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Level densities of iron isotopes and lower-energy enhancement of γ-strength function

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Abstract. The neutron spectrum from the ^{55}Mn$(d,n)^{56}$Fe reaction has been measured at $E_d = 7\ MeV$. The level density of ^{56}Fe obtained from neutron evaporation spectrum has been compared to the level density from Oslo-type ^{57}Fe$(^3He,\alpha\gamma)^{56}$Fe experiment [1]. The good agreement supports the recent results [1, 8] including an availability of a low-energy enhancement in the γ-strength function for iron isotopes. The new level density function allowed us to investigate an excitation energy dependence of this enhancement, which is shown to increase with increasing excitation energy.

Keywords: level density, γ-strength function, evaporation spectra
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INTRODUCTION

The unusual low-energy enhancement of the γ-strength function below the particle separation threshold has been found recently in Oslo-type experiments, first for ^{56}Fe and ^{57}Fe nuclei [1] then for the set of molybdenum isotopes [2]. This result contradicts an existing understanding based on different extrapolations of the tail of the giant dipole resonance function towards the low-energy region.

Although it has been proven that the Oslo method works well, the question remains about the applicability of the Axel-Brink hypothesis upon which the method is based. The hypothesis assumes that the γ-strength function depends on the energy of the γ-transition only and not on the excitation energy of initial and final states. It contradicts the modern understanding of damping properties of the giant resonance width, which should depend on the temperature of the final states [3, 4]. The Axel-Brink hypothesis allows one to factorise the first generation γ-matrix $P(E_i,E_\gamma)$ measured in Oslo experiments [5, 6] as

$$P(E_i,E_\gamma) \propto \rho(E_i - E_\gamma)\mathscr{T}(E_\gamma). \quad (1)$$

Here, ρ is the nuclear level density (NLD), $\mathscr{T}(E_\gamma)$ is the radiative transmission coefficient connected to the γ-strength function as $f(E_\gamma) \propto \mathscr{T}/E_\gamma^3$ and E_i is the energy of

an initial state. The ρ and $\mathscr{T}$ functions are determined by the iterative procedure [7] through the adjustment of each data point of these two functions until a global χ^2 minimum with the experimental $P(E_i, E_\gamma)$ matrix is reached. Furthermore, the Oslo method assumes that the γ-decay pattern from any excitation energy is independent if it is directly populated by a nuclear reaction or by a nuclear reaction followed by one or more γ-rays. In order to address all of the above concerns, the level density of ^{56}Fe has been measured independently from the particle evaporation spectrum of the ^{55}Mn$(d,n)^{56}$Fe reaction. Such spectra are described by the simple model based on the Hauser-Feshbach formalism implying that the shape of the particle spectra depends on the level density of final nuclei and transmission coefficients of outgoing particles. Because transmission coefficients are directly connected to the capture cross section of inverse reactions and can be obtained experimentally, the level density can be deduced from spectra.

In this work the level density obtained from the neutron evaporation spectrum is compared to one obtained from the Oslo type ^{57}Fe$(^3He, \alpha\gamma)^{56}$Fe experiment. Results of the latter experiment can be found in recent publications [1, 8]. In this work, we will concentrate solely on the ^{55}Mn(d,n)^{56}Fe experiment.

EXPERIMENTS AND METHODS

The experiment has been performed with a 7 MeV deuteron beam provided by John Edwards Laboratory Tandem at Ohio University. A self-supporting 1 mu manganese foil has been used as a target. The energy of outgoing neutrons is determined by a time-of-flight technique using a 7 m flight path, and the neutrons are detected in NE213 detectors. A pulse width of 3 ns provided the energy resolution of $\sim$100 and 800 keV at 1 and 14 MeV of neutrons, respectively. The detectors efficiency was measured by using the neutron "standard" spectrum obtained at an angle of 120° from the ^{27}Al(d,n) reaction on a thick, stopping Al target at $E_d = 7.44$ MeV [9]. The swinger beam facility has been used for the measurement of the angular distribution of neutrons from 20 to 150 degrees.

The procedure to extract the level density from evaporation spectra was proposed in Ref.[10]. It is based on the Hauser-Feshbach theory of compound nuclear reactions according to which the level density is determined by both the transmission coefficients of outgoing particles and the level density of the residual nucleus. In order to calculate the transmission coefficients, ten optical model potentials proposed in the RIPL-2 data base have been tested. All of them have been found to give the same result (the same shape of neutron evaporation spectra) within $\sim$15% over the range of 1-14 MeV of neutron energy. Finally, the potential of D.Wilmore and Hodgson has been adopted. In order to extract the level density of ^{56}Fe, the following procedure has been used: 1) The Fermi-gas level density model is chosen to calculate the neutron evaporation spectrum. The parameters of the model have been adjusted to reproduce the experimental spectrum as closely as possible. 2)The model level density has been improved by a binwise renormalization according to the expression:

$$\rho(E) = \rho(E)_{input} \frac{(d\sigma/d\varepsilon)_{meas}}{(d\sigma/d\varepsilon)_{calc}} \tag{2}$$

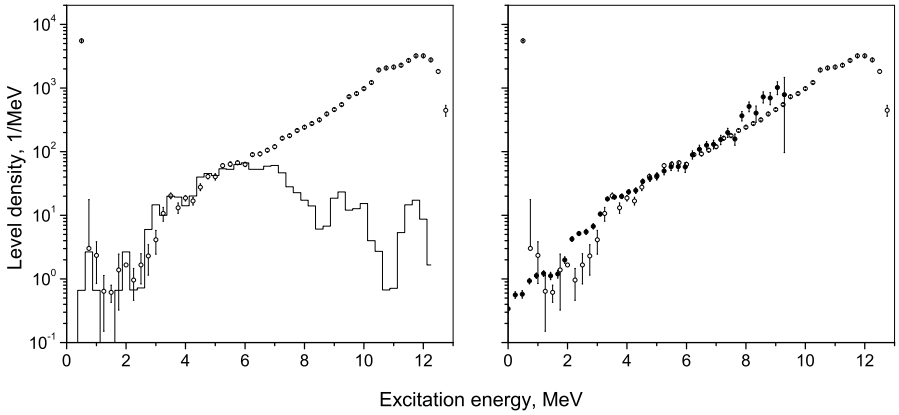

FIGURE 1. The comparison of the level density extracted from neutron evaporation spectra (open circles) with discrete level density (left panel) and with level density obtained from Oslo-type experiment (right panel)

The extracted level density $\rho(E)$ for the ^{56}Fe nucleus is shown in Fig.1. The absolute values of this function have been obtained from its normalization to the level density of discrete levels. One can see the good structural agreement between these two level densities up to about 6 MeV of excitation energy beyond which the discreet level density is incomplete. Figure 2 also shows the comparison between level densities obtained from both the current and Oslo experiments [8]. One can see the good general agreement which provides increased confidence to both methods. Moreover, the important result is that the step at 3 MeV obtained from the Oslo experiment discussed in the Ref.[8] is well reproduced by the current data. Also, the step at 6 MeV of excitation energy is now seen to be real as well because it is reproduced by both experiments. These steps have been interpreted as a result of the breaking of cooper pairs. The disagreement between Oslo and current data at the excitation energy of 2.5 MeV can be explained by too few levels available at this excitation energy. It results in a larger fluctuation of primary γ-transitions due to poor spin and parity averaging, thereby making population of some of these levels more preferable in the Oslo experiment.

Thus, in spite of the fact that these two methods rely on different underlying assumptions, different nuclear reactions and different mathematical techniques to extract NLD, they have very much in common, namely the dominance of statistical mechanism of nuclear reactions in both cases. It also serves as a double check of these two methods.

γ-STRENGTH FUNCTION OF ^{56}FE

The γ-strength functions for ^{56}Fe and ^{57}Fe have been obtained from the Oslo-type experiment in Ref.[1]. The striking feature of these functions is the increase of γ-strength in the region below 3 MeV. The main drawback of the Oslo method is the assumption of

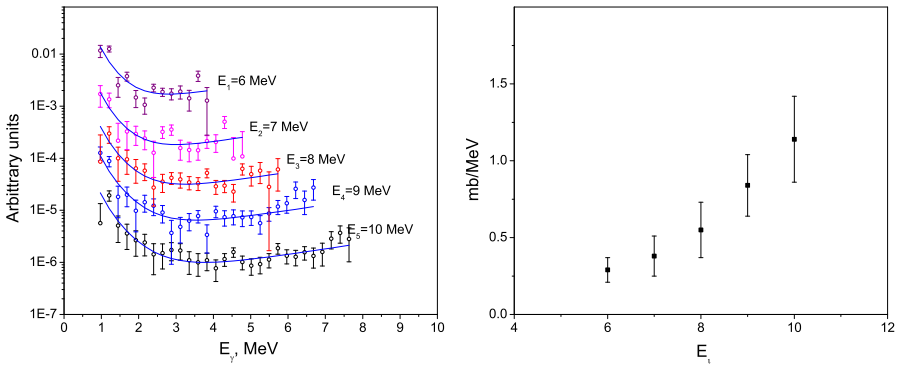

FIGURE 2. the left panel:The γ-strength function extracted from the Oslo experiment using the level density from neutron evaporation spectrum of the ^{55}Mn$(d,n)^{56}$Fe reaction;right panel: B_i coefficient obtained from the fit

Axel-Brink hypothesis, which prevents us from the study of the temperature dependence of γ-strength function. Such temperature dependence follows from the temperature dependence of giant resonance widths caused by different damping mechanisms debated in literature.

In this work, we can use the first generation matrix $P(E_i,E_\gamma)$ (1) obtained from Oslo experiments and the level density from the ^{55}Mn(d,n) reaction to get the γ-strength functions corresponding to different excitation energies of initial states:

$$f(E_\gamma,E_i)=\frac{1}{2\pi}\frac{N(E_i)P(E_i,E_\gamma)}{(\rho(E_i-E_\gamma)E_\gamma^3}, \tag{3}$$

where $E_i=E_\gamma+E_f$ is the energy of the initial state of the γ-transition. Because of unknown $N(E_i)$, it is possible to investigate only the shape of the function (3)at different E_i but not its absolute magnitude. We assume that it can be described by the combination of the low energy tail of the giant electric dipole resonance (GEDR) which is described by simple Lorentz formula, and the soft pole, for which the power function has been chosen, as it was used in [1]. In this case, the γ-strength function is reproduced by the following expression:

$$f(E_\gamma,E_i)=\frac{A_i}{3\pi^2\hbar^2c^2}(\frac{\sigma_0E_\gamma\Gamma^2}{(E_\gamma^2-E^2)^2+E_\gamma^2\Gamma^2}+\frac{B_i}{E_\gamma^C}) \tag{4}$$

where A_i,B_i and C are fitting parameters, and E=16.8 MeV and $\Gamma=4$ MeV are the position and width of the GEDR. The parameters B_i determine the relative contribution of the soft pole to the γ-strength at different E_i. The result of the fit is shown in the figure 2. We have observed that the parameter B_i increases gradually as E_i increases, thereby indicating the increase of the soft pole contribution.

SUMMARY AND CONCLUSIONS

The level density of the ^{56}Fe nucleus extracted from two different experiments are in good agreement with each other.It indicates the consistency of these two methods and the possibility to apply both methods to an investigation of a broad range of nuclei. It helps to eliminate most of the systematic errors associated with these methods, including the unknown contribution of direct processes in particle evaporation spectra and the assumption of the Axel-Brink hypothesis in the Oslo method.

The γ-strength function for the ^{56}Fe isotope obtained in Ref.[1] has now been extracted by taking into account the level density from the neutron evaporation spectrum. It allows one to investigate the γ-strength function at a different excitation energy of initial states. We confirm an availability of the low-energy enhancement that is present at all excitation energies from 5 to 10 MeV. The contribution of the soft pole increases with increasing excitation energy. This fact might indicate the temperature dependence of γ-strength caused by the damping properties of giant resonances.

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