

Experimental differential cross sections, level densities and spin cutoffs as a testing ground for nuclear reaction codes

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Proton double differential cross sections from $^{59}\text{Co}(\alpha, p)^{62}\text{Ni}$, $^{57}\text{Fe}(\alpha, p)^{60}\text{Co}$, $^{56}\text{Fe}(^7\text{Li}, p)^{62}\text{Ni}$, and $^{55}\text{Mn}(^6\text{Li}, p)^{60}\text{Co}$ reactions have been measured with 21 MeV alpha and 15 MeV lithium beams. Cross sections have been compared against calculations with Empire reaction code. Different input level density models have been tested. It was found that the Gilbert and Cameron level density model is best to reproduce experimental data. Level densities and spin cutoff parameters for ^{62}Ni , ^{60}Co above the excitation energy range of discrete levels (in continuum) have been obtained with a Monte-Carlo technique. Excitation energy dependencies were found to be inconsistent with Fermi-gas model.

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I. INTRODUCTION

Prediction of reaction cross sections remains a major problem in applications such as data evaluations [1] or/and astrophysics reaction rate calculations [2]. There is big progress in the development of nuclear reaction codes which now include different reaction mechanisms to take care of. However, these codes use many input parameters. The variety of input parameters helps to describe existing experimental data but it creates problems when it comes to predictions. For example, it is well known for data evaluators that calculations based on a global set of level density parameters are not able to reproduce experimental cross sections. Parameters have to be adjusted for specific nucleus and/or for specific energy interval. Therefore, the activity which would be directed to the experimental study of input parameters for nuclear reaction codes is urgently needed. In this work we will focus on analysis of level density input options of the Empire computer code [3] which is one of the most sophisticated publicly available codes currently used for data evaluations in ENDF file [1] and for cross section correlations.

There is a general understanding that one of the most uncertain parameters of nuclear reaction codes is the level density. The Empire code offers four input level density options to choose from. Level density models are usually adjusted to experimental data on neutron resonance spacings available for many nuclei at the neutron separation energy. For the bulk of the known neutron resonances the spin range of resonances is very limited and is determined as $I \pm 1/2$ where I is spin of the target. Parameters for different models are tabulated in RIPL-3 database [4]. However, such a procedure might contain uncertainties related to unknown spin and parity distri-

butions (or spin cutoff parameter) which are generally not available experimentally. The magnitude of such uncertainties is unknown. Generally, the spin cutoff factor is model dependent with uncertain parameters. So uncertainties related to spin and parity distributions remain the main uncertainties in calculation of level densities used as inputs in reaction codes. There is still a common belief that the right level density input for cross section calculations can be obtained from fitting level density parameters to discrete levels and to neutron resonance spacings. However, such a belief has not been thoroughly tested against experimental data yet. There is still uncertainty as to whether the Fermi-gas model [?] or the Gilbert and Cameron model [10] for the level density is superior at low excitation energies.

The corresponding considerations based on both the theory and the experiment can be found in Refs. [9? ? ?]

As opposite to neutron resonance data, the level densities can be inferred using comparison of Hauser-Feshbach calculations of particle double differential cross sections (or particle evaporation spectra) against experimental data [5]. However, this method has its own uncertainties mainly connected to unknown contribution of direct and pre-equilibrium reaction mechanisms which depend on type of nuclear reactions and beam energies. The lack of high quality experimental particle spectra originating from purely compound reactions has restricted progress. Also, the spin cutoff parameter determining the spin distribution remained model dependent. In modern reaction codes it is usually calculated according to the Fermi-gas model. The problem of how the spin cutoff parameter affects the particle spectra from compound reactions has not been addressed in detail so far.

The idea of this work is the following. Based on our experimental data, we will test recommended (by RIPL-3) input level density models for reaction codes. Then, using the simulation technique, we will obtain best level density functions and spin cutoff parameters which re-

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produce our experimental data points. An evaluation of the accuracy of level density parametrization based on neutron resonance spacing will be made.

For these purposes we have measured proton evaporation spectra from two α -induced reactions $^{59}\text{Co}(\alpha, p)^{62}\text{Ni}$ and $^{57}\text{Fe}(\alpha, p)^{60}\text{Co}$. These reactions are compared with proton spectra from lithium induced reactions populating the same compound and residual nuclei: $^{56}\text{Fe}(^7\text{Li}, p)^{62}\text{Ni}$ and $^{55}\text{Mn}(^6\text{Li}, p)^{60}\text{Co}$ with the 15 MeV lithium-7 and lithium-6 beams respectively. Experimental data on the neutron resonance spacing for both ^{62}Ni and ^{60}Co nuclei are available in Ref.[4]. Two types of reactions allow us testing the dominance of the compound mechanism because the decay pattern in compound reactions is determined exclusively by transmission coefficients and level densities in outgoing channels. It does not depend on specific entrance channel. Special attention has been dedicated to acquiring good quality spectra including the discrete level region, i.e. the region where first chance protons populate individual levels with low excitation energies, typically up to 2-3 MeV. Discrete levels have spins assigned to each level so the new feature of the analysis is that the spin cutoff parameter in continuum is obtained by analyzing both continuum and discrete level regions versus model calculations. The effect of the spin cutoff parameter is based on the magnitude of the cross section in addition to the angular distribution.

II. EXPERIMENT

Protons from the 21 MeV α -particle-induced reactions on ^{59}Co and ^{57}Fe targets have been measured with the ΔE - E technique at the cyclotron laboratory of the University of Oslo. The ΔE - E telescope consisted of a 150 μm ΔE and 1500 μm thick Si detectors. It was rotated around the target to measure the angular distribution of both protons and elastically scattered α -particles. Spectra were measured at seven angles: 35°, 50°, 70°, 90°, 115°, 135°, and 155° in the laboratory system. A separate 1500 μm thick silicon detector was placed at 45° to monitor the beam current by measuring elastically scattered α particles.

In order to convert the measured spectra to the absolute differential cross section of outgoing protons $\sigma(E_p)/dE_p$, the angular dependence of elastically scattered α particles was measured and scaled with optical model calculations. Different optical model parameters taken from the RIPL-3 compilation [4] were tested. The best parameters were found to be under the number 9400 in the compilation with the reference to Ref.[6]. The uncertainty of this scaling is mostly determined by the average deviation of the scaled experimental points from the calculated ones, which is about 8% in our case. Uncertainties due to the counting statistics do not exceed 1%.

The reaction mechanism can be inferred from the angular distribution of outgoing protons (Fig. 1). Low energy

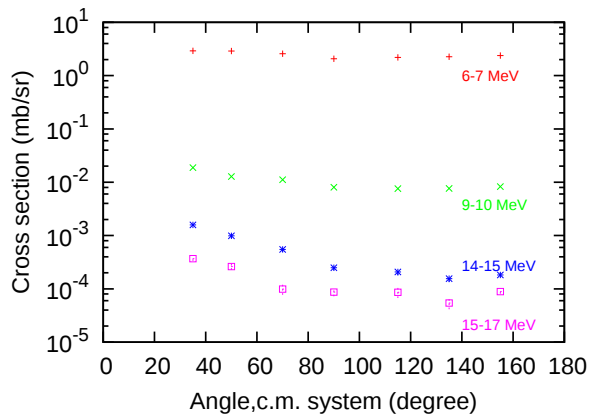


FIG. 1: (Color online). Angular distribution of outgoing protons from the $^{59}\text{Co}(\alpha, p)$ reaction.

TABLE I: Fermi-gas model level density parameters derived from the fitting the formula (1) to discrete levels and neutron resonance spacing with different spin cutoff formulas

Nucleus	σ , Eq.(3)		σ , Eq.(2)	
	a	delta	a	delta
^{62}Ni	5.76	0.43	6.39	0.50
^{60}Co	6.71	-1.54	7.11	-1.30

(6-7) MeV protons exhibit an angular distribution nearly symmetric about 90° indicating the compound reaction mechanism to be responsible for this energy group. For higher proton energies, the forward peaked angular distribution starts to appear indicating increasing contribution from pre-equilibrium processes. At backward angles, where the angular distribution flattens out, one may assume that the pre-equilibrium contribution becomes negligible. However, as it has been shown in our previous work [7], the angular distribution may flatten out or increase even if the pre-equilibrium contribution is dominant. Therefore, generally, it is difficult to estimate the relative contribution of pre-equilibrium/compound processes based only on angular distributions. Therefore we used proton spectra from $^{56}\text{Fe}(^7\text{Li}, p)$ and $^{55}\text{Mn}(^6\text{Li}, p)$ reactions measured by us recently. These reactions populate same compound nuclei as α -induced reactions do.

The experiment was performed at the Edwards Accelerator Laboratory of Ohio University with the tandem machine utilizing 15 MeV $^6, ^7\text{Li}$ beams. The high energy portion of the proton spectrum has been registered with a ΔE - E telescope consisting of 0.2 and 5 mm thick Si and Si(Li) detectors. The low energy protons were registered with the time of flight technique utilizing a 1.5mm Si detector located at the 2m distance from the target (see Refs.[8, 9] for details). Proton energy spectra have been measured at backward 155° angle to avoid contributions from non-compound reaction mechanisms. Spectra have been converted to differential cross sections $\sigma(E_p)/dE_p$

using the target thickness, the beam current integrator and detector solid angles.

III. DATA ANALYSIS

In this paper we focus on compound reaction mechanism so only double differential cross sections (we will also call them spectra) of protons measured at backward angles were analyzed. For theoretical calculations we used Empire computer code [3] which is the most sophisticated publicly available code designed for reaction cross section calculations. To see the effect of the different level density input options, we compared experimental spectra from both alpha and lithium induced reactions against compound model calculations using level density models embedded in Empire code (Figs. 2,3). Details about the models can be found in Empire article of Ref.[3]. We will provide the brief description of these models:

- Empire -specific level densities, BCS+Fermi gas with deformation-dependent collective effects [3]
- Generalized Superfluid model (GSM) of Ignatyuk [4]
- Gilbert-Cameron (GC) level density model consisting of constant temperature and Fermi-gas model functions according to the idea of Ref.[10]. Default parametrization was used.
- Microscopic model based on Hartree-Fock-Bogoliubov plus combinatorial method according to the formalism of Ref.[11]

Experimental data points versus theoretical predictions are presented in Figs.2 and 3. In Fig. 2 there are also comparisons for the neutron spectrum from the $^{59}\text{Co}(\alpha, n)$ reaction measured with 17.6 MeV alpha beam. Data are taken from Ref.[12]. When comparing calculations to experimental data, it is important to compare discrete level region versus continuum. Therefore we also showed calculations scaled to match experimental cross sections in the discrete level region. This scaling factor is mostly due to incorrect level densities for nuclei related to neutron outgoing channel. Discrete levels used in calculations have assigned spins and parities according to RIPL-3 datafile[4].

One can see that deviations of calculations from experimental data points are consistent for both alpha and lithium induced reactions meaning that deviations are exclusively due to level densities but not to different reaction mechanisms. Empire specific level density model strongly overestimates the proton cross section in continuum compared to discrete level region. The slope of theoretical continuum proton spectra is less steep compared to experimental data points. GSM model reproduces the shape of proton spectra well in case of reactions populating the ^{62}Ni nucleus. However, the absolute cross section for protons is strongly underestimated. This is due to

overestimated level densities for the ^{62}Cu nucleus populated by neutrons. It is clearly seen from comparison of neutron spectra. Although the shape of the experimental neutron spectrum is reproduced well, the calculated cross section in continuum is strongly overestimated compared to the discrete level region. This causes the underestimation of proton cross sections. In case of proton spectra from alpha and lithium induced reactions on ^{57}Fe and ^{55}Mn nuclei the calculated proton spectra strongly overestimate experimental ones. Obviously, GSM parameters from default systematics used by Empire fail to reproduce level densities for local nuclei including those for which the experimental information on neutron resonance spacing is available.

Gilbert and Cameron level density model is the best one among others to reproduce both shapes and absolute cross sections of protons from both lithium and alpha induced reactions. Both discrete level and continuum regions are reproduced consistently down to the point corresponding to the neutron binding energy of residual ^{62}Ni and ^{60}Co nuclei populated by the first stage of outgoing protons.

Calculations with microscopic level densities show results similar to those from GC model although the general agreement is slightly worse. Microscopical model gives slightly different shape of proton spectra compared to experimental one.

The important point is that calculations show consistent deviations for both lithium and alpha induced reactions. All discrepancies relate to discrepancies in level densities alone excluding other possible causes which are reaction mechanisms, the different spin population of compound nucleus, target contaminations or any other possible systematics uncertainties.

Despite the good agreement for the GC level density model, the default parameter systematics used by Empire do not always reproduce experimental values of neutron resonance spacings indicating the problems with spin cut-off parameters. In particular, default parameters which were used in calculations give the values of 2 and 0.8 keV for resonance spacings for ^{60}Co and ^{62}Ni nuclei versus experimental values of 1.45(15) and 2.1(15) keV [4] respectively. Therefore, in the following we will develop the procedure of estimating level densities and spin cut-off parameters which would reproduce both neutron resonance spacings and experimental proton spectra from both alpha and lithium induced reactions.

At the beginning, we will check the accuracy of level density functions which are traditionally obtained from fitting of model formulas to neutron resonance spacing and to discrete level densities. We performed such a procedure for both ^{62}Ni and ^{60}Co nuclei with traditional Fermi-gas formula:

$$\rho(E) = \frac{\exp(2\sqrt{a(E - \delta)})}{12\sqrt{(2\sigma)a^{1/4}(E - \delta)^{5/3}}} \quad (1)$$

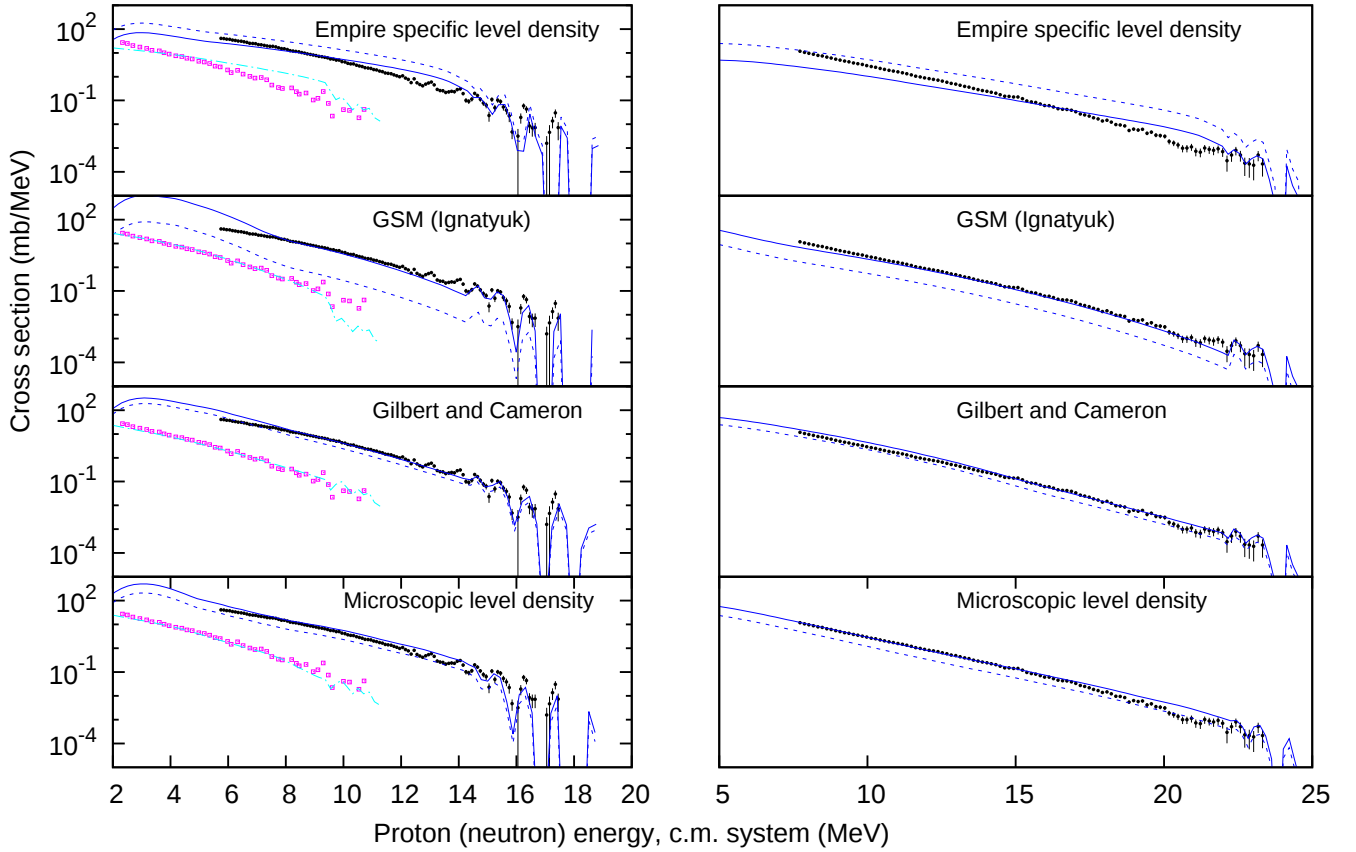


FIG. 2: (Color online). Experimental proton and neutron spectra versus Empire calculations with different input level density models. Neutron spectrum is from Ref.[12]. Left panel: $^{59}\text{Co}(\alpha, p)$ (points) with $E_\alpha=21$ MeV and $^{59}\text{Co}(\alpha, n)$ (squares) with $E_\alpha=17.6$ MeV. Right panel: $^{56}\text{Fe}(^7\text{Li}, xp)$ with $E_{^7\text{Li}} = 15$ MeV. Dashed lines are original calculations. Full lines are original calculations scaled to match experimental points in discrete level region.

with two commonly used expressions for the spin cutoff parameter σ :

$$\sigma_1^2 = 0.0146A^{5/3}t = 0.0146A^{5/3}\sqrt{((E - \delta)/a)}. \quad (2)$$

and

$$\sigma_2^2 = 0.089A^{2/3}a\sqrt{((E - \delta)/a)}. \quad (3)$$

These spin cutoffs have same excitation energy dependence but the magnitude of the second one is less by about 30%. Parameters found are presented in Table I. Empire calculations of proton spectra versus experimental data points are shown in Fig. 4. Calculations were scaled to match experimental cross sections in discrete level region. The figure clearly demonstrates the sensitivity of proton spectra to spin cutoff parameterizations. Although calculated curves are close to experimental data points, neither of them describe experimental spectra perfectly well. Results of such an analysis show that the level density parameters obtained from neutron

resonance spacings and discrete level densities do not always reproduce particle spectra from compound nuclear reactions well. The spin cutoff parameterizations plays essential role here.

IV. LEVEL DENSITY AND SPIN CUTOFF PARAMETER FROM SPECTRA SIMULATION TECHNIQUE

In order to get both level density functions and spin cutoff parameters which would precisely reproduce both our experimental data points and neutron resonance spacings, the Monte-Carlo simulation technique was employed. Availability of experimental data points related to both continuum and discrete level regions allowed to analyze not only level densities but also the spin cut-off parameter in continuum based on known spins of discrete levels. Along with traditional technique which uses the matching continuum level density function to the den-

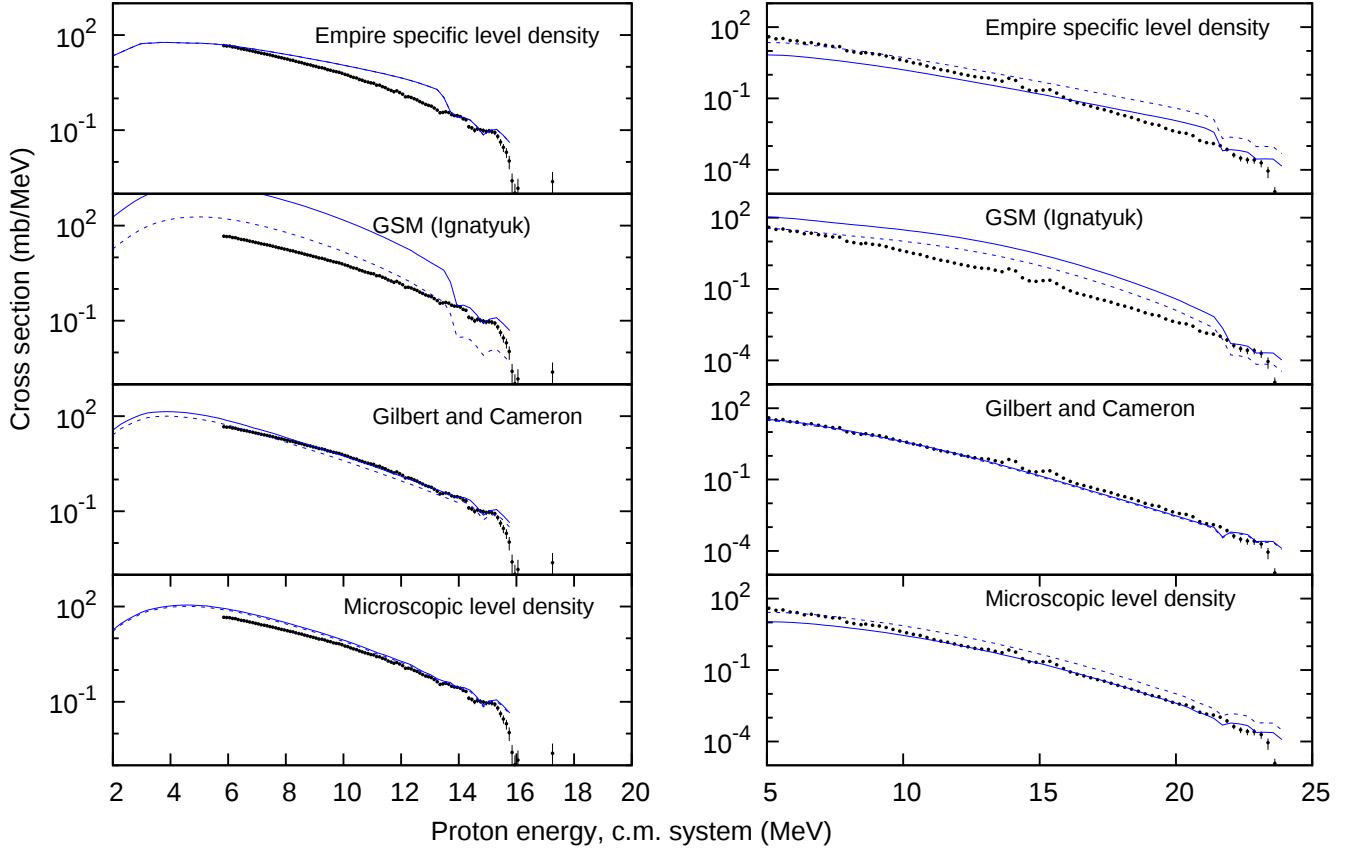


FIG. 3: (Color online). Experimental proton spectra versus Empire calculations with different input level density models. Left panel: $^{57}\text{Fe}(\alpha, p)$ with $E_\alpha = 21$ MeV. Right panel: $^{55}\text{Mn}(^6\text{Li}, xp)$ with $E_{^6\text{Li}} = 15$ MeV

sity of discrete levels, we used similar technique to match spin cutoff parameters. The matching of spin cutoff parameters is usually neglected when deriving level density model parameters from fitting of discrete levels and neutron resonance spacings. We used the experimental values of s-wave neutron resonance spacings which are 2 keV and 1.39 keV for ^{62}Ni and ^{60}Co respectively [13]. In the Fermi-gas formula (1) the spin cutoff parameter σ is usually coupled with the total level density ρ through the common model parameters a and δ . (see Eq.(3) and Eq.(2)). In simulations, we used an independent spin cutoff parametrization in the following form:

$$\sigma^2 = \sigma_{dis}^2 \left(\frac{E - \Delta}{E_c - \Delta} \right)^P \quad (4)$$

The σ_{dis} is the spin cutoff parameter in the discrete level region with the effective center energy E_c . Both these parameters were calculated from experimental level schemes. Number of discrete levels and cutoff energy (the excitation energy up to which the discrete level scheme is considered to be known) were taken from the RIPL-3

TABLE II: Parameters for the spin cutoff formula (4) used in simulation

Nucleus	σ_{dis}^2	$\Delta\sigma_{dis}^2$	E_c	δ
^{62}Ni	5.9	1.0	3.6	1.0
^{60}Co	9.8	2.3	1.7	1.0

data base [4]. Uncertainties of σ_{dis} include uncertainties of the spin assignment for some of the levels and uncertainties of the fitting procedure. Parameter Δ is not so important so it has been chosen arbitrary to be in the range $0 \div E_c$. Final parameters used in simulations are presented in Table II.

In simulation parameters σ_{dis}^2 and P have been varied randomly within the range of $\sigma_{dis}^2 \pm \Delta\sigma_{dis}^2$ and $0.0 \div 1.0$ respectively. For each realization, the level density function has been calculated with the Gilbert and Cameron approach [10] according to which the constant temperature formula $\exp((E - E_0)/T)/T$ was used up to the certain excitation energy E_x . Above this energy the fermi gas formula (1) was used. Both the E_x and T were also

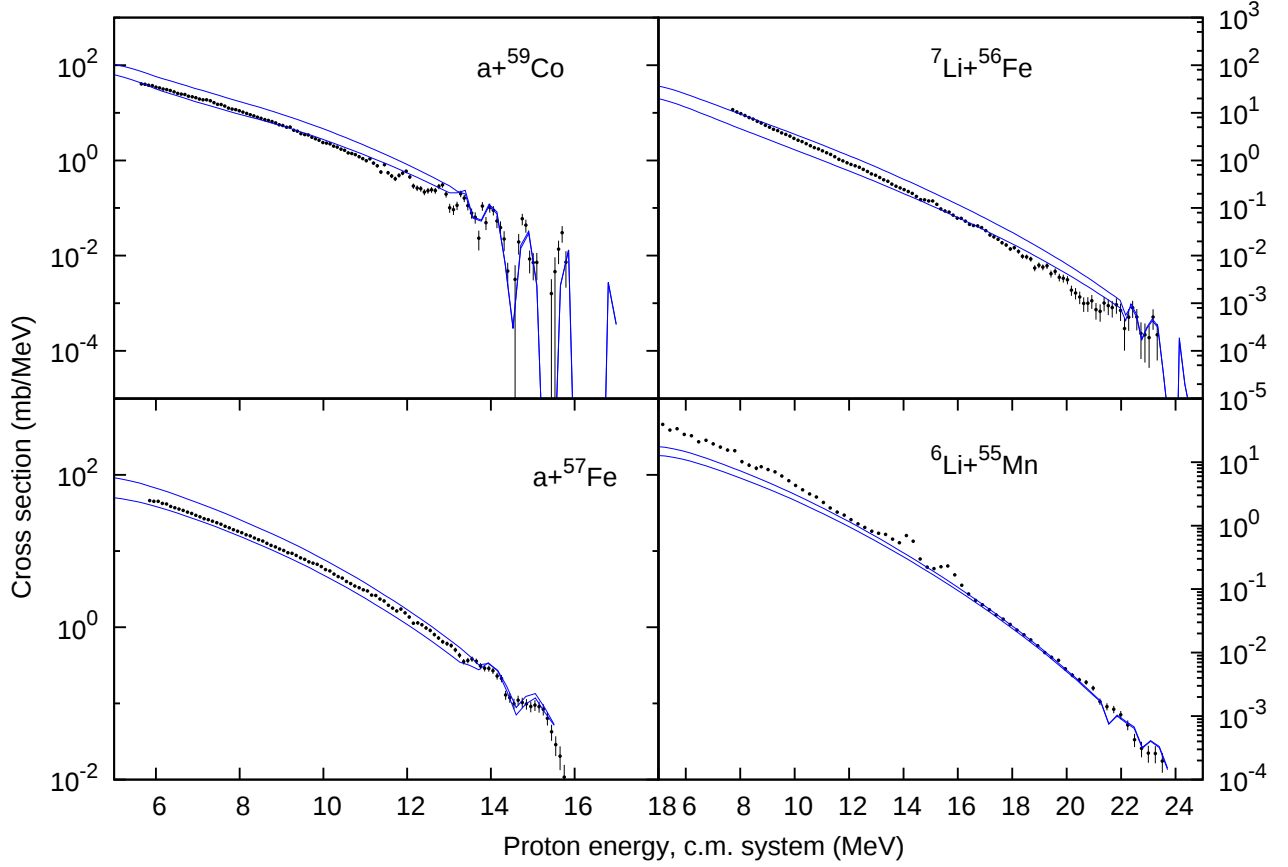


FIG. 4: (Color online). Experimental proton spectra (points) versus Empire calculations using Fermi-gas model with two spin cutoff parameters according to expressions (3) (bottom line) and (2) (top line)

random numbers within a reasonable range. So the level density was able to modify its shape depending on E_x . It was either Fermi-gas when E_x approaches to the discrete level region or the constant temperature plus Fermi-gas if E_x is close to the neutron binding energy (which has been used as a maximum number for the E_x).

Parameters T , a and δ in the level density composite formula have been obtained from the fit to discrete levels and neutron resonance spacings. Parameters were used then as inputs in Empire code [3] to calculate proton spectra. The level density subroutine in Empire code has been modified to be able to use the spin cutoff parameter in the form of Eq.(4). Because the neutron outgoing channel is dominant in these reactions, the spin distribution for residual nuclei populated by neutrons might affect the proton spectrum through the competition of outgoing channels in orbital momentum space (although we assume that this effect is small). Therefore, the spin cutoff parameters for nuclei ^{60}Ni and ^{62}Cu populated by neutrons have also been simulated according to Eq.(4). In these simulations we focus on energy range of protons

populating excitation energies up to the neutron binding energy of residual ^{60}Ni and ^{62}Cu nuclei. The calculated proton spectrum has been considered to reproduce the experimental spectrum if the maximum deviation from experimental points was not greater than 10% in this energy range.

Both spin cutoff and level density functions which reproduce experimental data points within 10% uncertainties are shown in Fig.5. For ^{62}Ni , the $\sigma^2(E)$ is steeper compared to what is expected from Fermi-gas formulas (3,2). It is in agreement with the formula (3) at the region of discrete levels and with the formula (2) at the neutron binding energy. The parameter P was obtained to be 0.85 ± 0.25 . However, for the ^{60}Co nucleus, the situation is opposite. The function $\sigma^2(E)$ is flatter (close to constant) compared to predictions of Fermi-gas formulas (3 and 2). It is in agreement with (2) at discrete levels and with (3) at the neutron binding energy. The parameter P for ^{60}Co was obtained from simulations to be around 0.06 ± 0.08 .

It is also important to mention that spin cutoff param-

ters for ^{60}Co and all other cobalt isotopes in the region of discrete levels systematically larger than for other neighboring nuclei (see data in Ref. [4]). We found that the energy dependencies for ^{60}Co and ^{62}Ni are different as well.

In order to be confident that our conclusions are not vulnerable to possible systematic experimental uncertainties, we used independent experimental data on proton differential cross sections of the $^{57}\text{Fe}(\alpha, p)$ reaction measured with a 18 MeV α beam [14]. The comparison with calculations used spin cutoff expressions (3) and (2) is presented in Fig.6 One can see the same features as in our measurements presented in Fig.4. Experimental data points lie in between two lines related to calculations with two different spin cutoff expressions. Cross sections of low energy protons are closer to calculation with the spin cutoff according to Eq. (3) while cross sections at higher energies approach calculations with Eq.(2). It is intuitively clear from this comparison that in order to reproduce experimental data points, the real spin cutoff parameter should be in agreement with Eq. (2) at the low excitation energy and it should approach the values of Eq. (3) at around the neutron binding energy. It is supported by simulation described above and presented in Fig.5.

In our analysis we always assume that number of levels with negative and positive parities are equal at the neutron binding energy. If this is not true, it would affect conclusions about spin cutoff parameters. We rely on the fact that there is no indications of non-equality of positive and negative parities. Theoretical calculations with the microscopical model of Ref.[11] give 15% difference only that is within experimental uncertainties of neutron resonance spacings. Also the phenomenological formulas of the parity distribution derived in Ref.[15] predicts equality of both parities at the neutron binding energy for these nuclei.

It follows from Fig.5 that level densities obtained from simulations are closer to a straight line in logarithmic scale that is more consistent with the constant temperature part of the Gilbert and Cameron model.

V. SPIN CUTOFF FROM ANGULAR ANISOTROPY

The degree of anisotropy of a symmetric at 90° angular distribution of outgoing particles from compound nuclear reactions has been shown to depend on the spin cut-off parameter of residual nuclei [16]. This technique was successfully used in the past to deduce spin cutoff parameters [12]. The main difficulties of this technique is due to the fact that non-statistical contribution which is almost always present at forward angles distorts symmetric compound angular distribution making it asymmetric. Using only backward angles from 90 degree and up can be tricky since it is not clear whether or not related cross sections are free from non-compound component. There-

TABLE III: Angular anisotropy from experiment and simulations. E_p and E_{ex} are average proton energy and corresponding excitation energy for which the angular anisotropy was determined.

Nucleus	E_{ex} (MeV)	E_p MeV	$\frac{W(90)}{W(155)}_{simul}$	$\frac{W(90)}{W(155)}_{exp}$
^{60}Co	8.6-9.6	6-7	0.84(2)	0.85(1)
^{62}Ni	11.6-12.6	6-7	0.92(2)	0.90(1)

fore, one should use only symmetric angular distributions or backward angles of asymmetric distribution with small forward peaked component.

In our measurements proton angular distributions have a forward peaked asymmetry at all energies. The asymmetry is larger for higher energy protons. For the low-energy protons with energies around 6-8 MeV the asymmetry is still present although its magnitude is much smaller. In our analysis we used angular distributions from backward angles for low-energy protons (6-7 MeV) for which the asymmetry is small. The assumption is that in this energy range non-compound protons have negligible effect on cross sections at backward angles. Since for our reactions the anisotropy is smaller for larger values of spin cutoff parameters, the possible contribution of nonstatistical protons at backward angles leads to overestimation of spin cutoff parameters. Thus, spin cutoff parameters obtained from such distributions reflect rather their upper limit. Experimental and calculated asymmetries are presented in Table III. For calculations of angular distributions we use HF computer code [17] which allows using arbitrary spin cutoff energy dependence. Calculations used spin cutoff parameters obtained from simulation technique as described in the previous section and presented in Fig. 5. The compound anisotropy was calculated as a ratio of cross sections at 90 and 155 degrees $\frac{\sigma(90)}{\sigma(155)}$, i.e. in the range covered by experimental points. Experimental points were fitted with the second order polynomial function. One can see the good agreement between experimental and calculated ratios. We consider this as an independent support of spin cutoff parameters obtained from our simulation technique based on analysis of double differential proton cross sections.

VI. CONCLUSION

Experimental proton spectra have been analyzed with different level density inputs of the Empire Hauser-Feshbach code. The analysis showed that the level density input based on GC model with default parameter systematics is best to reproduce presented experimental spectra in both discrete level and continuum regions. This is in line with recent experimental findings [9? ?] and theoretical developments [?]. However, the default parametrization does not reproduce experimental data on neutron resonance spacing meaning that the model parametrization needs to be modified.

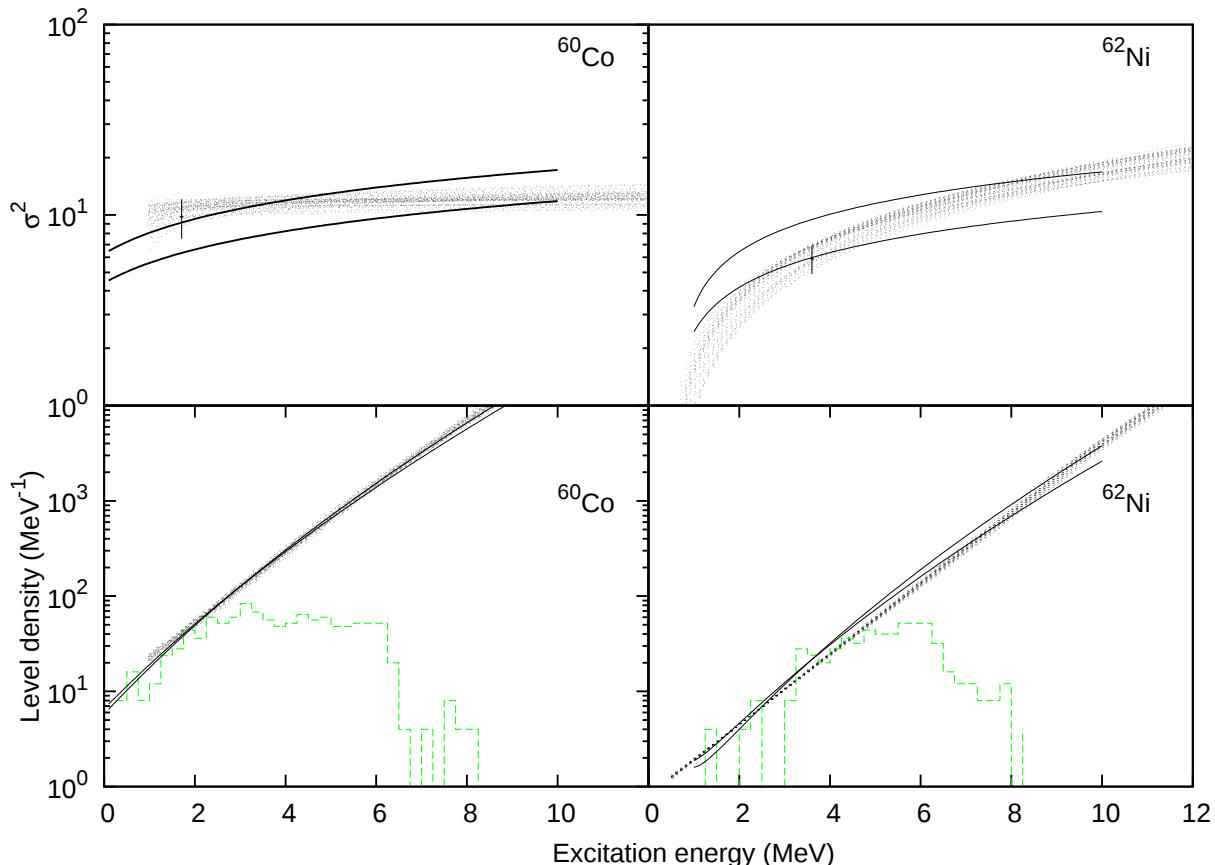


FIG. 5: (Color online). Shaded areas: level densities and spin cutoff functions obtained from Monte-Carlo simulations for ^{60}Co and ^{62}Ni nuclei. Lines: calculations according to Fermi-gas formula with spin cutoff expressions (3) (bottom lines) and (2) (top lines)

The spin cutoff parameter plays an important role and it can be source of uncertainties in calculations of reaction cross sections. The common practice of relying on level density model parameters obtained from neutron resonance spacing does not reproduce cross sections of evaporated protons well with the Fermi-gas model in its original form (1) neither with spin cutoff Eq. (2) nor with Eq. (3). The spin cutoff parameter need to be modified to reach good agreement with available experimental data.

For ^{60}Co and ^{62}Ni nuclei both level densities and spin cutoff parameters have been studied with Monte-Carlo simulation techniques. Also proton angular distributions have been used to deduce spin cutoff parameters independently. Results indicate that the excitation energy

dependence of spin cutoff parameters are different for these nuclei and do not follow traditional Fermi-gas expressions. This conclusion agree with that reached in Ref.[12].

VII. ACKNOWLEDGMENTS

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[1] M. Chadwick, P. Obložinský, M. Herman, N. Greene, R. D. McKnight, D. L. Smith, P. G. Young, R. E. Mac-

Farlane, G. M. Hale, S. C. Frankle, et al., Nuclear Data Sheets **107**, 2931 (2006).

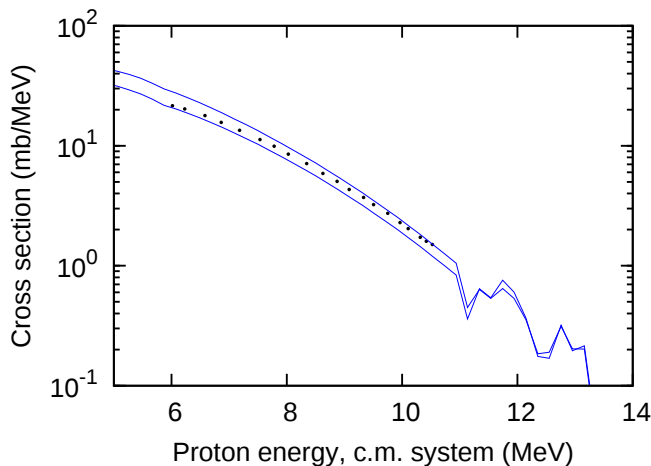


FIG. 6: (Color online). Experimental proton spectrum obtained with 18 MeV α beam in Ref.[14](points). Empire calculations using Fermi-gas model with two spin cutoff parameters according to expressions (3) (bottom line) and (2) (top line)

- [2] T. Rauscher, F.-K. Thielemann, and K.-L. Kratz, Phys. Rev. **C56**, 1613 (1997).
- [3] M. Herman, R. Capote, B. Carlson, P. Obložinský, M. Sin, A. Trkov, H. Wienke, and V. Zerkin, Nucl. Data Sheets **108**, 2655 (2007).
- [4] R. Capote, M. Herman, P. Obložinský, P. G. Young, S. Goriely, T. Belgia, A. V. Ignatyuk, A. J. Koning, S. Hilaire, V. A. Plujko, et al., Nucl. Data Sheets **110**,

- 3107 (2009).
- [5] H. Vonach, in *Proceedings of the IAEA Advisory Group Meeting on Basic and Applied Problems of Nuclear Level Densities*, edited by M.R.Bhat (Upton, LongIsland, New York 11973, 1983), p. 247.
- [6] B. Strohmaier, in *IAEA Advisory Group Meeting, Rad.Damage* (1981).
- [7] A. Voinov, S. Grimes, C. Brune, A. Burger, A. Gorgen, M. Guttormsen, A. Larsen, T. Massey, S. Siem, and C. Kalbach, Phys. Rev. **C83**, 054605 (2011).
- [8] B. M. Oginni, S. M. Grimes, A. V. Voinov, A. S. Adekola, C. R. Brune, D. E. Carter, Z. Heinen, D. Jacobs, T. N. Massey, J. E. O'Donnell, et al., Phys. Rev. **C80**, 034305 (2009).
- [9] A. V. Voinov, B. M. Oginni, S. M. Grimes, C. R. Brune, M. Guttormsen, A. C. Larsen, T. N. Massey, A. Schiller, and S. Siem, Phys. Rev. **C79**, 031301(R) (2009).
- [10] A. Gilbert, F.S.Chen, and A. Cameron, Can.J.Phys **43**, 1248 (1965).
- [11] S. Hilaire, S. Goriely, and A. J. Koning, Phys. Rev. **C78**, 064307 (2008).
- [12] S. Grimes, J. Anderson, J. McClure, B. Pohl, and C. Wong, Phys. Rev. **C10**, 2373 (1974).
- [13] S. F. Mughabghab, *Atlas of Neutron Resonances* (Elsevier, Amsterdam, 2006).
- [14] K. C. Chan, L. Shabason, B. L. Cohen, J. Alzona, and T. Congedo, Phys. Rev. **C15**, 1698 (1977).
- [15] S. I. Al-quraishi, S. Grimes, T. N. Massey, and D. A. Resler, Phys. Rev. **C67**, 015803 (2003).
- [16] A. Douglas and N. Macdonald, Nucl. Phys. **13**, 382 (1959).
- [17] S.M.Grimes, Tech. Rep. INPP-04-03, Ohio University (2004), unpublished.