THE EXCITATION FUNCTION OF THE $^{65}Cu(\gamma,\alpha)$ ^{61}Co REACTION IN THE GIANT RESONANCE REGION

YU. P. GANGARSKYI, KHR. G. KHRISTOV, F. G. KONDEV, A. P. TONCHEV

JINR, Dubna, USSR

A. D. ANTONOV, N. P. BALABANOV, S. G. MARINOVA AND V. J. TCHOLAKOV

Department of Nuclear Physics, Plovdiv University*

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The $^{65}Cu(\gamma, \alpha)^{61}Co$ reaction has been studied using induced radioactivity techniques at gamma-ray energies of 25 MeV. The cross section has a maximum value of 1.20 ± 0.24 mb. at the energy of 22.0 ± 0.4 MeV and an integrated cross section at 25 MeV is 7.8 ± 2.3 MeV mb. The statistical model gives a satisfactory interpretation of the cross section ratio of the $^{65}Cu(\gamma, \alpha)^{61}Co$ and $^{65}Cu(\gamma, n)^{64}Cu$ reactions.

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1. Introduction

The process of emission of α particles from the atomic nucleus is usually investigated in reactions induced by charged particles and neutrons. However it is of certain interest to use the photonuclear reactions because of the lack of barrier for γ-quanta and lower angular momenta transferred to the nucleus by absorption of γ-quanta.

Using the activation method described in [1] we have investigated the characteristics of (γ, α) reactions for a large range of nuclei. The results obtained show that in the $Z < 30$ range the reaction $^{65}Cu(\gamma, \alpha)^{61}Co$ has the largest yield and is suitable for investigating its characteristics in a large range of photon energies.

The aim of the present paper is to measure the yield and the cross section of the reaction $^{65}Cu(\gamma, \alpha)^{61}Co$ in the giant resonance region and to compare the obtained results with other similar reactions and theoretical calculations.

* Address: Department of Nuclear Physics, Plovdiv University, Tsar Asen Str. 24, 4000 Plovdiv, Bulgaria.

2. *The experiment*

The present investigations have been done with the bremsstrahlung beam from the accelerator Microtron MT-25 of the JINR, Dubna. One of the essential advantages of this accelerator is the small energy spread of accelerated electrons (30–40 KeV) at a high beam intensity (up to an average power of 500 W), which facilitates the experiment.

The electron beam extracted from the accelerator chamber is focused by a system of quadruple lenses and subsequently by means of a magnet directed on a bremsstrahlung target, which consists of a tungsten disk 2 mm thick and a 30 mm Al-absorber placed behind it.

The size of the electron spot on the target was about 6–8 mm. The mean current on the target equal to about 10 μA was measured continuously during the experiments.

The activation method [1] has been used to determine the yield of the reaction under study. Copper disks 10 μm thick and 60–80 mg in weight have been used as targets. The characteristics of the target nucleus and of the product nucleus are shown in Table I.

TABLE I

Characteristics of residual and target nuclei

Target nucleus	Isot. abund. %	Residual nucleus	Half life H	Gamma energies keV	Intensity %
^{65}Cu	30.96	^{61}Co	1.65	67.5	87

The activity of the nuclei obtained has been measured by two semiconductor detectors (one of them is a HPGe-type detector with the volume $V = 2.1$ cm^3 and the energy resolution for the ^{57}Co γ rays: $E_\gamma = 122.1$ KeV, $\Delta E = 0.6$ KeV; the other one is a Ge(Li) detector with volume $V = 60$ cm^3 and the energy resolution for ^{60}Co γ rays: $E_\gamma = 1322$ KeV, $\Delta E = 3$ keV).

The gamma-ray spectra obtained have been registered with 4096 pulse-height channel analyzer LP-4900 "NOKIA" and an autonomous analyzing system "MICAM-2" [2].

3. *Experimental results*

The yield of the investigated (γ, α) reaction has been measured by a relative method [1] at different maximum energies of the microtron photons ranging from 17 MeV to 25 MeV, in steps of 0.5 MeV. As a reference reaction, we used ^{65}Cu(γ, n)^{64}Cu whose characteristics are well known [3, 4].

The values obtained for the yield of the reaction ^{65}Cu(γ, α) at different maximum energies of the bremsstrahlung spectra are shown in Fig. 1.

The absolute errors in the yield values have been estimated taking into account the error in the yield values of the monitor reaction, the statistical error in measuring the photopeak area of the corresponding γ-ray, and the error of the registration efficiency. At the

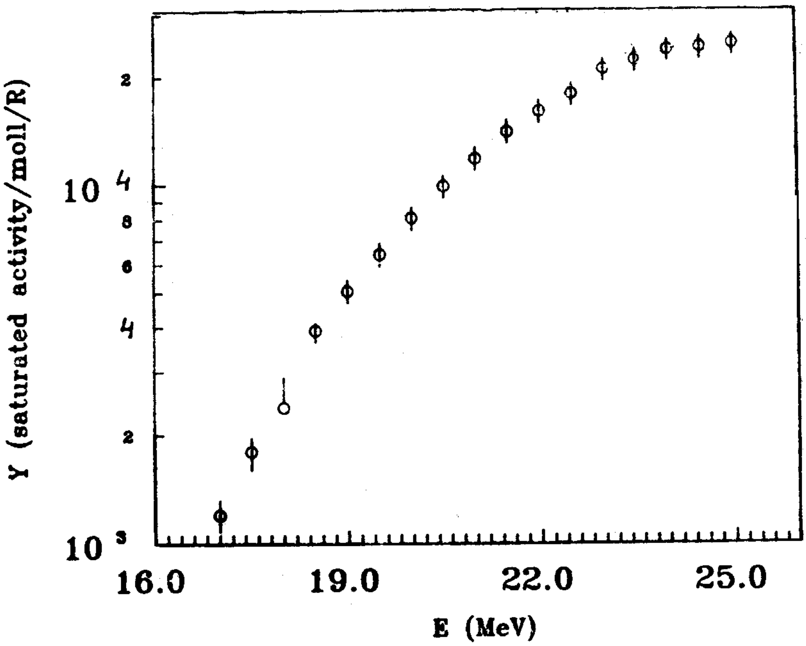

Fig. 1. Yield of the reaction $^{65}Cu(\gamma, \alpha)^{61}Co$ at different maximum energies of the bremsstrahlung spectrum

same time the relative error in determining the yield at different maximum photon energies does not exceed 1–2%.

According to [1] the integrated cross section of the reaction has been defined at different maximum energies of the bremsstrahlung spectrum $E_{\gamma max}$:

$$\sigma^{int}(E_{\gamma max}) = \int_{E_{thr}}^{E_{\gamma max}} \sigma(E) dE. \tag{3.1}$$

The threshold of the investigated reaction E_{thr} is taken to be the sum of the α particle binding energy Q_α [5] and the corresponding effective Coulomb barrier B_α [6]. Although the α particles are emitted from the nuclei with energies lower than B_α due to the tunnel effect, the contribution of this process is negligible.

The integrated cross section obtained in this way at $E_{\gamma max} = 25$ MeV is $\sigma^{int} = 7.8 \pm 2.3$ MeV · mb, $Q_\alpha = 6.8$ MeV, $B_\alpha = 7.4$ MeV.

Since in the interaction of electrons with the bremsstrahlung target a continuous spectrum of γ quanta is obtained, the investigated yields $Y(E_{\gamma max})$ are related to the photonuclear cross section by a system of integral equations:

$$Y(E_{\gamma max,i}) = \int_{E_{thr}}^{E_{\gamma max,i}} \sigma(E) N(E, E_{\gamma max,i}) dE \qquad i = 1, 2, 3, \ldots, n, \tag{3.2}$$

where $E_{\gamma max,i}$ is the maximum energy of the bremsstrahlung spectrum, $N(E, E_{\gamma max,i})$ is the bremsstrahlung spectrum [7], n is the number of experimental points.

When determining the cross section of the investigated reaction one usually replaces the system of integral equations with a system of linear equations for the unknown quantities $\sigma(E)$ [8]:

$$Y_i = \sum_{j=1}^{m} N_{ij}\sigma_j \qquad i = 1, 2, 3, \ldots, n, \quad m < n. \tag{3.3}$$

As the matrix in (3.3) is ill-conditioned, this problem is posed incorrectly and specia methods are needed for its solution.

One of these methods is the minimization of the directioned discrepancy (MDD), suggested by M. Z. Tarasko [9], which has been used to find for the first time the reaction cross section in a photonuclear experiment in [10].

The basic advantages of the method are:

1) Non-negative solution,

2) Quick operation and simple algorithm.

Fig. 2 shows the obtained dependence of the cross section of the reaction $^{65}Cu(\gamma, \alpha)^{61}Co$ on the γ quanta energy. The error of the cross section values does not exceed 20%.

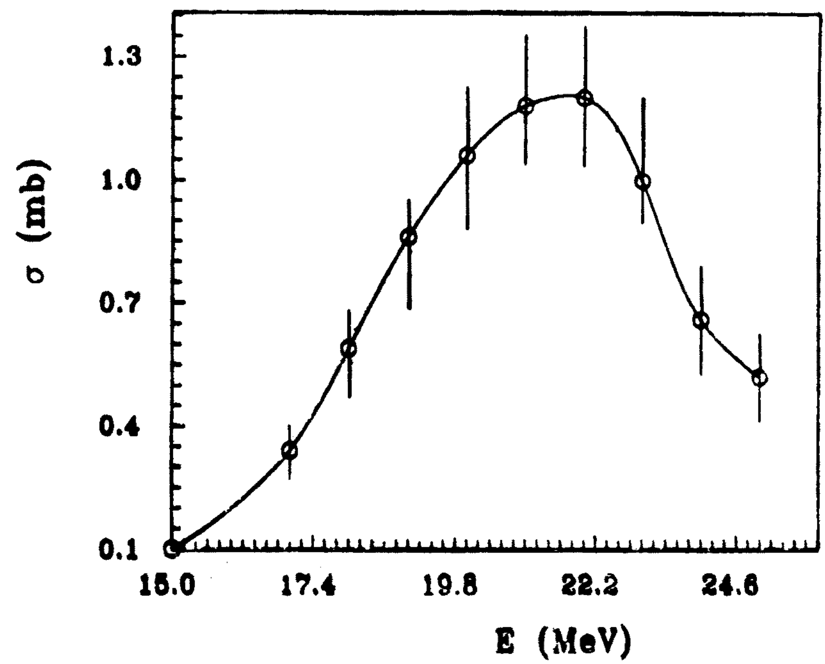

Fig. 2. Energy dependence of the cross section of the reaction $^{65}Cu(\gamma, \alpha)^{61}Co$

4. *Discussion*

The previous studies of photonuclear reactions involving the emission of alpha particles seem to indicate that they are mainly compound-nucleus processes. However, since the amount of the available data is quite limited, it is not known yet to what extent this is true.

Therefore it is of certain interest to compare experimentally obtained ratio of total alpha and neutron widths with calculations based on the statistical theory of nuclear reactions.

According to the statistical theory, the ratio of the cross sections of (γ, α) and (γ, n) reactions is equal to that of the total alpha and neutron widths:

$$\sigma_{(\gamma,\alpha)}/\sigma_{(\gamma,n)} = \Gamma_\alpha/\Gamma_n. \tag{4.1}$$

In the evaporation model the ratio of the total widths is given by the following expression [11]:

$$\Gamma_\alpha/\Gamma_n = \frac{m_\alpha(2i_\alpha+1)}{m_n(2i_n+1)} \cdot \frac{\int_{E_{\alpha\min}}^{E_{\alpha\max}} E_\alpha\sigma_\alpha(E_\alpha)\varrho_\alpha(E_{\alpha\max}-E_\alpha)dE_\alpha}{\int_0^{E_{n\max}} E_n\sigma_n(E_n)\varrho_n(E_{n\max}-E_n)dE_n}, \tag{4.2}$$

where $E_{\alpha\max}$ and $E_{n\max}$ are the maximum energies in the evaporation spectra of the alpha particle and the neutron, respectively; m_α and m_n are their masses; i_α and i_n are the spins of the α particle and the neutron, respectively; σ_α and σ_n are the cross sections of the inverse process; ϱ_α and ϱ_n are the level densities of the residual nuclei.

In case of high excitation energies of the residual nucleus, the level density is described by the Fermi gas model with varying temperature [12]:

$$\varrho_{VT}(E) = \frac{\sqrt{\pi}}{12 \cdot a^{1/4} \cdot U^{5/4}} \exp(2 \cdot \sqrt{a \cdot U}) \tag{4.3}$$

where: $E = E_{i\max}-E_i$ ($i = \alpha$ or n) is the excitation energy of the residual nucleus; $U = E-\delta$; δ is the pairing energy [13]; a is the level density parameter.

As shown in [12] the extrapolation of the Fermi gas relation (4.3) to the low energy region, does not describe the experimental data properly. In this region the level density is given by the Fermi gas model with constant temperature:

$$\varrho_{CT}(E) = (1/T)\exp[(U-E_0)/T], \tag{4.4}$$

where

$$E_0 = E_x - T\ln[T \cdot \varrho_{VT}(E_x)], \tag{4.5}$$

$$1/T = \left[\frac{a}{(E_x-\delta)}\right]^{1/2} - \frac{3}{2(E_x-\delta)}. \tag{4.6}$$

E_x is the excitation energy at which the level density can be described by the model with constant temperature [12].

In the above-mentioned algorithm an important step in determining Γ_α/Γ_n is the choice of the level density parameter a.

Usually one varies a in order to obtain a good fit between experiments and theoretical considerations, but the values of the level density parameter, obtained in this way, differ from the experimental ones determined by analyzing the neutron resonances.

The semi-classical estimate of $a = A/10$ does not take into account either the non--trivial dependence $a = a(A)$ near the magic nuclei, or the dependence of a on the excitation energy.

The experimental data, obtained from the neutron resonances show that at the excitation energy of the residual nucleus $E = 5$–7 MeV the value of the level density parameter is strongly influenced by shell effects.

As the excitation energy of the residual nucleus (in the case of $^{65}Cu(\gamma, \alpha)^{61}Co$ $E < 10$ MeV) after the "evaporation" of the alpha particle from the compound nucleus is comparatively low, neglecting shell effects leeds to the inaccurate account of the alpha particle emission probability from the highly excited compound state.

In the present paper there we used the phenomenological dependence of the level density parameter [14]:

$$a = \bar{a}[1+f(U)\Delta W/U], \tag{4.7}$$

where: $\bar{a}$ = constant, ΔW is the shell correction [13], $f(U) = 1-\exp(-\gamma U)$, $\gamma = 0.06$.

The values of the quantities in Eqs. (4.1)–(4.7) are given in Table II.

TABLE II

Values of parameters for statistical model calculations

Nucleus	U_x MeV	T MeV	δ MeV	E_0	$\bar{a}$	ΔW MeV
^{64}Cu	4.50	0.995	0	-1.222	8.903	-1.507
^{61}Co	4.96	0.947	1.285	-0.672	8.511	-1.619

For the cross sections $\sigma_n(E_n)$ and $\sigma_\alpha(E_\alpha)$ of the inverse reactions we have used the results given in Ref. [6] and [15] respectively.

The values obtained for $(\Gamma_\alpha/\Gamma_n)_{exp.}$ and $(\Gamma_\alpha/\Gamma_n)_{theor.}$ are shown in Fig. 3.

The good fit to the experimental data in a wide range of E_γ justifies the application of the statistical theory for describing the emission of alpha particles in the reaction $^{65}Cu(\gamma, \alpha)^{61}Co$ in the giant resonance region.

A characteristic feature of the measured cross section is the existence of a maximum at $E_\gamma = 22.0 \pm 0.4$ MeV and $\sigma_{max} = 1.2 \pm 0.24$ mb. The cross section decrease after 22 MeV is most likely to be due to the competition of the $(\gamma, \alpha n)$ reaction, whose cross section increases at $E_\gamma = 32$ MeV and is $\sigma_{(\gamma,\alpha n)} \approx 1/2\sigma_{(\gamma,\alpha)}$ [16].

Another feature of the (γ, α) reaction is its small cross section compared to similar reactions involving the emission of alpha particles, e.g. (n, α) or (p, α). A comparison of the (n, α) cross section for 14 MeV neutrons with the (γ, α) cross section shows that the former one is an order of magnitude larger than the latter ($\sigma_{(n,\alpha)} = 18.5$ mb [17]). Such behavior may mean that the direct processes that are playing a considerable role in the (n, α) reaction, are much less manifested in the (γ, α) reaction. Besides, the forbidnesses in the internucleon interactions, due to the law of angular momentum conservation, are

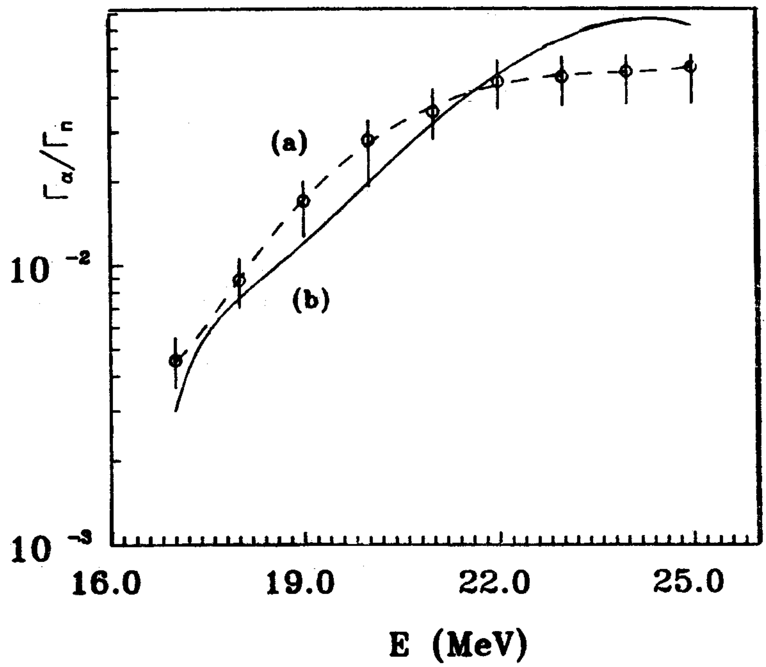

Fig. 3. Comparison of the experimental (*a*) and theoretical (*b*) results for the ratio Γ_γ/Γ_n

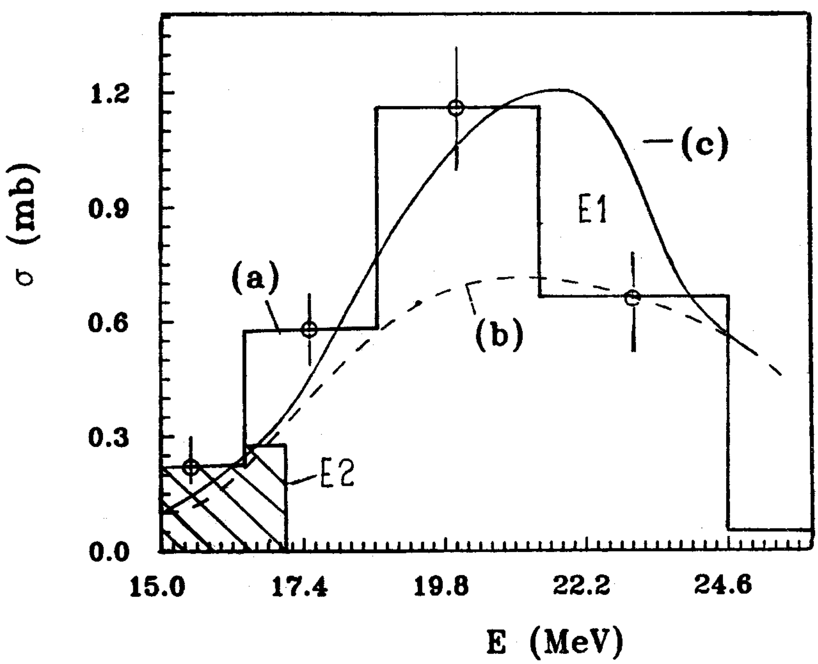

Fig. 4. Comparison of experimental results for (γ, α) cross section: (*a*) — results from Ref. [18], (*b*) — results from Ref. [19], (*c*) — our results

much stronger in (γ, α) reactions. The key-point is that the dipole γ-quanta may excite only those states of the compound nucleus, whose angular momentum differs from the spin of the target nucleus by $\Delta J = 0, \pm 1$, while the neutrons may be absorbed with angular momenta from 0 to $l_{max} = R/\lambda = 0.3\ A^{1/3}\ E_n^{1/2}$ and in case of ^{65}Cu they may excite states with ΔJ from 0 to ± 5.

In the recent years active studies of (γ, α) reactions have been started in experiments with "virtual photons" [18, 19]. The results obtained for $^{65}Cu(\gamma, \alpha)$ show a certain difference in the values of the cross section (the position of the maximum and its height), which some authors explain as being due to the use of various experimental methods.

As the bremsstrahlung spectrum contains γ-quanta with different multipolarities, the comparison of the (γ, α) cross sections obtained in experiments with bremsstrahlung and "virtual" photon spectra offers a possibility for a deeper insight into the interaction of electromagnetic radiation with the atomic nuclei. Fig. 4 shows the comparison of the results obtained.

On the one hand, the prevailing part of the reaction $^{65}Cu(\gamma, \alpha)^{61}Co$ cross section is due to the El-component, but on the other hand, it amounts to about 1% from the total cross section of absorption of dipole γ-quanta: $\sigma^{int} = 60NZ/A$. This indicates low probability for the process of α particle emission from the atomic nucleus in the giant resonance region in comparison with the other open channels, (γ, n) and (γ, p).

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