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ON THE MECHANISM OF PHOTONUCLEAR REACTIONS

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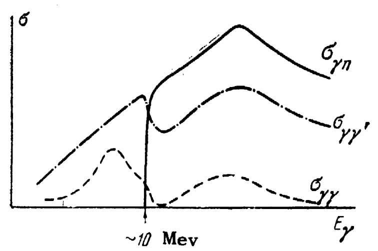
A number of empirical laws cannot be explained by the statistical mechanism of photonuclear reactions if the energy of the gamma quantum is less than or equal to 10 Mev. The facts can be explained only by assuming that a few single-particle states of the target nuclei contribute significantly to the cross section of the photonuclear reaction. The nature of these states is discussed.

In the investigation of photonuclear reactions in heavy and medium-weight nuclei, a statistical model of the nucleus is usually employed, in which such general quantities as the level density $\rho(E)$, the nuclear temperature $\overline{T}$, and the average values of various partial widths ($\overline{\Gamma}_\gamma$, $\overline{\Gamma}_n$, etc.) enter as parameters. The application of the statistical approach physically amounts to the assertion that a very large number of levels of the intermediate nucleus take part in the reaction, so that the cross sections become significant in spite of the fact that the contribution of each single level is small (since the average widths $\overline{\Gamma}$ are small).

However, another situation may also be considered, by which the reaction goes basically only via a small number of levels having large widths, for example, single-particle levels, the widths of which are close to the Weisskopf values. It is well known that the experimental values of the integral elastic and inelastic cross sections ($\sigma_{\gamma\gamma}$ and $\sigma_{\gamma\gamma'}$) for medium-weight and heavy nuclei seem to be of the order of 10 — 20 mb-Mev for energies in the interval 5 — 15 Mev. At the same time the integral cross section for elastic scattering ($\pi\Gamma\sigma_{max}/2$) arising from a single single-particle level of width $\Gamma_\gamma \sim \Gamma \sim 100$ ev is also equal to ~ 10 mb-Mev for gamma-quantum energies of the order of 10 Mev. Thus, if single particle levels were located at a distance from each other of approximately 1 Mev, then they alone might explain the order of magnitude of the observed values of the cross sections.

There have been few experiments in which the interaction of gamma rays with nuclei in the energy range 5 — 15 Mev has been studied. These include measurements of the elastic scattering of gamma quanta,[1] inelastic scattering with the formation of isomers,[2] and the first information about nuclear absorption.[3] From the data available it is possible to arrive at the following conclusions.



1. For the majority of elements there are definite peaks in the cross sections $\sigma_{\gamma\gamma}$ and $\sigma_{\gamma\gamma'}$ close to the thresholds for the reactions (γ, n) and (γ, p). The peak height is of the order of several millibarns, and its half-width $\Gamma \sim 1 - 3$ Mev. Usually in the medium weight nuclei the resonance in the cross section is associated with the (γ, p) threshold, and in heavy nuclei it is associated with the (γ, n) threshold.

2. The height and width of the peak vary irregularly from element to element[1] (see also the table).

3. A resonance in the absorption cross section has been observed. Data on nuclear absorption in the region below the threshold of (γ, n) reactions is available only for P, S, and Ca.[3]

Let us compare these results with the predictions of the statistical theory of nuclear reactions, which can be formulated as follows.

1. Nuclear reaction cross sections should be smooth functions of the atomic weight. However, the work of Fuller and Hayward[1] (see also the table) shows that in the scattering of gamma rays the individuality of nuclei appears very distinctly and cannot be explained on the basis of statistical considerations.

2. The cross section for elastic scattering ought to have the form of energy dependence schematically represented in the diagram. At first the cross section increases. However, on account of the rapid increase of the number of inelastic channels

Elastic scattering*				Inelastic scattering with the formation of isomers*			
Element	Threshold of the reaction: for (γ, n), E_n and for (γ, p), E_p	σ_{max}, mb	Position of the peak, Mev	Element	Threshold of the reaction (γ, n), Mev	σ_{max}, mb	Position of the peak, Mev
Mn	$E_n = 10.14, E_p = 9$	6	9				
Ni	$E_n = 12.8$	2.8	9.5	Y^{89}	11.8	1.3	10.5
Cu	$E_p = 6.13$	1.6	8	Rh^{103}**	9.35	5	9.3
Sn	$E_n = 6.1-9.2$	12	7	Ag^{107}	9.4	2.3	9
I	$E_n = 9.14$	2	7	In^{115}	9	1.9	8.9
Au	$E_n = 7.96$	3	—	Au^{197}	7.96	3.5	7.5
Pb	$E_n = 7.4$	17	7.4	Pb^{207}	6.9	Not observed	

*Experimental errors in the determination of the magnitude of the cross section (~1 mb) and the position of the maximum (~1 Mev) are not indicated in the table.
**Data from O. V. Bogdankevich and L. E. Lazareva.

with the increase of energy of excitation of the nucleus, the ratio of the elastic radiation width to the total radiation width decreases, and consequently the cross section for elastic scattering, $\sigma_{\gamma\gamma} = \sigma_{capt}\Gamma_\gamma/\Gamma$, decreases. For excitation energies $\gtrsim$ 5 Mev,[4] the order of magnitude of this quantity is:

$$\Gamma_\gamma/\Gamma = (\hbar\omega)^3/6\tau^4\rho(\hbar\omega) \sim 1\%$$

$[\rho(\hbar\omega) = \rho_0 e^{\hbar\omega/\tau}$ is the level density, and $\tau \approx 0.9$ Mev$]$.

In the energy range above 5 Mev the cross section for elastic scattering varies approximately as $(\hbar\omega)^4 e^{-\hbar\omega/\tau}$ (we assume that dipole absorption is taking place, that is,[5] $\sigma_{capt} \sim \hbar\omega$) with a maximum in the energy range ~ 4 Mev. The statistical theory is unable to explain the appearance of a maximum in $\sigma_{\gamma\gamma}$[1] in the immediate neighborhood of the nucleon threshold. A rapid decrease of the cross section with energy, correlated with the threshold for the formation of photoneutrons, is explained by the fact that the emission of nucleons is far more probable than the emission of gamma quanta.

3. The total cross section for inelastic scattering $\sigma_{\gamma\gamma'} = \sigma_{abs}\Gamma^{-1}\Sigma\Gamma_{\gamma'}$ ought to practically coincide with the absorption cross section for large excitation energies (below the neutron threshold), $\Sigma\Gamma_{\gamma'} \approx \Gamma$, and it ought to increase with increasing energy. Just above the nucleon threshold, $\sigma_{\gamma\gamma'}$ (see reference 6) falls rapidly at the expense of the appearance of the competing processes involving the ejection of nucleons. The sizes of the energy regions ΔE where the cross section is decreasing (refer to the figure) may be evaluated from the equation

$$\Gamma_n(\Delta E) \gtrsim \Gamma_\gamma(E_{\text{thresh}} + \Delta E).$$

For neutron thresholds we obtain from this $\Delta E \approx (\hbar^2/2MR^2)(\Gamma_\gamma/\gamma_n^2)^2$ (where R is the radius of the nucleus, and γ_n^2 is the reduced width for neutron emission). If, for example, one sets $\gamma_n^2 = 0.01\hbar^2/2MR^2$, then $\Delta E \sim 10$ kev. In the case of proton thresholds, the maximum of the cross section is located above the threshold, on account of the Coulomb barrier. Calculations show that for $Z = 30$ the maximum of the cross section ought to lie approximately 1 to 2 Mev above the proton threshold.

Thus, according to the statistical model, the maximum of the cross section for inelastic scattering ought to lie practically on the neutron threshold or a little above the proton threshold, and in any case, not below the thresholds. At present the accuracy in the determination of E_{max} is not great (± 1 Mev), and within these limits E_{max} usually coincides with E_{thresh}. However, in certain cases a displacement of the maxima into the region below the threshold is observed.[1] For example, in Y^{89}, $E_{max} \sim 10.5$ Mev, but $E_{thresh} = 11.8$ Mev.

4. The estimates given above show that in the statistical model, for $E \gtrsim 5$ Mev, the cross section $\sigma_{abs} \approx 100\,\sigma_{\gamma\gamma}$. Experiments[2] indicate, however, that $\sigma_{\gamma\gamma}$ is only a few times (2 to 10 times) smaller than the total absorption cross section, which is estimated by means of an extrapolation of the results on (γ, n) reactions.

Thus, the simple statistical model is incapable of explaining the results on photonuclear reactions in the range of excitation energy 5 to 10 Mev.

The contradiction between theory and experiment is, however, removed, if photonuclear reactions in the energy range considered are assumed to proceed fundamentally through only a few levels with large radiation widths. The strong levels near (γ, n) and (γ, p) thresholds observed in the cross sections of elastic and inelastic scattering correspond most closely to the so-called "threshold states," the existence of which has been predicted by one of us.[1] These states ought to have a single particle structure, and consequently, large radiation widths. A few "threshold" states with different moments and parities may be located close to the threshold for two-particle breakup of the nucleus.

This hypothesis explains in a natural manner a number of observations.

1. First, the very fact of the appearance of peaks in the cross sections of various photonuclear processes ($\sigma_{\gamma\gamma}$, $\sigma_{\gamma\gamma'}$, and σ_{abs}) near the thresholds of the reactions (γ, n), (γ, p), etc. The resonances observed[8] in the reactions $Zn^{64}(\gamma, d)Cu^{62}$ and $Zn^{66}(\gamma, d)Cu^{64}$ near the (γ, d) threshold may have such a "threshold" origin. According to reference 7, the threshold states may be shifted from the threshold on either side within an interval $E_{thresh} \pm (1$ to $2)$ Mev. Therefore, if further measurements confirm that the maxima in the cross sections are displaced relative to the neutron threshold, this will be a strong argument against the statistical model and for single-particle "threshold" states.

2. The irregular variation of the parameters (σ_{max}, Γ) as functions of the atomic weight. According to the results given in reference 7, the properties of "threshold states" depend strongly on the concrete structure of the nucleus.

3. The ratio of the magnitudes of elastic and inelastic scattering. This ratio is determined by the quantity $\Gamma_\gamma/\Sigma\Gamma_{\gamma'}$, and is, generally speaking, specific for each single particle (threshold) level. Thus $\sigma_{\gamma\gamma}$ may be of the order of $\sigma_{\gamma\gamma'}$ and in special cases may even exceed the cross section for inelastic scattering. (It is possible that such a situation, with $\Gamma_\gamma = \Gamma_{tot}$, was encountered in (γ, γ') scattering on Pb^{207}, when inelastic scattering was not observed at all.[9])

4. The absolute magnitudes of the cross sections $\sigma_{\gamma\gamma}$. Calculations by Kalinkin[10] based on the hypothesis that elastic scattering proceeds through separate single nucleon levels (nuclear fluorescence) led to satisfactory quantitative agreement with experiment.

Thus, the hypothesis presented above explains at least qualitatively the experimental results available at present.

The following should also be taken into consideration. The statistical model encounters difficulties in the attempt to explain the results on radiative capture of thermal neutrons.[11] Recently the idea of direct capture of the impinging neutron in the final level of the intermediate nucleus has become more and more attractive. Only in this way is it possible to understand why the spectrum of capture gamma rays contains exclusively strong lines corresponding to the capture of thermal neutrons in shell-model p-states in the final nucleus.

The presence of threshold states allows one to give another interpretation to the results on radiative capture. If these states actually exist, then the reaction (n, γ) would go basically through two stages: first the impinging neutron is captured in a single particle threshold state, and only after that a transition is made to lower levels, predominantly p-states. In the conception of "direct capture," the neutron, bypassing the first stage, immediately goes to the lower p-state.

The difference between these mechanisms is especially clear in the example of Pb^{208}. The results on (n, γ) reactions on Pb^{207} can be explained from two points of view: either by a direct process,[12] or by the existence of a single-particle s-state right on the neutron threshold of Pb^{208}. The results on $\gamma\gamma$-scattering prove directly the existence of such a level [$\sigma_{\gamma\gamma}$ has a strong peak at the threshold of the reaction (γ, n)[1]]. In the conception of direct capture this level is absent.

We can conclude that in the energy range 5 — 10 Mev one statistical theory cannot explain satisfactorily the results of experiment, which indicate that in the course of reactions in this energy range an important role is played by a small number of very strong levels of the intermediate nucleus. Basically these levels are concentrated close to the threshold and appear to be "threshold" states. For example, in the light nuclei, such states ought to be found in the energy range 6.5 — 7.5 Mev in Li^7, 11 — 11.5 Mev in B^{11}, 18.3 — 18.9 Mev in C^{12}, 15 — 16 Mev in O^{16}, 6 — 6.4 Mev and 8 — 8.4 Mev in O^{18}, 5 — 5.6 Mev in Ne^{20}, etc.

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