ is the center of spins, S_h and S_l are the spins of high- and low-spin states, respectively.

The average evaporation energy for the neutrons was assumed to be $\bar{E}_n = t$ and the γ-ray cut-off boundaries to be 1 and 2 MeV.

In the case of bremsstrahlung, the isomeric ratios are calculated by the formulae:

$$\bar{R} = \frac{\int_{E_{th}}^{E_m} \phi(E_\gamma)\sigma(\gamma,n) R \, dE_\gamma}{\int_{E_{th}}^{E_m} \phi(E_\gamma)\sigma(\gamma,n) \, dE_\gamma}, \qquad (10)$$

where E_{th}, E_m, $\phi(E_\gamma)$ are the reaction threshold, the maximum bremsstrahlung energy and the photon flux, respectively, and

$$\sigma(\gamma,n) = \frac{\sigma_m (E_\gamma \Gamma)^2}{(E_m^2 - E_\gamma^2)^2 + (E_\gamma \Gamma)^2}, \qquad (11)$$

where E_m, σ_m, Γ are respectively the resonance energy, the maximum cross section and the full width at half-maximum.

In calculating the isomeric ratios we used the calculation program provided by Prof. U.Kneissl of the University of Giessen, FRG and adapted for isomeric ratio calculation.

The values of reaction threshold energies E_{th}, full-widths at half-maximum Γ were taken from /8/ and the neutron binding energy from /9/.

4. Results and discussions

The table gives the isomeric yield ratios obtained in the photonuclear reactions $^{142}Nd(\gamma,n)^{141m,g}Nd$, $^{144}Sm(\gamma,n)^{143m,g}Sm$,

Table

Maximum bremsstrahlung energy	Isomeric ratios			
	$Nd141^{m,g}$	$Sm143^{m,g}$	$Zr89^{m,g}$	$Pb109^{m,g}$
15,0	0.022±0.002	0.031±0.003		0.060±0.005
16.5	0.045±0.004	0.039±0.003	0.70±0.04	0.062±0.005
18.0	0.049±0.004	0.043±0.003	0.75±0.05	0.068±0.005
20.5	0.052±0.004	0.044±0.003	0.92±0.06	0.072±0.006

$^{90}Zr(\gamma,n)^{89m,g}Zr$ and $^{110}Pd(\gamma,n)^{109m,g}Pd$ induced by bremsstrahlung irradiation at different photon energies. One can see that the isomeric ratios vary insignificantly with maximum bremsstrahlung energies. The isomeric yield ratios obtained in case of reactions of these nuclei with 14 MeV neutrons; i.e. the energy of the projectile particle is in the same order of that in our experiments, however, are greater than in the photonuclear reactions /10-17/. It can be explained by the fact that the transfered momentum is much greater in the case of 14 MeV neutron irradiation so that the probability of higher spin state production in the de-excitation of the compound nuclei must also be greater. Up to now there have been no reports on the isomeric yield ratios of the photonuclear reactions in such a low energy range as in our experiments, but only at very high maximum bremsstrahlung energies /7,17-22/. An exception is the paper /23/ dealing with one value of maximum bremsstrahlung energy, namely E_m= 14 MeV. So it is impossible to make any comparison between the results of our experiments and those of other authors.

In figs. 1 and 2 are presented the experimental isomeric yield ratios and those obtained by statistical model calculations using the Huizenga-Vandenbosch method (HVM) for Sm144 and Nd142. The calculations were carried out with different values of the level density parameter a. There are also shown the excitation functions for these nuclei, taken from /8/.

According to the Huizenga and Vandenbosch formalism, there are three cases which can be seen from formula (9)

1. $R \sim 1$ if SCOP = COS
2. $R < 1$ if SCOP $<$ COS
3. $R > 1$ if SCOP $>$ COS

In our case, fitting the calculated isomeric ratios to the experimental ones we have found the value of SCOP = 2.4 for both the nuclei ND141 and Sm143. As we know, the value of COS is 3.5 for these two nuclei, so the experimental isomeric ratios obtained in the present paper are logical.

In figs. 1 and 2 one can see the general trend of the obtained data, which shows an increase in isomeric yield ratios with energy up to about 18-19 MeV, i.e. up to a point by about 3-4 MeV above the peak cross section σ_m (the σ_m values are 15.32 and 14.94 MeV for Sm144 and Nd142, respectively /8/). In the higher-energy part the isomeric yield ratios remain almost unchanged. One can see a good agreement in the energy range from 15 to about 18-19 MeV, whereas at higher energies there is a great difference between the experi-

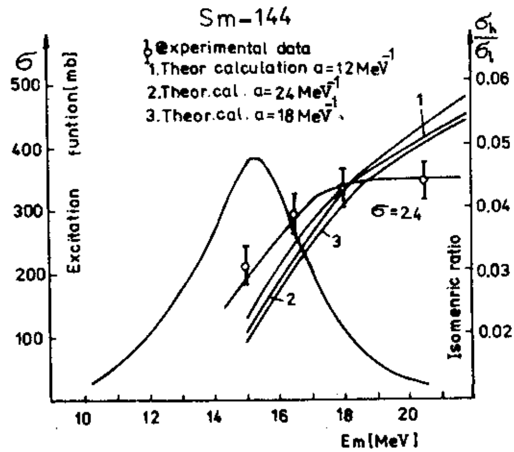

Fig. 1

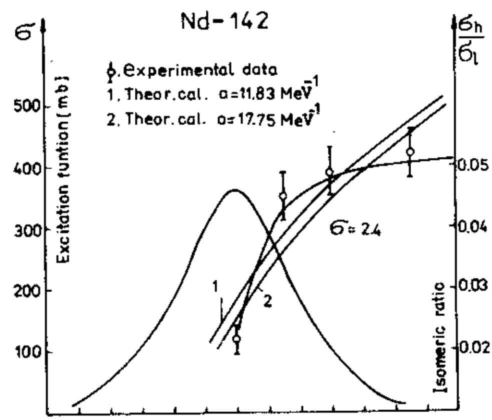

Fig. 2

Excitation functions and comparision between the experimental and the model calculated isomeric ratios for the reactions Sm144(γ,n)Sm143^{m,g} and Nd142(γ,n)Nd141^{m,g} respectively (figs.1,2) mental results and the theoretical model calculations. While the experimental data remain unchanged, the theoretical values continue to increase with energy. A similar observation is shown in [24], but it is for the case of the $^{93}Nb(He^3,xn)$ reactions with χ =2 and 3, in particular the isomeric ratio increases with energy up to a point at the tail of the excitation function, about 10 MeV higher than the cross section peak, where pre-equilibrium processes begin to account for a significant fraction of the cross section of producing the isomeric pair and the ratio starts to decrease.

In conclusion we would say that: First, the isomeric yield ratios vary insignificantly with bremsstrahlung energy. This fact has also been observed by other authors, but at energies far from the threshold [21,22]. Second, up to about 18-19 MeV, the Huizenga-Vandenbosch method can be used for the calculation of isomeric yield ratios or in other words, in this energy range the statistical model is applicable for the description of the photonuclear reactions and the equilibrium process is a predominant one.

Thirdly, in the higher-energy part there is a great difference between the experimental results and the theoretical calculations. It means that in this case, pre-equilibrium and direct processes should be taken into account.

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