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The low-energy M1 γ-strength from radiative proton capture experiment

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Abstract. The multipolarity of the low-energy (< 3 MeV) $\gamma-$strength function has been experimentally studied with the ^{55}Mn(p,2γ)^{56}Fe reaction at 1.65 MeV proton beam energy. The spectrum of two-step $\gamma-$cascades populating the ground state of ^{56}Fe has been measured and compared with calculations assuming that E1 or M1 multipolarities dominate in the low-energy region. It was found that experimental data points are reproduced only if the assumption on dominance of the M1 multipolarity is used.

1 Introduction

Experimental measurements of the γ-strength function below the particle separation threshold have always been a challenge for experimentalists. For the last decade considerable progress has been made with the Oslo type technique [1] which is based on the measurements of the particle-γ coincidences from (x,yγ) type of reactions. It allows one to extract both the level density and the γ-strength function. One spectacular feature is the low-energy enhancement of the γ-strength function observed in the A~60 and ~90 mass regions [2, 3].

The physics of this enhancement is not understood. The dipole character of the low-energy enhancement has been recently confirmed experimentally in Ref. [4]. However, the multipolarity of the enhancement, whether it is E1 or M1 one, still remains uncertain. From the point of view of theoretical considerations it could be either E1 [5] or M1 [6]. In the last case it has been predicted that the increased M1 strength can appear between low-energy close-lying states with configurations including proton as well as neutron high-j orbits that recouple their spins and add up their magnetic moments coherently.

The experimental determination of the multipolarity of the low-energy $\gamma-$transitions is very important for further progress in this field. The γ-strength function obtained from the Oslo type of experiments represents only the sum of all multipolarities of γ-transitions. It has been shown in Ref.[7] that the decomposition can be performed in some cases with an auxiliary experiment based on two-step $\gamma-$cascade (TSC) technique [8–10]. In case of the cascade consisting of E1 first and M1 second transitions, its intensity is determined by product of corresponding f_{E1} and f_{M1} strength functions. If the sum $f_{E1} + f_{M1}$ is known from Oslo experiment and the product $f_{E1} \cdot f_{M1}$ is known from TSC experiment, the individual components can be determined [7].

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In this work we performed the ^{55}Mn(p,2γ)^{56}Fe experiment to study individual f_{E1} and f_{M1} components of the γ-strength function for ^{56}Fe. The sum $f_{E1} + f_{M1}$ has been reported from Oslo experiments in Ref. [4]. It was shown to feature the low-energy enhancement.

2 Experiment

The experiment has been performed on the tandem accelerator of the Edwards Laboratory of Ohio University. The 1.65 MeV proton beam hit the self-supporting 1μm Mn target coated with 10nm carbon layers. The γ-radiation has been registered with two HPGe detectors set-up at the distance of about 8cm from the target. The data acquisition system allowed us to save coincident events as well as single histograms from detectors.

The detector efficiency has been determined from the separate run of 0.95 MeV protons on a thin natural aluminum target. The standard absolute intensities of γ-transitions from this reaction have been used for detector calibration in the energy range from 0.5 to 11 MeV [11].

Fig.1 presents the spectrum of a sum of coincident γ-rays. Because of poor statistics and high Compton background one can see only peaks corresponding to population of the ground 0^+ state and the first excited 2^+ of ^{56}Fe. Gating on this peak allows extracting all TSC populating these states. Intermediate levels of cascades span the whole excitation energy range from the ground state up to 11.8 MeV which is the excitation energy of the ^{56}Fe compound state. Background subtraction was performed using events obtained by gating on energy intervals to the left and to the right sides of the peak.

To determine the absolute cascade intensity (the fraction per proton capture), we used the intensity of the $2^+ \rightarrow 0^+$ 847 keV γ-transition of ^{56}Fe measured in the same experiment. The intensity of this transition constitutes about 90 % of the proton capture rate.

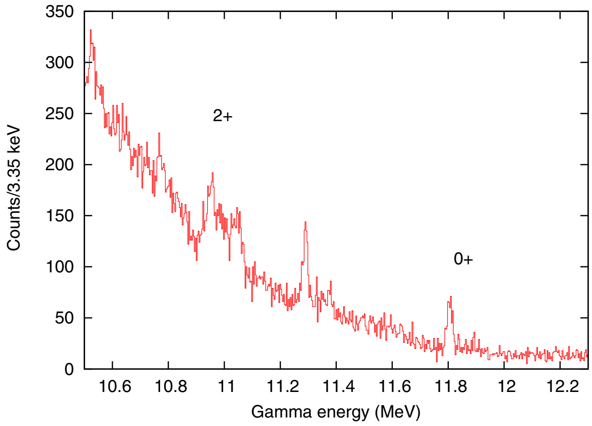

Figure 1. (Color online). Sum E_1+E_2 spectrum of two-step γ-cascades from the $^{55}Mn(p,2\gamma)^{56}Fe$ reaction.

3 Data analysis

Theoretical calculations of γ-spectra require knowledge of the nuclear level density and γ-strength functions for dipole electric, magnetic and electric quadrupole γ-transitions. The intensity of each cascade transition proceeding between the initial i and the final f states is determined in terms of branching ratios of the first and the secondary transitions.

$$I_{if}(E_1,E_2) = \sum_{XL,XL',J^\pi_m} \frac{\Gamma^{XL}_{im}(E_1)}{\Gamma_i}\rho(E_m,J^\pi_m)\frac{\Gamma^{XL'}_{mf}(E_2)}{\Gamma_m} + \sum_{XL,XL',J^\pi_{m'}} \frac{\Gamma^{XL}_{im'}(E_2)}{\Gamma_i}\rho(E'_m,J^\pi_{m'})\frac{\Gamma^{XL'}_{m'f}(E_1)}{\Gamma_{m'}} \quad (1)$$

The sums take into account momentum and parity conservation. The presence of two terms in the sum is due to the fact that the first E_1 and the second E_2 γ-transitions are indistinguishable experimentally. Two energies are correlated according to $E_1 + E_2 = E_i - E_f$. The width of the γ−transition is expressed in terms of the γ-strength function f_{XL} and the level spacing D_x as $\Gamma^{XL}_{x\to y} = f_{XL}(E_\gamma)E_\gamma^{2L+1}D_x$. Generally, because the experimental information on both the level density and the γ function is scarce the result of such calculations is prone to uncertainties. Usually, the strategy of the analysis of the TSC spectra consists of testing different combinations of strength function and level density models. However, even the best combination does not guarantee that individual components are correctly determined. The parameters of the magnetic strength function are only approximately known, the level density parity dependence is not taken into account, the uncertainties of the spin cutoff parameter have not been studied. All of these uncertainties make conclusions on individual components uncertain even if experimental γ-spectra are well reproduced.

In our approach we used the Monte-Carlo technique to simulate both f_{E1} and f_{M1} strength functions with different functional dependence on γ-ray energy. The experimental constraints imposed by data obtained from Ref.[4] used then on sum of $f_{E1} + f_{M1}$. In general, there is an indefinite number of options on fractions of individual components. However, we start with established practice when the E1 strength is determined in terms of the low-energy tail of the Giant Electrical Dipole Resonance (GDER), the M1 and E2 strengths are governed by the Giant Magnetic Dipole and Quadrupole Resonances (GMDR). Parameters of these resonances are taken from Ref. [12]. The E1 component was calculated with the analytical Kadmensy-Markushev-Furman(KMF) model [13] with the temperature parameter T assumed to be independent of γ-ray energy (constant temperature concept). Using the temperature as a variable parameter allowed us to generate different shapes of f_{E1} function. The concept of the constant temperature is also consistent with the experimental level density for ^{56}Fe [14] which is better reproduced by the constant temperature model. In order to describe the low-energy enhancement of the γ-strength function analytically, the exponential parametrization was adopted. The final expression used to fit experimental data points is the following: $f = f_{E1} + f_{M1} + B\exp(-CE_\gamma)_{E1(M1)}$ where C and B are variable parameters. The exponential term describing the low-energy energy enhancement is of unknown multipolarity and was used in TSC calculations as either E1 or M1 type.

The spin population of the compound ^{56}Fe nucleus was estimated from optical model parameters of Ref.[12]. The computer code was developed which uses Monte-Carlo technique to simulate the γ−decay simultaneously taking into account competition of neutron and proton outgoing channels. It allowed us to calculate correctly the effective spin distribution of initial levels decaying down with γ-cascades.

The level density for ^{56}Fe has been measured by us from the ^{55}Mn(d,n)^{56}Fe reaction [14]. The spin distribution still remains dependent on a particular model for which, as a first approximation, the formula of the Fermi-gas model [12] was used.

It is known from the level scheme of ^{56}Fe that positive parity levels dominate up to an excitation energy of about 4.5 MeV. This was taken into account in the level density model where individual positive and negative parity level densities were used such that they reproduce both the number of discrete levels and the total level density function obtained in Ref.[14]. For each pairs of f_{E1} and f_{M1} strength functions both intensity of TSC cascades and Oslo strength function $f_{E1}+f_{M1}$ were calculated. Gating on experimental data points allows us to select strength functions which reproduce both sets of data. Fig.2 presents the result of Monte-Carlo simulations along with experimental data points. One can see that gating on experimental data points from Oslo type and TSC experiment allows selecting those f_{M1} strength functions which have low energy enhancement and those f_{E1} which do not have one. Results show that the method allows us to make decomposition of the strength function obtained from Oslo type of experiment [4] and it supports the M1 low-energy enhancement for the ^{56}Fe case.

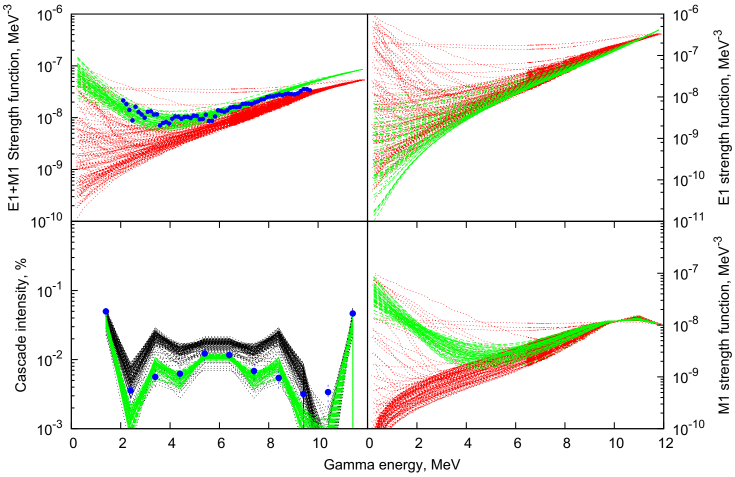

Figure 2. (Color online). Decomposition of the γ-strength function obtained from Oslo experiment into E1 and M1 components. Points are experimental data from Ref. [4] and from present TSC experiment. Dots are phase space of all strength functions simulated by Monte-Carlo method. Lines are strength functions which describe experimental data points within 15% uncertainties.

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