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YIELD OF BREMSSTRAHLUNG INDUCED REACTIONS AS A PROBE OF NUCLEON–NUCLEON CORRELATIONS IN HEAVY NUCLEI

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Выходы реакций под действием тормозного излучения как средство
для тестирования нуклон-нуклонных корреляций в тяжелых ядрах

Относительные выходы (γ,α)-реакций могут быть использованы для проверки теоретических моделей, предполагающих полную α-кластеризацию или мультикварковые образования в тяжелых ядрах. Сравнительно простые активационные эксперименты позволяют расширить круг данных и преодолеть недостаток сведений о вероятности (γ,α)-процесса. Выделены пять конкретных реакций, в которых обеспечиваются выгодные условия для регистрации маловероятной ветви реакции (γ,α). Важны следующие требования: вещество мишени, доступное в форме обогащенного изотопа, удобные свойства радиоактивного распада продукта реакции и благоприятные фоновые условия. В настоящем эксперименте на пучке тормозного излучения при $E_e = 23$ МэВ измерения вероятности (γ,α)-реакции успешно осуществлены для двух мишеней и еще в трех случаях получена верхняя граница выхода. Доказана низкая вероятность (γ,α), на порядки величины меньше вероятности (γ,p)-реакции. Не подтверждена альфа-кластеризация тяжелых ядер.

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Yield of Bremsstrahlung Induced Reactions
as a Probe of Nucleon–Nucleon Correlations in Heavy Nuclei

Relative yields of (γ,α) reactions could serve as a probe to verify the theoretical models which assume total alpha-clustering, or multiquark objects in heavy nuclei. A deficit of data on the (γ,α) process probability must be covered in relatively simple activation experiments. Five concrete reactions are distinguished providing favorable conditions for detection of the low-probability reaction branch (γ,α). The following requirements must be satisfied: the target species available in an enriched form, the convenient properties of the product activity, and reasonably soft background restrictions. In the present experiment with bremsstrahlung at $E_e = 23$ MeV, new results are successfully obtained for (γ,α) reactions in two cases and upper limits are deduced for three other ones. Much lower probability of (γ,α) compared to (γ,p) reactions is proved. Alpha-clustering in heavy nuclei is not supported.

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

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1. INTRODUCTION

The status of nucleons within a nuclear matter is not yet well-clarified point despite the great interest since the decades. The simplest assumption that nucleons conserve their individual properties, the same as in vacuum, was under criticism from different points of view. There is known a spectrum of ideas: on necessity to replace the nucleons by quasi-particles, on interacting bosons inside the nucleus and on complete alpha-clustering in nuclear matter. Over recent decade, an idea of short range nucleon–nucleon correlations with formation of a quark bag attracts attention, and is tested in reactions at GeV energies [1]. The mentioned above models also find some application and reach a success in simulation of different processes. The additional tests in experiments are yet relevant. We propose now to use the reactions induced by photons at moderate energy of about 20–25 MeV. Electromagnetic radiation perturbs the nucleons in a target nucleus only slightly unlike the influence of strongly interacting projectiles. The product particles are released by the electromagnetic field, and the yield of different reactions may serve as a probe of bonds and correlations between nucleons within the heavy target nucleus.

Recently, there are presented [2] the evidences for regular threshold dependence of the photon-induced reactions. Relative yields were systematized versus the $(E_e - E_{\mathrm{th}} - B_c)$ parameter containing an excess of the end-point energy E_e above the sum of reaction threshold E_{th} and the Coulomb barrier B_c for particle emission. The different reaction yields are normalized to the yield of the most abundant (γ, n) reaction and they show a systematic growth with the increase of the mentioned threshold parameter. A common behavior of the neutron and proton yields confirms the similar mechanism of the release by electromagnetic field including both the compound and direct emission patterns. The multiparticle reactions dominate at $E_e \geqslant 40$ MeV due to the sequential mechanism and they could not be involved in common systematic together with the elementary processes of nucleon emission. The exclusion is obviously revealed for the (γ, d) reaction [2], despite possible contribution from (γ, pn) sequential emission.

For light targets, the (γ, α) reaction was since many decades under the scope of the astrophysics relevant studies. However, the literature data are poor for medium-weight and heavy targets. Cross sections of electro and photonuclear reactions were measured in [3, 4] for ^{58}Ni and ^{60}Ni targets. Recently, the abundant yields of the (γ, α) products have been reported in [5, 6] for antimony and mercury targets, respectively. The great specific activity of ^{195m}Pt has been deduced in [5] due to the ^{199}Hg(γ, α) reaction at $E_e = 30$ MeV. Strictly speaking, this is not a confirmation of the great reaction yield, just an indication that the ^{195m}Pt nuclide supplies a significant part of the total Pt production when the mercury target is exposed to photons.

In [6], the yield of ^{121}Sb$(\gamma, \alpha)^{117}$In reaction is reported in a value near 0.8% of the (γ, n) yield. This looks too high, significantly higher than the result of [3]. For Ni target in [3], the yield of alphas was observed at a level by 20 times lower the (γ, p) yield, i.e., about 10^{-4} in comparison to the rate of (γ, n) reaction. In our measurements [7], the ^{181}Ta$(\gamma, \alpha)^{177}$Lu reaction was observed, and the yield was appeared to be $\approx 0.7 \cdot 10^{-5}$ in ratio to the (γ, n) abundance. Due to such a scattering of results over different publications and also due to the general lack of reliable data, one may conclude a necessity to explore relative yields of the bremsstrahlung induced reactions, especially for (γ, α) reactions, in the weakly studied domain of heavy targets. Comparison of the nucleon and alpha emission rates must be productive for conclusions about the nucleon–nucleon correlation status, or at least, for testing an idea of complete alpha clustering in heavy nuclei. Experimental data for (γ, n) and (γ, p) yields are compiled in [2] and novel regularity is deduced.

2. RESULTS

Inspecting the Nuclide Chart from $A = 100$ to 208 we have tried to find the most promising cases for detection of the (γ, α) reaction by activation method with γ-spectroscopy measurements of the induced activity. The mass numbers of potential targets correspond to the domain of heavy nuclides but out of the alpha radioactive nuclide range. The best five cases are selected for experimental tests in bremsstrahlung irradiations with MT-25 microtron of FLNR, JINR at end-point energy of 23 MeV. The activities listed in Table 1 are chosen because they are characterized by the relatively intense γ-lines convenient for detection at moderate halflives. The major problem of such experiments would be a presence of the background radiation generated by the isobaric nuclides due to the same transition at the same daughter nuclide but after ε instead of β^- decay.

This internal physical background could not be excluded by a better shielding of the detector, or so. In two cases at Table 1, the background is absent and they must be considered as the best for reliable detection of the (γ, α) reaction and for the yield estimate. For other targets, the experimental conditions must involve the enriched target isotopes because the background is created typically in reactions with the complementary isotopes present in a target. In our experiment, the targets of natural isotopic composition have been exposed to the bremsstrahlung generated with 23 MeV electron beam in 3 mm W converter. The activated target was located downstream the converter, after 15 mm Al radiator to stop the electrons.

Table 1. Encounters for the (γ, α)-reaction experiment

Target	Abundance, %	Product	Halflife of β^- decay	Major γ line, keV	Internal background	Origin of the background
^{109}Ag	48.2	^{105}Rh	35.4 h	318.9	^{105}Ag; 41.3 d	^{107}Ag$(\gamma, 2n)$
^{113}Cd	12.2	^{109}Ag	13.7 h	88.0	^{109}Cd; 463 d	^{110}Cd(γ, n)
^{119}Sn	8.6	^{115}Cd	53.4 h	527.9	—	—
^{181}Ta	100	^{177}Lu	6.47 d	208.4	—	—
^{193}Ir	62.7	^{189}Re	24.3 h	245.1	^{189}Ir; 13.3 d	^{191}Ir$(\gamma, 2n)$

The metal target foils of natural isotopic composition were taken typically in a full weight of 0.2–0.5 g, and the highly-enriched materials were not used because of relatively high cost. Past irradiation during about 5 h at the electron beam intensity of 10 μA, the induced activity measurements were continued over one week and in some cases even longer, up to one month. The gamma spectra were taken using HPGe detector with energy resolution better 1.8 keV by the ^{60}Co lines. The set of standard sources was used for energy and efficiency calibration of the detector. Series of spectra measurements were resulted in observation of the γ-lines belonged to the products of (γ, α) reactions in Sn and Ta targets, despite a great activity of other radionuclides produced in more abundant reactions. A number of produced ^{115}Cd and ^{177}Lu atoms could be evaluated from the measured γ-line intensities using the standard procedure for gamma spectra processing, the decay schemes from Nuclear Data Sheets, and the mathematical formalism for account of the accumulation and decay factors for the radioactive products. At the same γ spectra, there were observed the activities produced in (γ, n) reactions. Finally, the (γ, α)-reaction yield is calibrated to that of the (γ, n) reaction, and the ratio is reduced in Table 2.

Perfect measurements were carried out also for other targets listed in Table 2, but the (γ, α) yields in Ag, Cd and Ir targets could only be estimated in a form of the upper limit. This is due to the presence of internal background as was explained above. The backgrounds could be eliminated using the highly-

Table 2. Experimental results for the yield of (γ, α) reactions

Target	Product	Threshold parameter $(E_{\rm th} + B_c)$, MeV	Relative yield $(\gamma, \alpha)/(\gamma, n)$	Importance of background
$^{\rm nat}$Ag	^{105}Rh	13.56	$\leqslant 3.5 \cdot 10^{-4}$	Yes
$^{\rm nat}$Cd	^{109}Pd	14.32	$\leqslant 2.4 \cdot 10^{-4}$	Yes
$^{\rm nat}$Sn	^{115}Cd	15.31	$(2.9 \pm 0.4) \cdot 10^{-5}$	No
$^{\rm nat}$Ta	^{177}Lu	14.51	$(0.70 \pm 0.12) \cdot 10^{-5}$	No
$^{\rm nat}$Ir	^{189}Re	15.84	$\leqslant 2.8 \cdot 10^{-4}$	Yes

enriched targets. The additional experiments with purified by orders of magnitude sensitivity might be requested. Nevertheless, one can see in Table 2 that the yields of ^{115}Cd and ^{177}Lu products of the (γ, α) reactions are now successfully measured, and they are as low as $\approx 10^{-5}$ of the (γ, n) reaction abundance. For three other cases, the upper limits near 10^{-4} additionally confirm the low value of the order of 10^{-5} for (γ, α)-to-(γ, n) ratio. For ^{177}Lu, the present experiment is in accurate agreement with the earlier results of [7]. It must be mentioned that both ^{115}Cd and ^{177}Lu nuclides may exist in a form of high-spin isomers: $11/2^-$ and $23/2^-$, correspondingly. Their activities could not be detected now because of much lower yields due to the spin factor [2]. Isomers contribute an insignificant addition to the total (γ, α) yield, and even the standard deviation must be left without changes in Table 2.

Finally, a concluding result of the present measurements appears in relatively low probability of the (γ, α) reaction ($\approx 10^{-5}$), and this is established reliably for the group of reactions with medium-weight and heavy ($A > 100$) targets. Definitely, the experiments could be continued applying the highly-enriched targets to replace the upper limits with the accurate values for three reactions mentioned above. It is clear that other cases also could be experimentally explored to incorporate more data into the phenomenology of the (γ, α)-reaction yields. Possible candidates for activation measurements are listed in Table 3. Some of them could be pretty convenient in real experiments, because of the background absence in four cases, and some others are not so attractive due to the long halflife of the (γ, α) product and necessity to use the highly-enriched target materials. The perspectives are yet promising.

Table 3. Additional possibilities for detection of the (γ, α) reaction

Target	Abundance, %	Product	Halflife	E_γ, keV	Background
^{115}In	95.7	^{111}Ag	7.45 d	342	^{111}In from $(\gamma, 2n)$
^{137}Ba	11.2	^{123}Xe	5.25 d	81	$^{133\mathrm{m}}$Ba from (γ, n)
^{143}Nd	12.2	^{139}Ce	138 d	166	—
^{145}Nd	8.3	^{141}Ce	32.5 d	145	^{141}Ce from (γ, n)
^{153}Eu	52.2	^{149}Pm	53.1 h	286	^{149}Eu from $(\gamma, 2n)$
^{160}Gd	21.9	^{156}Sm	9.4 h	204	—
^{163}Dy	24.9	^{159}Gd	18.5 h	364	^{159}Dy from (γ, n)
^{176}Yb	12.8	^{172}Er	49.3 h	610	—
^{176}Lu	2.6	^{172}Tm	63.6 h	1094	^{172}Lu from $(\gamma, 3n)$
^{187}Re	62.6	^{183}Ta	5.1 d	246	^{183}Re from $(\gamma, 2n)$
^{203}Tl	29.5	^{199}Au	75.3 h	158	—
^{207}Pb	22.1	^{203}Hg	46.6 d	279	^{203}Pb from (γ, n)

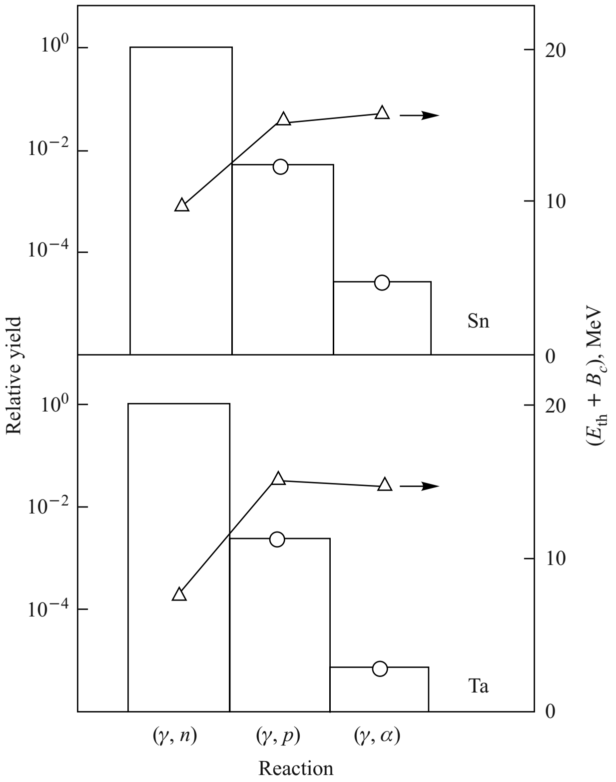
3. DISCUSSION

A role of (γ, α) reactions in nucleosynthesis at stellar conditions is out of discussion here because such special topics must be developed and described elsewhere. We are interested for the nuclear physics conclusions. When many reactions are studied, it would be possible to follow the variations of the (γ, α) yields with Z and A of a target nucleus and also to look for the shell-structure manifestations in the observed yields. At the moment, the results are not enough developed to establish these regularities. However, in general, the low probability of α emission from excited nucleus must be explained within some realistic interpretation.

There was clear from [2] that nucleon emission (γ, n) and (γ, p) yields both satisfy a common regularity if the Coulomb barrier is accounted for proton emission. The yield depends on the «threshold» parameter $(E_e - E_{\rm th} - B_c)$ that was defined above in Introduction. For α emission the similar approach could be applied, but the regularity is not confirmed. High binding energy of α particle makes the effective threshold practically the same for alphas and protons. The numerical values of effective threshold $(E_{\rm th} + B_c)$ are given for studied (γ, α) reactions in Table 2. The Coulomb barrier was calculated using the well-known Bass equation [8]. The scale of 14–15 MeV corresponds also to a typical value for (γ, p) reactions similarly to (γ, α). But the yields are very different being lower for alphas by two–three orders of magnitude.

In the Figure the alpha-emission and nucleon-emission yields are compared for Sn and Ta/Hf targets exposed to the bremsstrahlung at $E_e = 23$ MeV. The data of [2, 7] for the (γ, p) reaction are included after averaging of the yields measured for several target isotopes. Error bars are not greater than the size of points. The (γ, n) yield is taken equal unity being a reference point for the calibration. The values of effective reaction threshold $(E_{\rm th} + B_c)$ are also shown in the Figure by triangles connected with a solid line. Despite practically similar threshold values for (γ, α) and (γ, p) reactions, the suppressed probability of (γ, α) is evident for both targets. Higher mass number of alphas compared to protons could influence the probability of penetration through the barrier, but in our case, the processes well above the barrier are detected. Indeed, both for protons and alphas, the parameter $(E_e - E_{\rm th} - B_c)$ exceeds a value of 8–10 MeV. Therefore, a subbarrier penetration factor could not be used as real reason for explanation of the much lower α-emission probability.

After all, one must assume that the pre-formation factor regulates the yield of (γ, α) reaction. Unlike to protons ready for release, the alpha particle must be formed at the first stage of the reaction, and then emitted, if energy is enough. As follows from the Figure, the probability of pre-formation should be as low as about $3{\cdot}10^{-3}$. This conclusion contradicts the ideas of a complete alpha-clustering inside the nuclear matter. Clusters may permanently exist in light nuclei, but not



Comparison of measured yields for (γ, n), (γ, p) and (γ, α) reactions

in $A > 100$ species. Another point is open for additional analysis, namely, the idea of nucleon–nucleon correlations with formation of the quark bags instead of the nucleon gas (liquid) in the bound nuclei. Without theoretical calculations, it would be difficult to make a solid conclusion, whether our result cancels the idea on multiquark objects inside a nucleus, or just means some restricted probability for short-range nucleon–nucleon correlations. The theoretical analysis was performed for reactions at GeV energies [1], but the (γ, α) reaction at low energy was not yet theoretically studied in such a sense.

4. SUMMARY

Possibilities for detection of (γ, α) reactions in relatively simple activation experiments were analyzed and some favorable cases are distinguished. When the experiment is performed at relatively low photon energy, the measurements could be informative to clarify a status of nucleons in the heavy nucleus. Yields of five (γ, α) reactions are measured with bremsstrahlung beam at the end-point energy of 23 MeV, and pretty low probability of about 10^{-5} is deduced for the (γ, α)-to-(γ, n) yield ratio. The conclusion follows that the models describing a nucleus as construction built of α-clusters are not supported. Probably, the pre-formation factor for alphas must be taken into account. Short-range nucleon–nucleon correlations leading to formation of multiquark objects (quark bags) in nucleus could also influence the (γ, α) probability. This point must be additionally analyzed in theory for conclusive simulation of the experimental data.

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