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S. A. Karamian [*]

# THRESHOLD AND SPIN FACTORS IN THE YIELD OF BREMSSTRAHLUNG-INDUCED REACTIONS

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[*] E-mail: karamian@nrmail.jinr.ru

Карамян С. А. E15-2012-65

Влияние порога и спинового фактора
на выход реакций под действием тормозных фотонов

В зависимости от параметра, связанного с порогом реакции, систематизированы выходы реакций на ядрах мишеней средней массы под действием фотонов при граничной энергии тормозного спектра ниже 30 МэВ. Для группы реакций $(\gamma,\ n)$, $(\gamma,\ p)$ и $(\gamma,\ d)$ установлена регулярная зависимость, в то время как выходы $(\gamma,\ \alpha)$ и $(\gamma,\ 2n)$ отклоняются от регулярного поведения. Предложено применение данной систематики в процессе обработки данных, а также обсуждаются полученные физические выводы. В частности, могут быть разделены факторы, определяющие зависимость изомерного отношения от спина и порога. Регуляризация зависимости от спина достигается введением нового параметра, что позволило обнаружить прежде скрытые особенности.

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Karamian S. A. E15-2012-65

Threshold and Spin Factors
in the Yield of Bremsstrahlung-Induced Reactions

Relative yields of photon-induced reactions are systematized in a function of the threshold parameter for moderately heavy targets at the bremsstrahlung end-point energy lower than 30 MeV. Regular dependence is established for the group of $(\gamma,\ n)$, $(\gamma,\ p)$, and $(\gamma, d)$ reactions while the yields of $(\gamma,\ \alpha)$ and $(\gamma,\ 2n)$ reactions deviate from the regularity. Physical conclusions are discussed and possible application of this systematics for data processing is proposed. In particular, the constituent threshold and spin factors in the isomer-to-ground state ratio could be separately isolated. For spin dependence of the yields, a new regularization parameter is introduced and previously hidden peculiarities are concluded.

The investigation has been performed at the Flerov Laboratory of Nuclear Reactions, JINR.

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# INTRODUCTION

Nuclear reactions induced by photons seem the most elementary ones because the product particles are released by the influence of electromagnetic field without dominating effect of strong interaction between the projectile and target nucleons. In the mechanism of direct reactions, the target nucleons are suddenly perturbed by the field of external photon and product particles are emitted instantaneously. Therefore, reaction yield conserves a spot of bonds and correlations between nucleons in the target. Observed reaction pattern is similar to a photo of the frozen nucleon distribution in the coordinate and momentum space. Even within the mechanism of photon absorption due to giant resonance, the latter collective (shape) mode may co-exist with the particle states without strong perturbation of them but providing the link to exit channels. In both mechanisms, ejection of the product particles is possible only if energy is enough to overcome a threshold of the corresponding reaction. For emission of charged particles, their Coulomb barrier must be added to obtain the effective threshold parameter.

Excess of the projectile energy above effective threshold makes the reaction yield more abundant. The corresponding correlations are commonly known, in particular for direct nucleon-transfer reaction between complex nuclei. The latter trend was called since many years using a term of «$Q_{gg}$-systematics» [1, 2]. Nothing would be unexpected if the yield of photon-induced reactions follows the regular dependence of a threshold parameter. One complication arises in the data processing because photonuclear reactions are typically studied using the continuous bremsstrahlung spectra. However, recently the regular threshold dependence has been proved for the thick target yields in the direct reactions with alpha particles [3]. Definitely, the regularity survives in the case of wide-spectrum projectiles and not necessarily for heavy ions but also for reactions induced by relatively light $\alpha$ particles. We expect a similar behavior for the photon induced reactions as well.

For compound reactions, the product excitation function $\sigma_P\ (E)$, is defined by the function of compound nucleus formation $\sigma_C(E)$, by the effective threshold factor for particle emission $F(E,\ E_{\mathrm{th}})$, and also by a factor including the probability of sequential emission $(1{-}P_S)$:

$$\sigma_P(E) = \sigma_C(E)\, F(E, E_{\mathrm{th}})\ [1 - P_S\,(E)]. \tag{1}$$

Such a factorization ignores the spin dependence of cross sections and is applicable to the total reaction yields. In the case of direct reactions, the threshold dependence factor originates in essence from another physical pattern, but in both cases it reflects the influence of a phase volume in the momentum space for the emitted particles. Thus, at some range of the encounter parameters the specific mechanism of reactions could be ignored. For emission of nucleons and $\alpha$ particles, the threshold factor must dominate at the bremsstrahlung end-point energy lower than 30 MeV, while at higher energies, the sequential emission probability becomes high, and, in general, it defines the yield of any particular reaction.

In the present work, we took for the analysis the literature data [4–12] obtained at the end-point energy $E_e \leqslant 30$ MeV. This series of works was performed over recent five years, except the paper [4] published 15 years ago. But the latter article involves the original results taken with high-spin target and product nuclei and remains of interest for the modern analysis. Selected data set of [4–12] must be enough to establish regular trends and manifestations in the reaction yields.

However, the measured data are often incomplete. The activation method is widely used, and in some cases, a partial yield of the isomer or of the ground state could only be measured because of the individual decay properties of the products. The partial yield is not enough because we need to operate with the full yield of the reaction. Fortunately, a survey of the isomer-to-ground state ratios ($m/g$) was developed earlier based on the analysis of the data taken since 30–40 years ago.

The collection of those results was reviewed in the papers [13, 14]. The systematic function of the $m/g$ ratio must be helpful to evaluate the full yield $Y_{\mathrm{tot}}$ of the reaction when only $m$ or $g$ state was detected due to the radioactive properties. The total yield is expressed through the partial yields and the $m/g$ ratio as follows:

$$Y_{\mathrm{tot}} = Y_g(1 + m/g) = Y_m\,(1 + m/g)(m/g)^{-1}. \tag{2}$$

Below, we start from the isolation of the threshold dependence factors from experimental results of [4–7]. Total yields are available there and if not, the recalculation through Eq. (2) could be applied. The traditional approach to the system of $m/g$ ratios as a function of spin difference allows one to estimate the realistic $m/g$ ratio when it is not measured. The threshold factor makes influence on the $m/g$ ratio as well, but that could be noticeable only when the excitation energy of the isomer is high, exceeding 0.5 MeV. In such cases, the second iteration is possible correcting the observed $m/g$ value to the difference of thresholds for $g$ and $m$ product states. This iteration was performed for the group of data taken from [4–7], and the results are shown below. At the same time, in some publications of recent years [9–12], only isomer-to-ground state ratios are reduced, while yields of different reactions are not compared even in relative units. Therefore, they could not be used for construction of the threshold dependence, either for evaluation of the corrected $m/g$ values. In the discussed below dependence of $m/g$ ratio on the spin parameter, the data of [9–12] are taken as they are. The threshold factor in $m/g$ ratio is relatively low at moderate excitation of isomers, and the systematics is not strongly distorted due to that. However, the yield of such isomers as $^{178m2}$Hf excited to 2.45 MeV is influenced by the higher threshold and this has been taken into account.

## 1. THRESHOLD DEPENDENCE OF YIELDS

Reaction thresholds could be calculated using known masses (binding energies) for the reaction participants: projectile, target, product and ejectile. Nuclide masses are tabulated and are available in literature, for instance, in Handbook [15]. For selected reactions, we have calculated numerically the threshold values $E_{\rm th}$. In the case of charged ejectiles, the Coulomb barrier $B_C$ must be added to receive real start point for the successful emission, therefore $B_C$ values were calculated using the well-known and accepted Bass barrier equation [16]. The systematization parameter for threshold dependence is taken in a form of $(E_e - E_{\rm th} - B_C)$, where $E_e$ is the bremsstrahlung end-point energy. The parameter defines an excess of the maximum photon energy above the reaction effective threshold.

In Fig. 1, relative yields of the reactions studied in works [4–8] are plotted as a function of $(E_e - E_{\rm th} - B_C)$. Each consequence of points is taken for definite target and $E_e$ value and looks as a separate function. That is because only relative yields are given in publications and they are normalized to the most abundant yield of the $(\gamma,\ n)$ reaction. These separate functions, in principle, could be merged into a unified dependence to get a common general function of the yield versus threshold parameter. However, the absolute yields are not given in [4–8], and only partial systematization of Fig. 1 is possible for each individual group of the yield values. In some cases, the inclusive yield of only $m$ or $g$ state is given, and we recalculate them to the full reaction yield, as was described above with Eq. (2). The spin dependence regularities are commented below in the following section.

The regular behavior of the yield as a function of the threshold parameter is nevertheless clearly manifested in Fig. 1. Each separate curve may be used as a threshold factor $F(E,\ E_{\rm th})$ for partial collection of yields with the definite target and end-point energy. It would be interesting to stress that the points, corresponding both to the $(\gamma,\ n)$ and $(\gamma,\ p)$ reactions, demonstrate a regular increase versus the $(E_e - E_{\rm th} - B_C)$ parameter in Fig. 1. The common variation may confirm a similar mechanism of the neutron and proton emission. Most probably, they are emitted through the evaporation mechanism from the compound

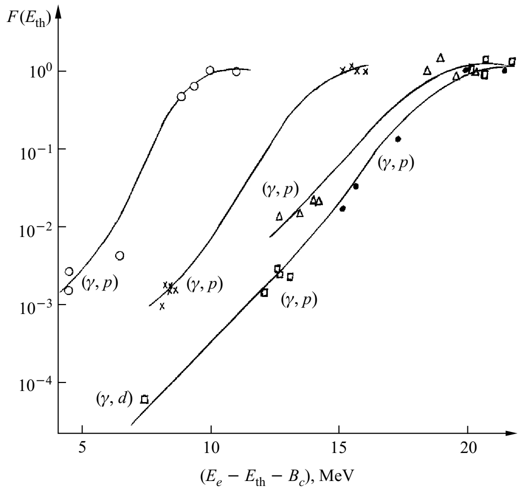

Fig. 1. Relative yields of the bremsstrahlung-induced reactions as a function of the threshold-dependent parameter. Experimental results are indicated by points: ○ — for the data taken in [6], at the end-point energy of 19.5 MeV, with the Sn target; $x$ — [4], 23.5 MeV, Hf and Ta; △ — [7], 29.1 MeV, Sn; □ — [5], 29.1 MeV, Hg; ● — [8], 30 MeV, Pd. Curves are given to guide the eye

nucleus past photon absorption or, with lower probability, are released directly by the electromagnetic field of a photon. In both cases, the regular threshold dependence of the single nucleon-emission yield could be expected until the end-point energy exceeds strongly a threshold for multinucleon emission.

The multinucleon reactions became dominating at high excitation energy suppressing the yields of elementary neutron and proton channels because of a successful competition. This mechanism is well known in physics of fusion-evaporation reactions induced by heavy ions. The probability $P_x$ of consequent emission of $x$ neutrons was mathematically described within statistical model as early as 60 years ago [17]. The most accurate recurrent equations for $P_x(E*)$ functions were given in [18]. The similar approach is also exploited in the modern computer codes for calculation of the reaction cross sections. Within the mechanism of sequential emission, the threshold dependence must be destroyed because the competition between different reaction channels is regulated by the statistical factors. The ratio of yields is mainly defined by the spectrum of the projectile energy and by the competition functions $P_x(E*)$. This is correct for photon-induced reactions as well.

Because of the described reaction scenarios, we could not include in the present systematics the results taken recently by Moscow and Kharkov groups for ($\gamma$, $xn$) reactions at $E_e$ up to 90 MeV. In such a case, the statistical competition defines the excitation function for each definite channel. Even the $(\gamma,\, 2n)$ reaction yields measured in the papers of our citation [4–8] deviate from the regularity at Fig. 1. Two-neutron evaporation accomplishes the $(\gamma,\, n)$ reaction yield and the probability is defined by the energy spectrum of residual excitation past emission of the first neutron. The second one is emitted with high probability of about unity when the energy is enough. Thus, the $(\gamma,\, 2n)$ yield deviates to a higher value from the regular yield prescribed by the threshold dependence. The corresponding points are not shown in Fig. 1 since they may destroy the regular dependence.

The threshold-parameter dependence must be valid also when the products are formed in the direct reactions and not through the compound mechanism. This is true even for emission of multinucleon clusters provided that a set of selected reactions contains the processes of a similar mechanism. The $(\gamma,\, d)$ yield [5] in Fig. 1 exceeds a little the regular prediction, probably indicating a contribution from the consequent mechanism of $p$ plus $n$ evaporation, in addition to the single-step emission. Unlike that, the $(\gamma,\, \alpha)$ yield measured in [4] appears by two orders of magnitude lower as compared to the $(\gamma,\, p)$ yields despite practically the same effective threshold values both for proton and alpha emission. A suppressed yield of $(\gamma,\, \alpha)$ may be explained by the necessity to account the alpha preformation factor, the same as known for the radioactive alpha decay. If so, one concludes that nucleons in major conserve their individual status inside the nuclear matter and the $\alpha$-clusterization takes place with restricted probability. Similarly, a total dissolution of nucleons with formation of the common or partial quark bags within the nuclear matter is not supported. Some probability for nucleon–nucleon correlations was deduced [19] from the analysis of the reactions at GeV energies, but complete missing of nucleon individuality had never been confirmed.

## 2. SPIN FACTOR IN THE ISOMER YIELD

A spin dependence of the isomer yields was evident since the decades and was extensively discussed, for instance, in the review articles [13, 20]. The spin difference parameter $(I_m - I_t)$ is typically used to establish the regular dependence of isomer-to-ground state ratio on spin. $I_m$ and $I_t$ are spin values of the isomeric state and of the target nucleus, correspondingly. Some authors prefer to use parameter $I_g$ instead of $I_t$, but this does not change a main idea that observed $m/g$ ratio is defined by the spin deficit in reaction. Following such a recommendation, we plot in Fig. 2 the recently measured $m/g$ ratios as a function of the $(I_m - I_t)$ parameter. The numerical data are collected in the Table as well.

The error bars are not reduced in the Table because, in some cases, they are not given in the original publications. In addition, the typical accuracy of such measurements could not be much better than 20% because of the influence of different factors. In addition to straight statistical errors, there are also some

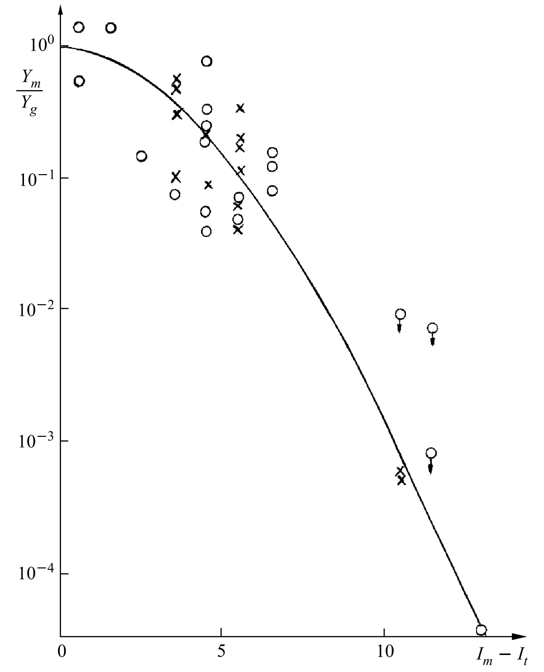

Fig. 2. Isomer-to-ground state ratio as a function of the spin-difference parameter: ○ — results of papers [4–7] corrected by the threshold factor; × — straight values given in papers [9–12]. Guide line is drawn through the points

systematical ones due to the detector efficiency calibration and to the tabular data for parameters of individual activities — the nuclide halflife and quantum yield of definite gamma lines. A high-accuracy measurement by gamma spectroscopy is possible but it requires much more efforts and could be performed only in special cases. The cited experiments are of regular grade performed using standard commercial detectors and calibration sources. Thus, we assume typical inaccuracy of about 20% and do not care about the scattering of points within such a range.

For reactions studied in [4–7], the threshold factor $F$ was determined and shown in Fig. 1. Therefore, measured values of $m/g$ ratio are corrected and the $mF_g/gF_m$ values are shown by open points in Fig. 2. In [9–12], the $m/g$ ratios are given, not the reaction yields, and this excludes a possibility for threshold corrections. Corresponding $m/g$ ratios are presented without corrections by crosses in Fig. 2. In principle, no great split is visible between the systems of open points and crosses. This could be expected because threshold corrections are relatively little for isomers with low excitation energy. But in some special case, it must be of significance, and in general, it would be right to insert the

**Isomer-to-ground state ratios in ($\gamma$, $n$) and ($\gamma$, $p$) reactions. The results obtained in [4–7] are processed with the inclusion of the threshold factor corrections and the other data [9–12] are processed without their inclusion**

| Ref. | $E_e$, MeV | Reaction | $I_t$ | $I_m$ | $Y_m/Y_g$ |
|---|---|---|---|---|---|
| [4] | 23.5 | $^{181}\mathrm{Ta}\ (\gamma,\ p)\ ^{180m}\mathrm{Hf}$ | 7/2 | 8 | 0.037 |
| | | $^{180m}\mathrm{Ta}\ (\gamma,\ p)\ ^{179m2}\mathrm{Hf}$ | 9 | 25/2 | 0.072 |
| | | $^{179}\mathrm{Hf}\ (\gamma,\ p)\ ^{178m}\mathrm{Lu}$ | 9/2 | 9 | 0.75 |
| | | $^{178}\mathrm{Hf}\ (\gamma,\ p)\ ^{177m}\mathrm{Lu}$ | 0 | 23/2 | $\leqslant 0.9 \cdot 10^{-3}$ |
| | | $^{178m2}\mathrm{Hf}\ (\gamma,\ n)\ ^{177m2}\mathrm{Hf}$ | 16 | 37/2 | 0.144 |
| [5] | 29.1 | $^{200}\mathrm{Hg}\ (\gamma,\ n)\ ^{199m}\mathrm{Hg}$ | 0 | 13/2 | 0.076 |
| | | $^{198}\mathrm{Hg}\ (\gamma,\ n)\ ^{197m}\mathrm{Hg}$ | 0 | 13/2 | 0.121 |
| | | $^{196}\mathrm{Hg}\ (\gamma,\ n)\ ^{195m}\mathrm{Hg}$ | 0 | 13/2 | 0.148 |
| | | $^{201}\mathrm{Hg}\ (\gamma,\ p)\ ^{200m}\mathrm{Au}$ | 3/2 | 12 | $\leqslant 0.9 \cdot 10^{-2}$ |
| | | $^{199}\mathrm{Hg}\ (\gamma,\ p)\ ^{198m}\mathrm{Au}$ | 1/2 | 12 | $\leqslant 0.72 \cdot 10^{-2}$ |
| [6] | 29.1 | $^{124}\mathrm{Sn}\ (\gamma,\ n)\ ^{123m}\mathrm{Sn}$ | 0 | 3/2 | 0.75* |
| | | $^{118}\mathrm{Sn}\ (\gamma,\ n)\ ^{117m}\mathrm{Sn}$ | 0 | 11/2 | 0.067 |
| | | $^{120}\mathrm{Sn}\ (\gamma,\ p)\ ^{119m}\mathrm{In}$ | 0 | 1/2 | 0.72* |
| | | $^{119}\mathrm{Sn}\ (\gamma,\ p)\ ^{118m}\mathrm{In}$ | 1/2 | 5 | 0.241 |
| | | $^{117}\mathrm{Sn}\ (\gamma,\ p)\ ^{116m}\mathrm{In}$ | 1/2 | 5 | 0.205 |
| | | $^{116}\mathrm{Sn}\ (\gamma,\ p)\ ^{115m}\mathrm{In}$ | 0 | 1/2 | 0.508 |
| [7] | 19.5 | $^{124}\mathrm{Sn}\ (\gamma,\ n)^{123m}\mathrm{Sn}$ | 0 | 3/2 | 0.195* |
| | | $^{118}\mathrm{Sn}\ (\gamma,\ n)\ ^{117m}\mathrm{Sn}$ | 0 | 1/2 | 0 |
| | | $^{117}\mathrm{Sn}\ (\gamma,\ p)\ ^{116m}\mathrm{In}$ | 11/2 | 5 | 1/2 |
| | | $^{112}\mathrm{Sn}\ (\gamma,\ p)\ ^{111g}\mathrm{In}$ | 0.048 | 0.332 | 0.054 |
| [9] | 29.1 | $^{197}\mathrm{Au}\ (\gamma,\ n)\ ^{196m1}\mathrm{Au}$ | 3/2 | 5 | 0.1 |
| | | $^{197}\mathrm{Au}(\gamma,\ n)\ ^{196m2}\mathrm{Au}$ | 3/2 | 12 | $5 \cdot 10^{-4}$ |
| [10] | 25 | $^{197}\mathrm{Au}\ (\gamma,\ n)^{196m2}\mathrm{Au}$ | 3/2 | 12 | $5.6 \cdot 10^{-4}$ |
| | | $^{144}\mathrm{Sm}\ (\gamma,\ n)\ ^{143m}\mathrm{Sm}$ | 0 | 11/2 | 0.042 |
| | | $^{82}\mathrm{Se}\ (\gamma,\ n)\ ^{81m}\mathrm{Se}$ | 0 | 7/2 | 0.57 |
| | | $^{81}\mathrm{Br}\ (\gamma,\ n)\ ^{80m}\mathrm{Br}$ | 3/2 | 5 | 0.46 |
| [11] | 18 | $^{110}\mathrm{Pd}\ (\gamma,\ n)\ ^{109m}\mathrm{Pd}$ | 0 | 11/2 | 0.065 |
| | | $^{87}\mathrm{Rb}\ (\gamma,\ n)\ ^{86m}\mathrm{Rb}$ | 3/2 | 6 | 0.085 |
| | | $^{85}\mathrm{Rb}\ (\gamma,\ n)^{84m}\mathrm{Rb}$ | 5/2 | 6 | 0.289 |
| [12] | 18 | $^{130}\mathrm{Te}\ (\gamma,\ n)\ ^{129m}\mathrm{Te}$ | 0 | 11/2 | 0.34 |
| | | $^{122}\mathrm{Te}\ (\gamma,\ n)\ ^{121m}\mathrm{Te}$ | 0 | 11/2 | 0.19 |
| | | $^{120}\mathrm{Te}\ (\gamma,\ n)\ ^{119m}\mathrm{Te}$ | 0 | 11/2 | 0.11 |
| | | $^{116}\mathrm{Cd}\ (\gamma,\ n)\ ^{115m}\mathrm{Cd}$ | 0 | 11/2 | 0.164 |

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[*] Here are reduced the $Y_g/Y_m$ ratios because higher spin corresponds to $g$ state instead of $m$ state in other cases.

threshold-factor corrections. The moderate scattering of points in Fig. 2 may be explained by different reasons, in particular by the inappropriate choice of the systematization parameter. It is possible that another combination of spins may define the reaction yield more precisely.

The spin dependence trend for $m/g$ ratios is in agreement with the statistical model principles. It is known that population of isomeric (or ground) state proceeds via the cascade of electromagnetic transitions in the residual excited nucleus past particle emission. The density and consequence of levels must depend on the spin value while they could be individual for each nuclide. When statistical model is applied to nuclear reactions, the level density is typically great and the probability of a process is referred to the level density $\rho(E^*, I)$ at definite excitation and spin. Over the cascade of transition, $E^*$ and $I$ serve as motion integrals and they define the cascade path resulted in a final-state population. According to [21]:

$$\rho(E^*, I) = \frac{\rho(E^*)(2I+1)}{\sigma^3} \ \exp -\frac{I(I+1)}{2\sigma^2}, \tag{3}$$

where $\sigma$ is a parameter weakly dependent on $E^*$. In the first approximation, the energy and spin dependences could be factorized independently. In Eq. (3), the level density depends on the «rotational» energy of a nucleus proportional to $I(I+1)$ in a quantum formulation, instead of angular momentum square $I^2$ in classics.

The rotational energy looks, in essence, as some sort of kinetic energy and it should be subtracted from the total $E^*$ to get a «thermal» energy. In thermodynamics, the probability of processes is linked to a number of microstates involved in formation of the macrostate with definite thermal energy. The probability is thus defined by the level density that is mathematically expressed by Eq. (3). Consequently, the relative probability of processes accompanied by the spin change must correlate with a following term:

$$I_m(I_m+1) - I_t(I_t+1). \tag{4}$$

Expression (4) is practically a difference of spin squares in quantum approach. One may expect the exponential dependence of the yield from the parameter (4), and not from the straight spin difference used in Fig. 2.

The yields measured in [4–8] were calibrated to the most abundant ($\gamma$, $n$) yield and divided by the threshold factor $F(E_{\rm th})$ shown in Fig. 1. The corrected $Y/F$ values are plotted in Fig. 3 as a function of the $[I_p(I_p+1) - I_t(I_t+1)]$ parameter. Now, a spin of the reaction product $I_p$ is taken instead of $I_m$ in (4) because we include in systematics both products in isomeric and ground states. Sometimes, the ground state possesses higher spin than isomer, but in Fig. 3 there is no necessity to distinguish such cases. Addition of the ground state yields increases the number of points in Fig. 3. The results of papers [9–12] are excluded because only $m/g$ ratios are reduced there.

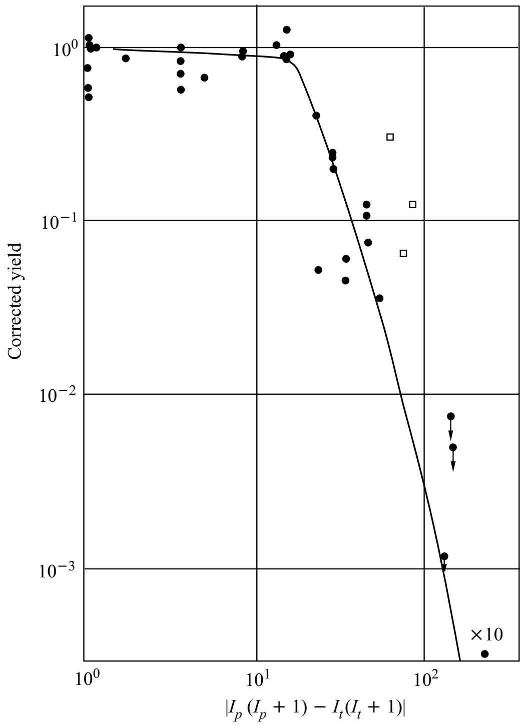

Fig. 3. Relative yields of the isomeric and ground state products as a function of a new spin-deficit parameter, Eq. (4). Experimental results of [4–8] are shown by black points, and the squares correspond to the specific reactions with high-spin targets [4]. Guide line connects the points

## 3. DISCUSSION

The physical conclusions are deduced from the obtained systematics as follows. The pattern in Fig. 3 looks more regular as compared to Fig. 2 because of appropriate choice of the systematization parameter. Inserted threshold corrections and restriction of the number of experiments selected for the analysis are also productive for the reduction of the point scattering. However, one can see that at low values of $[I_p(I_p+1) - I_t\,(I_t+1)] \leqslant 10$, the points lie near unity and the scattering is acceptable. Then, with the growth of the parameter, the yield exponentially drops to lower values. Such a behavior could be explained by the following arguments: the spins of the lowest excited states for odd and odd–odd nuclei are defined by the single-particle structure, practically by the orbital momentum of a valence neutron. There is more or less random variation of the energy, spin and parity of levels for different nuclei. Respectively, the spin of ground and isomeric states and position of the isomer are defined by random reasons. When a group of nuclides are merged for common analysis, these random factors modulate the level density and the order of levels. A regular decrease of the level density due to the effect of growing rotational energy is switched on at moderate and high spins. These reasons generate a random noise in the values of $m/g$ ratio at low $I_p$ and $I_t$ values. However, at higher spins, the growing rotational energy produces the level-density regular decrease and random fluctuations are suppressed. The dependence becomes regularly dropping because a strong factor normally cools down the random fluctuations.

In Fig. 3, several points indicate only upper limits achieved in experiments, naturally, they are at position above the line. Surprisingly, three points displayed by squares show the higher yields. They all correspond to the reactions with relatively high-spin targets of $^{180m}$Ta, $^{179}$Hf, and $^{178m2}$Hf. The $^{179}$Hf ground-state target possesses a moderately high spin — 9/2. In the $^{179}$Hf ($\gamma$, $p$) $^{178m,g}$Lu reaction, the target spin is just at mid position between the product isomeric and ground states of $^{178}$Lu. A similarity of this reaction to those with high-spin isomeric targets is explainable. The detected $m/g$ ratios in this case and also in the $^{180m}$Ta ($\gamma$, $p$) $^{179m2,}$Hf and $^{178m2}$Hf ($\gamma$, $n$) $^{177m2}$Hf reactions exceed the regular values shown by the curve in Fig. 3. By the way, such a new peculiarity is invisible in Fig. 2, and it is manifested only after introduction of a new systematizing parameter in Fig. 3.

A preferential population of high-spin isomers when the reaction starts from a high-spin state of the initial target nucleus was supposed in advance of the experiments described in [4, 20]. But the systematic dependence type shown in Fig. 2 did not bring a confirmation, and that was explained by the complete structure mixing for the continuum of states at excitation energies above the nucleon-departure energy. Some authors call «$K$-mixing» for such a lack of preferential population, supposing a violation of the $K$-quantum-number conservation. From Fig. 3, it follows that the preferential population yet exists and provides one-order excess in the magnitude of the $m/g$ ratio due to a similar structure of high-spin states both in the target and in the product nuclei. From first principles, one could assume a factor of preference much greater than 10. The observed one order-of-magnitude factor indicates that the $K$-mixing still exists being incomplete.

## CONCLUSION

Published experimental yields of the bremsstrahlung-induced reactions are analyzed and regular dependence as a function of the reaction threshold is established commonly for emission of neutrons and protons. The threshold factor could be isolated and then used for construction of the yield dependence on the spin parameter for reaction products. The isomer-to-ground state ratios are systematized. A new form of the spin-deficit parameter is introduced and a new yield-dependence is obtained. The conclusions relevant for reaction mechanisms are discussed. Surprisingly, the yield of alpha particles is suppressed deviating from the expected threshold dependence constructed for nucleon emission. This may reflect a necessity to account the preformation factor, the same as in alpha decay.

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141980, г. Дубна, Московская обл., ул. Жолио-Кюри, 6.
E-mail: publish@jinr.ru
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