ISOMER RATIOS FOR ^{52}Mg - PRODUCT OF PHOTONUCLEAR REACTION ^{54}Fe(γ, np)^{52m,g}Mg

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Photonuclear reactions with escape of neutrons for some target nuclei are often accompanied with proton emission. To derive isomer ratios for the products of ^{54}Fe(γ, np)^{52m,g}Mg reaction one has to take into account the interfering contribution of beta-decay for products of corresponding photoneutron reactions ^{54}Fe(**γ**, 2n)^{52m,g}Fe and ^{54}Fe(**γ**, n)^{53m,g}Fe. Bremsstrahlung with end-point energies within 32,8 - 43,6 MeV generated by electron linear accelerator LU-40 was used for irradiation of targets. Analytical solution for differential system of 4 equations was derived and used for correct estimation of contribution for all interfering reactions.

1. Introduction

Using high energy gamma-quanta as projectiles in nuclear reactions has some essential advantages for study of nuclear structure and nuclear reaction mechanisms. Indeed, gamma-quanta do not introduce large angular momentum into compound nucleus and additional contribution to excitation energy of compound nucleus due to binding energy of projectile is absent. In addition, the precise nondiscrete control of the gamma-quanta energy is possible.

Characteristics of photonuclear reactions are well studied in the energy region of Giant Dipole Resonance (GDR) and above the pion-producing threshold (PPT). The energy region between GDR and PPT (within 30 ÷ 100 MeV) was studied to a smaller extent both theoretically and experimentally. The reason is due to small values of photonuclear reaction cross sections in this energy region and limited availability of high intensity quasi mono-energetic gamma ray sources with well controlled gamma-quanta energy.

During the last several years essential progress has been achieved in development of the new theoretical models for the photonuclear reactions and in improvement of the existing ones in the considered energy region. The quasi-deuteron model was further improved [1], some new pre-equilibrium models have been developed for description of the multi-particle emission [2, 3]. Permanently growing interest to Accelerator Driven Systems and progress in the design of high intensity quasi mono-energetic gamma-quanta sources [4, 5] also stimulate study of the photonuclear reactions above the GDR energy region. Very limited number of experimental data for the photonuclear reactions in the energy range 30 - 100 MeV for testing newly developed and available theoretical models was the major motivation for the present work.

The main purpose of this study is to obtain the experimental isomer ratios for nuclei ^{52m,g}Mg as the product of the ^{54}Fe(γ, np)^{52m,g}Mg reactions and compare them with predictions of the modern theoretical models.

2. Theoretical background and experimental techniques

De-excitation time of nuclei by γ-cascade irradiation usually does not exceed 10^{-12} s. In some cases transitions between levels of the same nucleus are suppressed due to the large difference of angular momenta for these levels involved and the nucleus may remain long enough in a specific state called the isomer state. Usually such isomeric states have not large excitation energies and its angular momentum (named as a spin in the text below) differs from spin of ground state by a few units of $\hbar$.

The isomer or ground levels with large values of spin are populated mainly from highly excited states with large spin values. Population of isomer or ground levels with smaller values of spin can occur mainly from highly excited states with small values of spins. Therefore investigations of relative populations of the isomer and ground states [6, 7] can be very useful to derive spins of highly excited levels and to study the de-excitation mechanisms via gamma emission.

For mono-energetic gamma beam with energy E the isomer ratio is determined as the ratio of cross sections $\frac{\sigma_m(E)}{\sigma_g(E)}$, where $\sigma_g(E)$ is the cross section of the photonuclear reaction leading to the ground state, $\sigma_m(E)$ is the cross section for the same nucleus leading to the isomeric state. Also the isomer ratio is often determined as a ratio of the cross section σ_H for state with higher spin to the cross section σ_L for state with lower spin:

$$\xi = \frac{\sigma_H(E)}{\sigma_L(E)}. \quad (1)$$

If gamma beam is non-monoenergetic (that is the case for experiments with bremsstrahlung sources), the isomeric yield ratio is determined as:

$$d\left(E_{\max}\right)=\frac{Y_m}{Y_g}, \tag{2}$$

where the reaction yield is given by

$$Y_{m,g}=N_t\int\limits_{E_{thr}^{m,g}}^{E_{\max}}\sigma_{m,g}(E)\cdot W(E,E_{\max})dE, \tag{3}$$

with N_t - number of the target nuclei; $Y_{m,g}$ - reaction yield for nucleus in the isomer (m) or ground (g) state; $E_{\max}$ - maximal gamma energy; $W\left(E,E_{\max}\right)$ - bremsstrahlung spectrum; $\sigma_i(E)$ with i = m, g – the reaction cross section for nucleus to be formed in meta-stable (m) or ground (g) state for gamma energy E, E_{thr}^{i}, i = m, g – the energy threshold of the reaction leading to the meta-stable (ground) state.

For some target nuclei photonuclear reactions with multiple escapes of neutrons are accompanied by proton emission. To study the products of these reactions one has to take into account an interfering contribution of beta-decay for products of corresponding photoneutron reactions. Often contribution of beta-decay from precursor nuclei in isobar chain (^{52m,g}Fe) is essential.

Production of isomeric pair, precursors from interfering reactions and its decay can be described by the following differential equation system (see Fig.1):

$$\begin{cases}\dfrac{dN_{Am}}{dt}=Y_{Am}(t)-\lambda_{Am}N_{Am}\\ \dfrac{dN_{Ag}}{dt}=Y_{Ag}(t)-\lambda_{Ag}N_{Ag}+p_{AmAg}\lambda_{Am}N_{Am}\\ \dfrac{dN_{Bm}}{dt}=Y_{Bm}(t)-\lambda_{Bm}N_{Bm}+p_{AmBm}\lambda_{Am}N_{Am}+p_{AgBm}\lambda_{Ag}N_{Ag}\\ \dfrac{dN_{Bg}}{dt}=Y_{Bg}(t)-\lambda_{Bg}N_{Bg}+p_{AmBg}\lambda_{Am}N_{Am}+p_{AgBg}\lambda_{Ag}N_{Ag}+p_{BmBg}\lambda_{Bm}N_{Bm}\end{cases} \tag{4}$$

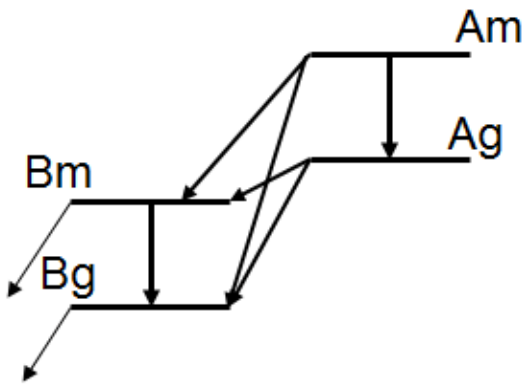

Fig. 1. General cheme of isomer nucleus (B) decay with interfering contribution of precursor nucleus (A) of isobaric chain.

where N_i - population of i-state (m - isomer state, g – ground state) of nuclei A and B; $i=Am,Ag,Bm,Bg$; Y_i - reaction yield according to (3); λ_i - decay constants for isomer and ground state; p – branching factor (transition probability from one level to other level).

Analytically solving this system the experimental values of isomer ratios were obtained by us.

Experimentally, the method of induced activity was applied to obtain the isomer ratios. Irradiations of ^{54}Fe targets have been carried out with bremsstrahlung endpoint energy 32,8, 38,3, 43,6 MeV. Linear accelerator LU-40 (Research and Development Complex “Accelerator” NSC KIPT) was used as a source of electrons [8]. Instability of electron beam intensity was within 2 %. Inner monitor of electron beam was calibrated by values from Faraday cup of the magnetic analyzer, placed at the accelerator outlet. The tantalum converter with 1.05 mm thickness was placed on the exit window of the accelerator facility, close to which the cylindrical aluminium gamma absorbers (thickness 5.5 and 10 cm) were installed. Diameter of beam spot on the conversion target was less than 9 mm. Energy of electron beam was determined using magnetic analyzer and was checked in the low energy region by reaction thresholds. A distance between tantalum converter and absorber was 2 and 4 cm, between tantalum converter and target – 20 and 30 cm (depending on electron energy). We used highly enriched ^{54}Fe targets. These target samples enriched by isotope ^{54}Fe (enrichment 99.85 %) were formed as metal disks of iron 10 mm in diameter and 236 mg mass for first sample (215 mg for second one). Then within 3 - 8 s the irradiated sample was moved by pneumatic transfer system to the measurement area. HPGe detector with the energy resolution 1.9 keV for ^{60}Co γ-line 1332 keV was used to acquire the instrumental gamma-ray spectra of the activation products as a set of serial measurements with various time periods. Distances between sample and detector (dozen centimetres just after irradiation and few centimetres at the end of

measurement period) were chosen to optimize both statistics and dead time/pile-up effects due to large contribution of interfering reactions. Minimum distance was limited by condition of negligible contribution of cascade gammas summing. Efficiency calibration of spectrometer was carried out for each detector-to-sample distance.

3. Results and discussion

Examples of spectra from the induced activities for the ^{54}Fe targets are shown in Fig. 2.

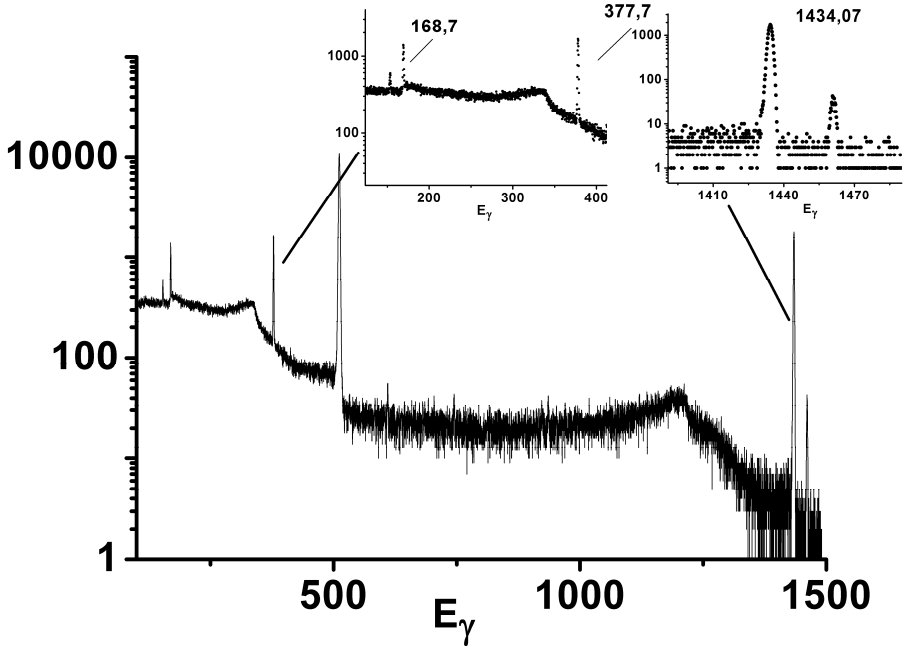

Fig. 2. Gamma-ray spectra from the induced activities in the target enriched in ^{54}Fe. The analytical gamma lines which were used for determination of the isomer ratios are indicated separately. All values of E_γ are presented in keV.

Reaction, the bremsstrahlung energy end-points $E\gamma_{max}$, spins of the target nuclei (*It*), spins of the meta-stable (*Im*) and ground (*Ig*) states and the experimental isomer ratios $IR = Y_H/Y_L$, obtained in experiments

Reaction	*It*	*Im*	*Ig*	$E\gamma_{max}$, MeV	*IR*
^{54}Fe(γ, np)^{52m,g}Mn	0+	2+	6+	32,8	0.123 ± 0.005
				38,3	0.124 ± 0.005
				43,6	0.146 ± 0.09

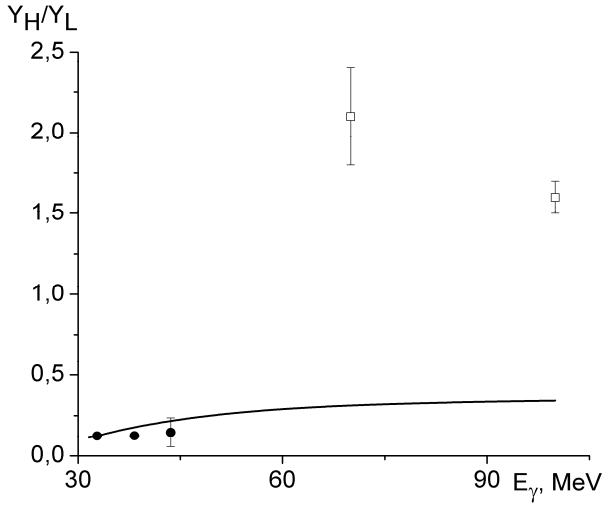

Fig. 3. Isomer ratios of yields for ^{52m,g}Mn from reaction ^{54}Fe(γ, np)^{52m,g}Mn. Solid line – calculation with using code TALYS, filled circles – experimental data obtained in this work, squares – experimental values from ref. [11].

Our subject if interest was isomer ratio of nucleus ^{52m,g}Mn, reaction product of ^{54}Fe(γ, np)^{52m,g}Mn. However, due to reaction ^{54}Fe(γ, 2n)^{52}Fe the nucleus ^{52}Fe as precursor of ^{52}Mn in isobaric decay chain may cause a significant contribution in population of isomer and ground levels of ^{52m,g}Mn. Using solution of equation system (4) we derived isomer ratios for ^{52m,g}Mn taking into account contribution of ^{52}Fe. We used for isomer ratio calculation the 1434 keV gamma line, which is generated during decay of both isomer and ground state of ^{52m,g}Mn nucleus. Gamma-line 168.7 keV (due to decay of ^{52}Fe ground state) is used to take into account a precursor contribution. Isomer state of ^{52}Fe with spin-parity 12^+ was not populated (it is confirmed by absence of decay gamma lines with energies 621.7 keV, 869.9 keV, 929.5 keV, 1416.1 keV). Using gamma line with energy 377.7 keV from ^{52m,g}Mn isomer transition is not correct, because in decay of ^{53}Fe as a product of ^{54}Fe(γ, n)^{53}Fe reaction with larger cross section, the interfering gamma line with energy 377.9 keV does overlap with 377.7 keV. Nuclides decay data for this work were taken from ENSDF database [9].

All obtained experimental values of the isomer ratios, corresponding reactions and characteristics of investigated nuclei are presented in the Table.

The uncertainties given in the Table include contributions from photopeak efficiency calibration (2 %), abundance(<1 %), geometry configuration (2 %) and intensities of gamma-rays (3 %, excluding case for 43.6 MeV). Statistical uncertainties of photopeak areas were the mojor contributors to total uncertainty of result. We used code TALYS [10] for theoretical calculations of isomer ratios for investigated nucleus (Fig. 3). Optimal default parameters were applied for calculation.

As one can see from Fig. 3 our experimental data are in rather good agreement with theoretical calculation results comparing with other experimental data given in Ref. [11].

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