Level density of ^{56}Fe and low-energy enhancement of γ-strength function

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The ^{55}Mn$(d, n)^{56}$Fe differential cross section is measured at $E_d = 7$ MeV. The ^{56}Fe level density obtained from neutron evaporation spectra is compared to the level density extracted from the ^{57}Fe(^{3}He, $\alpha\gamma$)^{56}Fe reaction by the Oslo-type technique. Good agreement is found between the level densities determined by the two methods. With the level density function obtained from the neutron evaporation spectra, the ^{56}Fe γ-strength function is also determined from the first-generation γ matrix of the Oslo experiment. The good agreement between the past and present results for the γ-strength function supports the validity of both methods and is consistent with the low-energy enhancement of the γ strength below ~4 MeV that was first discovered by the Oslo method in iron and molybdenum isotopes.

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I. INTRODUCTION

The unusual low-energy ($E_\gamma \lesssim 4$ MeV) enhancement of the γ-strength function has been found recently, first for ^{56}Fe and ^{57}Fe nuclei [1,2] and then for the set of molybdenum isotopes [3]. The (^{3}He, $\alpha\gamma$) and (^{3}He,^{3}He$'\gamma$) reactions and sequential extraction procedure developed at the Oslo Cyclotron Laboratory were used for this purpose. These results contradict the existing understanding based on different extrapolations of the giant dipole resonance (GDR) to the low-energy region. The strength of the observed enhancement may indicate a different mechanism (in contrast to the GDR) in the low-energy region of the γ-strength function. This requires additional theoretical efforts to explain the observed enhancement.

The Oslo method allows one to extract both the nuclear level density (NLD) and the γ-strength functions from the first-generation γ matrix $P(E_i, E_\gamma)$ obtained from particle-γ coincidences in the (^{3}He, $\alpha\gamma$) reaction. Although it has been established that the method works reasonably well in practice, the question of the applicability of the Axel-Brink hypothesis remains open. This hypothesis assumes that the γ-strength function depends only on the energy of the γ transition and not on the excitation energies of the initial E_i and final $(E_i - E_\gamma)$ states [4,5]. This assumption leads to the factorization of the first-generation γ matrix obtained from an Oslo experiment as

$$P(E_i, E_\gamma) \propto \rho(E_i - E_\gamma)\mathcal{T}(E_\gamma), \tag{1}$$

where ρ is the NLD and $\mathcal{T}$ is the radiative transmission coefficient, which is connected to the γ-strength function through the relation $\mathcal{T}(E_\gamma) = 2\pi \sum_{XL} f_{XL}(E_\gamma) E_\gamma^{(2L+1)}$. The ρ and $\mathcal{T}$ functions are determined by an iterative procedure [6] through the adjustment of these two functions at each data point until a global χ^2 minimum with the experimental $P(E_i, E_\gamma)$ matrix is reached. Another assumption is that the γ transitions originating from some energy interval feed levels with the same decay properties as those populated in the (^{3}He, α) reaction at the same excitation energy in the residual nucleus. This assumption has been partially supported by comparison of the results from two different reactions, namely, (^{3}He, α) and (^{3}He,^{3}He$'$) [7], populating the same residual nucleus. Although the Oslo method has been thoroughly tested, concern remains particularly about the validity of the Axel-Brink hypothesis. For example, the theory developed in Ref. [8] claims that the γ strength for spherical nuclei should depend on the temperature of the final state, implying that the Axel-Brink hypothesis is not valid.

In order to address the above concerns, the NLD in Eq. (1) should be measured independently by a different kind of experiment. One of the most reliable methods used to extract the NLD below the particle separation threshold is based on measurement of particle evaporation spectra from nuclear reactions. Such spectra are described by a simple model of nuclear reactions based on the Hauser-Feshbach formalism; according to this formalism, the shape of the particle spectra depends only on the NLD of the final nuclei and the transmission coefficients of outgoing particles. Because transmission coefficients can be tested experimentally through the capture cross section of an inverse reaction, the NLD can be deduced from spectra. The concern with this method is with the possible contribution of preequilibrium and/or direct reaction mechanisms which potentially can distort the shape of statistical evaporation spectra and thus affect the

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NLD functions. The Oslo method uses γ transitions that have been proven to be statistical. Therefore, the comparison of NLDs obtained from these two experiments employing different reactions and extraction procedures will allow us to not only compare the two methods but also estimate the possible distortion of particle evaporation spectra caused by direct reaction contributions.

In this work, we investigated the ^{55}Mn$(d, n)^{56}$Fe reaction. The NLD obtained from the neutron evaporation spectrum was analyzed and compared to the NLD determined from the Oslo experiment, in which the ^{57}Fe(^{3}He, $\alpha\gamma)^{56}$Fe reaction was used. Since the method and results of the latter experiment have been thoroughly described in recent publications [2,9], we will concentrate on describing the ^{55}Mn$(d, n)^{56}$Fe experiment.

II. EXPERIMENT AND METHOD

The experiment was performed with a 7 MeV deuteron beam from the John Edwards Accelerator Laboratory tandem at Ohio University. To measure the neutron spectrum, the beam swinger facility [10] was used. This allows the measurement of angular distributions by rotating the incoming beam and the target chamber with respect to the direction of outgoing neutrons. A self-supporting 0.74 mg/cm^2 manganese foil was used as a target. The energy of the outgoing neutrons was determined by the time-of-flight method with a 7 m flight path and NE213 neutron detectors. A 3 ns pulse width provided an energy resolution of about 100 and 800 keV for 1 and 14 MeV neutrons, respectively. The neutron detector efficiency was determined with the calibrated neutron flux from the ^{27}Al(d, n) reaction on a $\sim$2 mm thick stopping Al target at $E_d = 7.44$ MeV [11]. This allowed the determination of the detector efficiency from 0.2 to 14.5 MeV neutrons with an accuracy of $\sim$6%. The neutron spectra were measured at nine different angles from 20° to 150° to determine the angular distribution of outgoing neutrons. Additional measurements with an empty target were performed at each angle to determine the background contribution. The absolute cross section was determined by taking into account the target thickness, the accumulated charge of the incoming deuterons, and the detector efficiency. The angular distribution of outgoing neutrons is shown in Fig. 1. The observed angular anisotropy indicates the contribution from noncompound reactions at angles less than $\sim$70°. The contribution of the nonisotropic part to the total neutron cross section is estimated to be about 30%. The deuteron breakup mechanism is also responsible for the cross section anisotropy at lower neutron energies. The angular dependence of the cross section at backward angles is flat and assumed to be due to the compound nuclear mechanism. Therefore, the spectra averaged over backward angles (>120°) have been used to extract the NLD of the residual ^{56}Fe nucleus (see Fig. 2).

The procedure used to extract the NLD from the evaporation spectra was proposed in Ref. [12]. This extraction procedure is based on the Hauser-Feshbach theory of compound nuclear reactions, according to which the particle emission cross

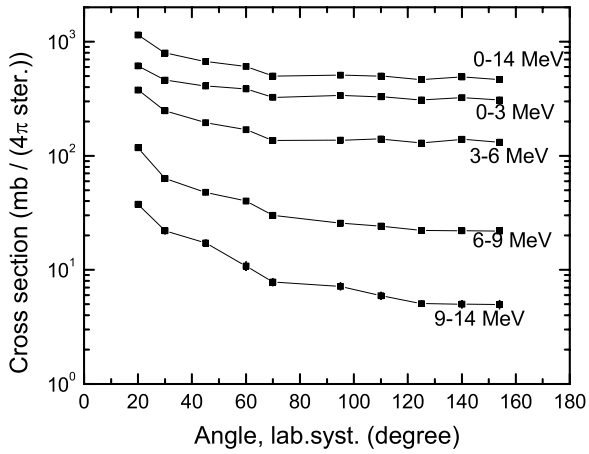

FIG. 1. Angular distribution for different energy groups of outgoing neutrons from ^{55}Mn(d, n) reactions.

section is

$$\frac{d\sigma}{d\varepsilon_b}(\varepsilon_a, \varepsilon_b) = \sum_{J\pi} \sigma^{\mathrm{CN}}(\varepsilon_a) \frac{\sum_{I\pi} \Gamma_b(U, J, \pi, E, I, \pi)\rho_b(E, I, \pi)}{\Gamma(U, J, \pi)}, \quad (2)$$

with

$$\Gamma(U, J, \pi) = \sum_{b'} \left(\sum_{k} \Gamma_{b'}(U, J, \pi, E_k, I_k, \pi_k) + \sum_{I'\pi'} \int_{E_c}^{U-B_{b'}} dE'\, \Gamma_{b'}(U, J, \pi, E', I', \pi') \times \rho_{b'}(E', I', \pi') \right). \quad (3)$$

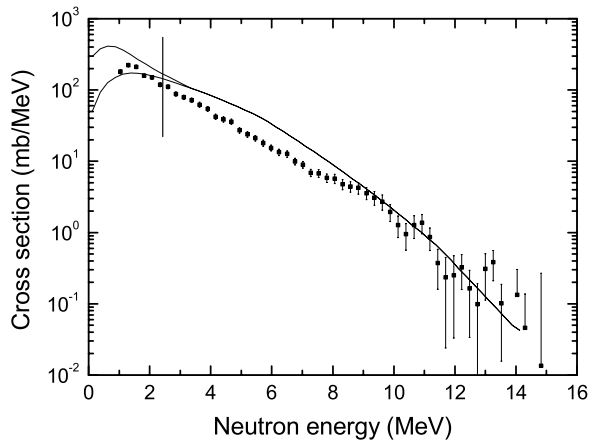

FIG. 2. Neutron evaporation spectrum at backward angles (points). Solid line shows spectrum calculated with the EMPIRE program [13] taking into account the level density according to the microscopic model of Ref. [19]. Vertical line shows neutron energy limit beyond which the first stage contribution to the total yield is greater than 90%.

Here $\sigma^{CN}(\varepsilon_a)$ is the fusion cross section, ε_a and ε_b are energies of relative motion for incoming and outgoing channels ($\varepsilon_b = U - E_k - B_b$, where B_b is the separation energy of particle b from the compound nucleus), Γ_b are the transmission coefficients of the outgoing particle, the quantities (U, J, π) and (E, I, π) are the energy, angular momentum, and parity of the compound and residual nuclei, respectively, and E_c is the continuum edge. It follows from Eq. (3) that the shape of the particle spectra is determined by both the transmission coefficients of outgoing particles and the NLD of the residual nucleus $\rho_b(E, I, \pi)$. Transmission coefficients can be calculated from optical model potentials usually based on experimental data for elastic scattering and total cross sections in the corresponding outgoing channel. This leaves the NLD as the only unknown parameter, which can be extracted from this equation by using the experimental differential cross section. Details and assumptions of this procedure are described in Refs. [12,14].

Neutron transmission coefficients are calculated from the optical model potentials taken from the RIPL-2 data base [15]. Ten potentials have been tested. These are potentials based on global systematics such as given by Wilmore and Hodgson [16] as well as those obtained for the local mass range near $A = 56$ nuclei. All of them have been found to give the same result (the same shape of neutron evaporation spectra) within ~10% for 1–15 MeV. Finally, the potential of Wilmore and Hodgson was adopted, and 10% errors were added to the neutron transmission coefficients. In order to extract the NLD of the residual nucleus, the following procedure was adopted: (i) The NLD model was chosen to calculate the differential cross section of Eq. (3). The parameters of the model were adjusted to reproduce the experimental spectrum as closely as possible. (ii) The input NLD was improved by binwise renormalization according to the expression

$$\rho_b(E, I, \pi) = \rho_b(E, I, \pi)_{\text{input}} \frac{(d\sigma/d\varepsilon_b)_{\text{meas}}}{(d\sigma/d\varepsilon_b)_{\text{calc}}}. \qquad (4)$$

This procedure is only correct when the main contribution to the differential cross section comes from the first stage of the nuclear reaction populating the residual nucleus of interest. In our case, the second stage contaminations open up above particle separation energies and come mainly from $(d, \alpha n)$, (d, pn), and (d, nn) reactions. But as proposed in Ref. [17], as long as these contributions are less than the total error of the extracted NLD, the energy interval chosen for the extraction of the NLD can be extended beyond the particle separation threshold. Assuming 10% experimental errors (or more), the excitation energy interval at which the second stage contributions do not exceed 10% is 0–11.5 MeV for the ^{55}Mn(d, xn) reaction (see Fig. 2).

III. LEVEL DENSITY OF ^{56}Fe

The extracted NLD for the ^{56}Fe nucleus is shown in Fig. 3 along with the density of discrete low-lying levels (upper panel) and the NLD obtained from the Oslo experiment (lower panel). The good counting statistics in the region corresponding to the location of known discrete levels allowed

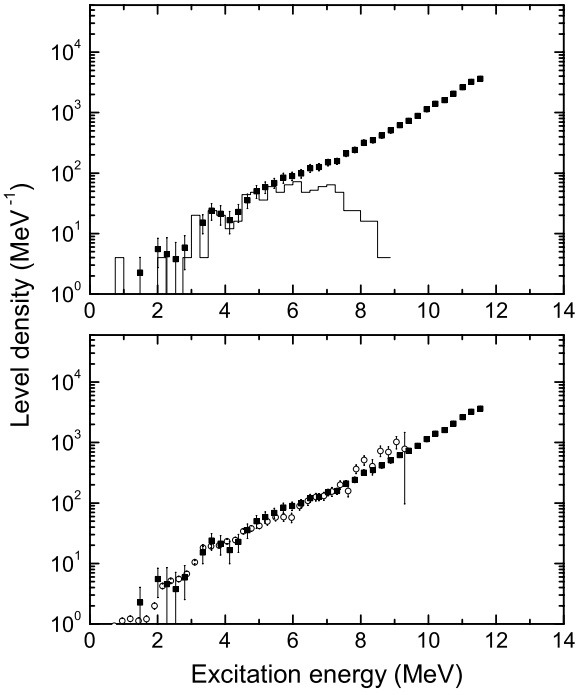

FIG. 3. Comparison of NLD extracted from neutron evaporation spectra (full circles) with discrete NLD (upper panel) and with NLD (open circles) obtained from Oslo-type experiment (lower panel).

an absolute normalization of the extracted NLD. This is necessary because the scaling factor also depends on NLDs and transmission coefficients of other outgoing channels (mainly proton and α).

Figure 3 demonstrates that up to about 6 MeV excitation energy the extracted NLD almost perfectly follows the shape of the NLD function based on discrete levels. This implies that the transmission coefficients used in calculating the theoretical spectrum are correct. Above this point, the discrete levels are not complete and their density drops, while the NLD obtained from our experiment continues to increase. It also agrees well with the NLD obtained from the Oslo experiment [9]. One can see the good general agreement up to ~8 MeV.

Both curves show the same step structures at around 4 and probably at 6 MeV excitation energy. Similar steps have been interpreted in [9] as a result of the breaking of Cooper pairs. Above about 7.8 MeV, these curves start to diverge, ending with differences of about 50% at an excitation energy of ~8.8 MeV. This deviation may stem from imperfections in the two methods, perhaps connected with violations of the underlying assumptions. Some local deviations of the neutron transmission coefficients are also possible. However, the almost perfect agreement below ~8 MeV gives confidence in both methods.

Generally, one can conclude that in spite of the fact that these two methods use different underlying assumptions, different nuclear reactions, and different mathematical techniques to extract the NLD, a fairly consistent result has been obtained. This implies that the statistical mechanism dominates in both reactions. The observed difference between NLDs at higher excitation energy requires further investigation. The

observed small bump in the differential cross section at ~9 MeV neutron energy transforms to the corresponding bump in the extracted NLD at about 5.5 MeV excitation energy. Previously, similar structures observed in Oslo-type experiments for a variety of nuclei have been explained as being the result of pairing correlations. The NLD of ^{56}Fe from the Oslo experiment also exhibits structure at ~5.5 MeV, although the shape is slightly different from that observed in the particle evaporation spectrum in Fig. 3. This is probably due to systematic uncertainties still inherent in both methods.

The presence of the step structure in the NLD is an important feature from a practical point of view, because this might introduce corrections to available systematics of NLD parameters widely used to calculate reaction rates. Almost all systematics are primarily based on NLDs obtained from neutron resonance spacings at the neutron separation energy B_n and the NLD of low-lying discrete levels. To calculate the total NLD at B_n, the spin cutoff parameter is used; this parameter is not known to high accuracy in this energy region. The NLD in the intermediate region is often obtained by a simple interpolation between these two anchor points, assuming some NLD model. The Fermi-gas model is most often used. For example, the NLD according to the Fermi-gas model with parameters from the latest systematics of Ref. [18] is shown in Fig. 4. This curve fits the discrete NLD well, but overestimates the experimental points by a factor of ~1.7 at higher excitation energies. A slightly better result is given by the microscopic model [19] recommended in the RIPL-2 data base [15]. However, because this NLD is also renormalized to the neutron resonance spacing and density of low-lying levels, the discrepancy is still present. These or other similar models may cause a sizable overestimation of calculated reaction cross sections and incorrect ratios of cross sections for different channels.

To fit the experimental NLD, the Fermi-gas formula has been adopted, that is,

$$\rho(E) = \frac{\exp(2\sqrt{a(E-\delta)})}{12\sqrt{2}a^{1/4}(E-\delta)^{5/4}\sigma}, \tag{5}$$

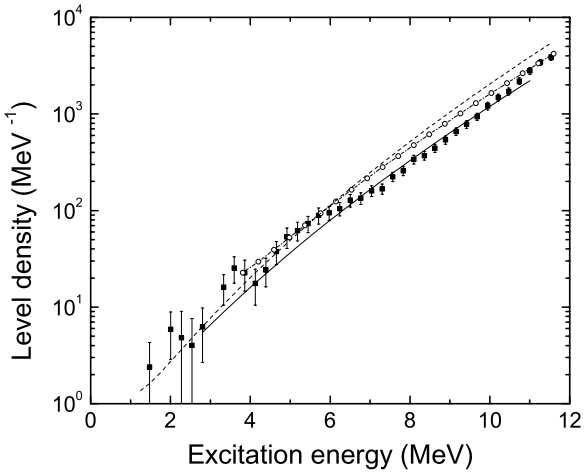

FIG. 4. NLD extracted from neutron evaporation spectra (full circles) compared to Fermi-gas (dashed) and microscopical model (open circles) calculations. Full line shows the fit to the data.

where the spin cutoff parameter σ based on a rigid body moment of inertia is expressed as

$$\sigma^2 = 0.0145\,[\mathrm{MeV}^{-1}]A^{5/3}\sqrt{(E-\delta)/a}\,. \tag{6}$$

The Fermi-gas parameters which give the best fit to experimental points between 2 and 11 MeV are $a = 5.65(10)$ MeV^{-1} and $\delta = 0.65(20)$ MeV. The spin cutoff formula based on half of the moment of inertia does not cause large changes. These parameters are slightly smaller than those obtained from the systematics of Ref. [18] ($a = 6.19$ MeV^{-1}, $\delta = 0.93$ MeV). However, this difference is enough to cause ~70% discrepancy in corresponding NLDs at 6–10 MeV excitation energies (see Fig. 4).

The NLD parameters for ^{56}Fe have also been obtained in Refs. [20] and [21] from (p, p'), (p, α), and (α, α') reactions. Even though the same reactions and the same techniques have been used in these experiments, different results were obtained. The first measurement reported $a = 5.7$ MeV^{-1} and $\delta = 0.7$ MeV (in good agreement with our results), while the second measurement gave $a = 6.5$ MeV^{-1} from (p, p') and $a = 7.0$ MeV^{-1} from (p, α) reactions. Part of the problem might be the strong correlation of the a and δ parameters when they are extracted from particle evaporation spectra. When the extracted NLD is not normalized, one needs to assume some value of δ in order to obtain the value of a. As shown in [19], a 1 MeV increase of δ causes approximately 1 MeV^{-1} decrease of parameter a (the correlation is negative).

More recently Mishra *et al.* [22] reexamined this problem. Their result confirmed the conclusion of Ref. [20] if it is assumed that the slope of the NLD is matched. On the other hand, if the parameters are extracted from the absolute value of NLD at a particular point (as in neutron resonance analysis), the correlation between a and δ has a positive sign.

In addition to the von Egidy compilation, other compilations have been prepared by Rohr [23] and Al-Quraishi *et al.* [24]. These parameters are shown in Table I. It is interesting to note that the three compilations have predicted slopes which are within 10% of one another (same nuclear temperature). The magnitude predicted for the NLD between 6 and 10 MeV differs by more than an order of magnitude. Rohr predicts the smallest NLD, Al-Quraishi the next highest, the present data are second largest, and von Egidy *et al.* predict the highest NLD. These differences in magnitude point out the importance of performing absolute magnitude normalization in inferring NLD. In this work, we were able to obtain the absolute NLD function by normalizing it to the NLD of known low-lying levels. This gave us the possibility of obtaining both the a and δ values simultaneously.

TABLE I. NLD parameters of ^{56}Fe from different systematics.

Systematics	a	δ
Von Egidy	6.19	0.93
Rohr	5.61	2.81
Al-Quraishi	5.98	1.68
Present	5.65 (10)	0.65 (20)

Thus, in order to establish the systematics of NLD parameters, it is necessary to take into account the absolute NLD for the whole excitation energy interval. Such information can be obtained either from particle evaporation spectra by using Eqs. (2), (3) and (4) or from the Oslo-type experiments by using the sequential extraction method applied to the particle-γ coincidence matrix.

IV. γ-STRENGTH FUNCTION IN ^{56}Fe

The γ-strength functions for ^{56}Fe and ^{57}Fe have been obtained from an Oslo-type experiment in Ref. [2]. The striking feature of these functions is the increase in γ strength in the region below 4 MeV; this cannot be understood within existing models. The main concern about the Oslo method is that possible violation of the Axel-Brink hypothesis might result in some systematic deviation of the obtained γ strength, that is, if the γ-strength function depends not only on the energy of the γ transition but also on the temperature of the final state. Such temperature dependence may stem from the temperature dependence of the GDR width caused by different damping mechanisms debated in the literature [25]. According to the Fermi-liquid model [26], the width is determined by the collision of quasiparticles in the nuclear volume that results in the temperature dependence

$$\Gamma(E_\gamma, T) \propto \left(E_\gamma^2 + 4\pi^2 T^2\right), \tag{7}$$

where $T = \sqrt{U/a}$. But as shown in Ref. [27], the systematic deviation of the γ-strength function due to such temperature dependence is only about 15% in the region below 2 MeV. The other mechanism is connected to nuclear shape fluctuations, leading to a square root temperature dependence of the GDR width. The experiments on Sn and Pb [28] support the temperature dependence of the GDR, but the mechanism responsible for such effects is still under debate. A good fit to these experimental data is obtained with the Fermi-liquid model accounting for damping of the GDR according to Eq. (7), while taking into account the dipole-quadrupole interaction term arising from the nuclear deformation [29].

The low-energy enhancement of the γ-strength function observed in the Oslo experiment for iron isotopes might stem from different (i.e., not GDR) modes of nuclear excitation and therefore might exhibit a different temperature dependence. Therefore, it is important to investigate the validity of the Axel-Brink hypothesis in the Oslo method for the iron isotopes. For this purpose, we can use the first-generation matrix $P(E_i, E_\gamma)$ obtained from the Oslo ^{57}Fe(^{3}He, $\alpha\gamma$)^{56}Fe experiment and the NLD from the ^{55}Mn$(d, n)^{56}$Fe reaction to obtain the γ-strength function of ^{56}Fe, giving

$$f(E_\gamma, E_i) = \frac{1}{2\pi} \frac{N(E_i) P(E_i, E_\gamma)}{\rho(E_i - E_\gamma) E_\gamma^3}, \tag{8}$$

where $E_i = E_\gamma + E_f$. It is clear that the obtained γ-strength function should not deviate considerably from that extracted solely from the $P(E_\gamma, E_x)$ obtained by the sequential iterative procedure because the corresponding NLD functions agree well (see Fig. 3). However, because of slightly different slopes of these functions in the region of 4–7 MeV and $\sim$1.7 times disagreement above this region (which in principle can be caused by temperature effects), it is interesting to investigate the magnitude of corresponding local changes in the γ-strength function. The normalization constant $N(E_i)$ in Eq. (8) has been determined in Ref. [3] at $E_i = B_n$ by using supplementary experimental information from systematics of total γ widths of initial states (neutron resonances). The comparison of γ-strength functions obtained from both the sequential extraction Oslo method and Eq. (8) using the NLD from the evaporation spectrum is shown in Fig. 5. There is no significant disagreement. It can be concluded that possible temperature effects on the extracted γ-strength function are rather small compared to total uncertainties in the experimental data. Thus, the applicability of the Axel-Brink hypothesis in the Oslo method is justified within the accuracy of the experimental data. However, one should keep in mind that in both cases investigated here, one extracts an averaged γ-strength function for a wide region (several MeV) of final energies. In order to detect a possible temperature dependence of the γ-strength function, one could extract the γ-strength function from several limited regions of final energy; however, one would need to increase the statistics of the experiment to be able to reduce statistical errors.

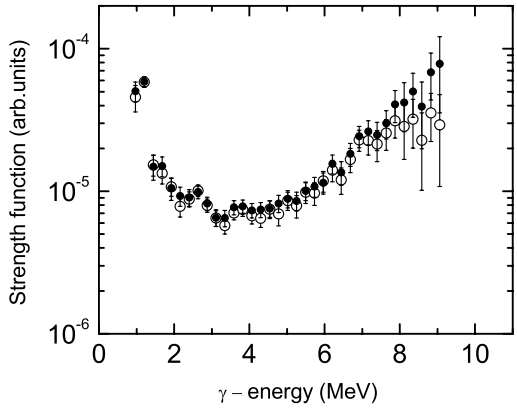

FIG. 5. γ-strength function obtained from Oslo first-generation matrix $P(E_\gamma, E_x)$ with NLD from (d, n) reaction (filled circles). γ-strength function obtained solely from $P(E_\gamma, E_x)$ (open circles).

V. SUMMARY AND CONCLUSIONS

The ^{56}Fe NLD has been extracted from the neutron evaporation spectrum of the ^{55}Mn$(d, n)^{56}$Fe reaction. This NLD has been compared to that obtained from the ^{57}Fe(^{3}He, $\alpha\gamma$)^{56}Fe reaction by using the sequential extraction technique developed at the Oslo Cyclotron Laboratory. The NLDs obtained from these two different types of experiments are in good agreement with each other. This indicates the consistency of these two methods and the possibility of applying such methods to investigate a broader range of nuclei. This agreement helps to eliminate most of the potential systematic errors inherent in these methods, including such important problems as the unknown contribution of direct processes in

particle evaporation spectra. The neutron evaporation spectrum from the (d, n) reaction measured at backward angles does not contain such a contribution.

The NLD function of ^{56}Fe can be fit by the conventional Fermi-gas model in the region of 2–11 MeV excitation energy. However, a local deviation of the order of $\sim$40% has been observed at 5 MeV. The presence of this structure leads to disagreement in the Fermi-gas parameters obtained from our current data and from available systematics. To verify the character of these structures, more experimental data are needed for neighboring nuclei.

The γ-strength function for the ^{56}Fe isotope obtained in Ref. [2] has been extracted by using the NLD from the neutron evaporation spectrum. The new γ-strength function agrees well with the previous one within experimental errors. This indicates small temperature effects on the extracted γ-strength function. Thus, the Axel-Brink hypothesis used in the Oslo method appears to be justified within the present experimental uncertainties.

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