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Relation of Photonuclear Reactions to π-Meson Photoproduction Process

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Abstract—Neutron–proton pair knocking-out by photons from iron (Fe^{56}) nuclei is studied by measuring induced gamma activity of Mn^{54} isotope. Experiments are performed in a synchrotron beam at two maximum photon energies, 150 and 650 MeV. It was found that the yield of the reaction under study at the maximum energy of 150 MeV is almost zero, whereas a significant yield of gamma active Mn^{54} nuclei is measured at the energy of 650 MeV. The cross section of the neutron–proton pair production reaction on Fe^{56} at an energy of 650 MeV is estimated as $4 \cdot 10^{-27}$ cm^2.

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Introduction. One of the promising directions in nuclear physics is the study of properties of barion resonances in atomic nuclei. Already in the first experiments for studying the π-meson photoproduction on nuclei, it was shown that the probability of producing mesons by photons on the nucleus nonlinearly depends on the number of nucleons in the nucleus, $\sigma_A = \sigma_P A^\alpha$, where σ_A and σ_P are the cross sections of π-meson photoproduction on the nucleus with the number of nucleons A and on the proton, respectively. In this case, α is usually 2/3. This was interpreted as "surface" production, since the number of nucleons on the nucleus surface is proportional to $A^{2/3}$ [1].

It was assumed that mesons produced on inner nucleons are absorbed by the nucleus and do not escape outwards. However, measurements with meson beams showed that the probability of pion absorption by the nucleus varies with the meson energy and, as the latter decreases, this probability becomes so small that it cannot already explain the "surface" nature of the meson production in nuclei.

To test this observation, an experiment was designed, in which the A-dependence of the cross section of the neutral π-meson photoproduction was studied in such geometry that only mesons in the energy range of 0–10 MeV were detected, for which the nucleus should be transparent. In this case, the dependence close to $\sim A^{2/3}$ was obtained again [2].

One of the possible explanations of this effect was proposed by R.R. Wilson [3]. If the π-meson photoproduction occurs via excitation of the Δ_{33} isobar which then decays into a pion and a nucleon, the isobar within the nucleus has a higher probability to transfer its excitation energy to the neighboring nucleon, rather than to produce a πN pair. As a result, the nucleus will emit a pair of nucleons. Neutron and proton emission is most probable. In this case, the π-meson production does not occur. Thus, the meson production will occur mostly on the nucleus surface. The validity of this assumption can be tested by measuring the neutron–proton pair yield from nuclei upon exposure to gamma-rays at energies below the π-meson photoproduction threshold and comparing it to the yield at above-threshold energies.

The nucleus photodisintegration with emission of one nucleon has a cross section maximum of tens and, for heavy nuclei, hundreds of millibarns in the energy region of 10–30 MeV. This phenomenon was called the "giant resonance". As for the cross sections of a nucleon pair emission in photonuclear reactions, there are few experimental data which are not always in agreement with each other. In [4], an increase in the $B^{11}(\gamma, 2p)Li^9$ reaction cross section was observed in the gamma-ray energy range from

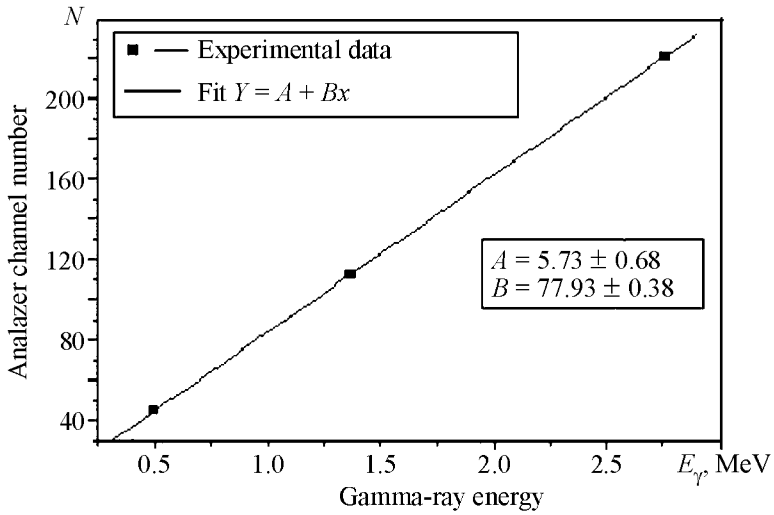

Fig. 1. Calibration curve of the scintillation gamma spectrometer, obtained by measuring the position of maxima in the spectra of C^{11} and Na^{24} isotopes.

100 to 300 MeV. At the photon energy of 300 MeV, the total cross section reached 15 μbarn; at 100 MeV, the cross section was close to zero.

As for the (γ, np) reaction cross section in the gamma-ray energy range from 100 to 300 MeV, we failed to find published data. It is of interest to obtain experimental data about the cross section of this reaction at energies below the meson photoproduction threshold and at energies above π-meson production threshold. If the assumption by R.R. Wilson is valid, the neutron—proton pair yield at energies above the π-meson photoproduction threshold should increase due to the production of Δ-isobars followed by their excitation energy transfer to neutron—proton pairs due to their interaction with nuclear matter.

Experimental. To test this assumption, the energy dependence of the $Fe^{56}(\gamma, np)Mn^{54}$ reaction was studied in the energy range from 150 to 650 MeV. At the Laboratory of electromagnetic interactions of the Department of High Energy Physics, the induced radioactivity arising during target irradiation with a bremsstrahlung beam of the PAKHRA synchrotron was measured [5]. The irradiation of a steel target caused accumulation of Mn^{54} nuclei with half-life $T_{1/2} = 291$ days in it, which decay emitting gamma-rays with energy $E_\gamma = 0.8$ MeV. The induced gamma activity was measured using a scintillation gamma spectrometer with a NaI(Tl) crystal 100 mm in diameter and 100 mm high. Figure 1 shows the calibration curve of the gamma spectrometer, obtained based on several lines of monochromatic photons, i.e., the position of the gamma line at 0.51 MeV from the C^{11} isotope decaying with positron emission and spectral lines $E_\gamma = 1.38$ and $E_\gamma = 2.76$ MeV of the ^{24}Na isotope. Experimental points were fitted by the linear dependence

$$N = (5.73 \pm 0.68) + (77.93 \pm 0.38)E_\gamma.$$

To clarify how the cross section varies in this energy range, two identical steel targets were irradiated, one at an energy of 150 MeV (a system for producing low-energy photons with small bremsstrahlung beam divergence was used [6]), the other at 650 MeV. At the same energies, a carbon target was irradiated, in which the C^{11} isotope was accumulated due to the reaction $C^{12}(\gamma n)C^{11}$ during irradiation, which decays with positron emission resulting in the 0.51-MeV line in the gamma spectrum. Its half-life is 20 min. Since it is known that the main contribution to the γn reaction is made by low-energy photons (10—30 MeV), we can assume that the yield of this reaction will not change significantly as the bremsstrahlung beam energy changes from 150 to 650 MeV. Thus, measurements of the induced activity of the carbon target were used to control the photon flux.

Results. Figures 2 and 3 show the experimentally measured spectra of gamma-rays emitted by the iron target after irradiation in the bremsstrahlung beam with a maximum energy of 650 and 150 MeV, respectively. Measurements were performed in three months after the irradiation end, when short-lived

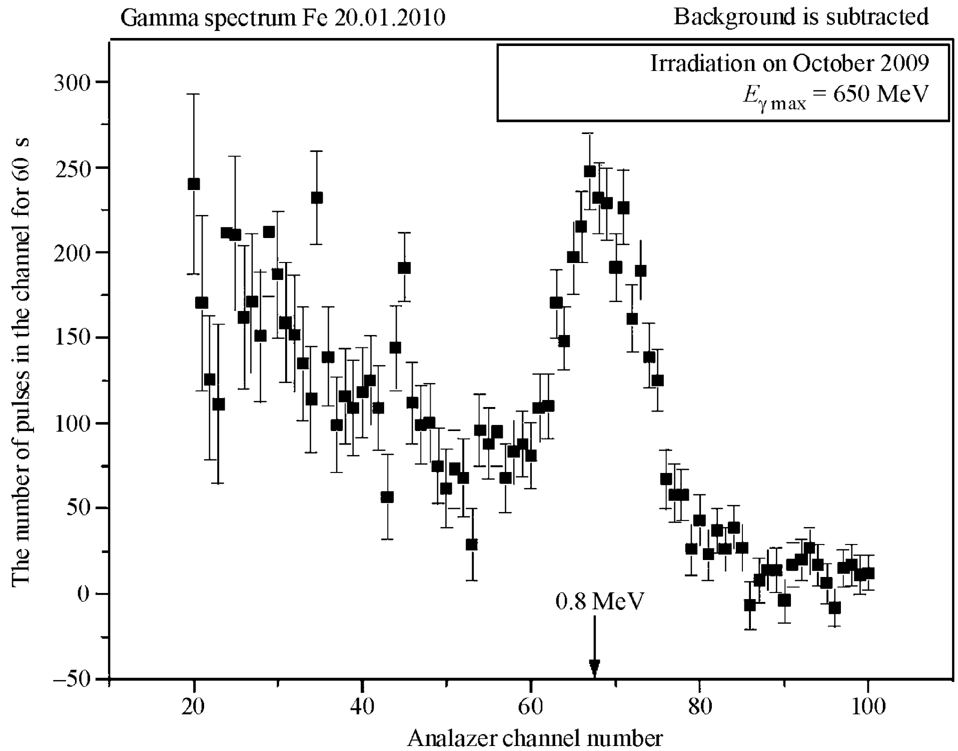

Fig. 2. Gamma spectrum of the iron target, measured in three months after irradiation in October 2009 in the bremsstrahlung beam with a maximum energy of 650 MeV. The background is subtracted.

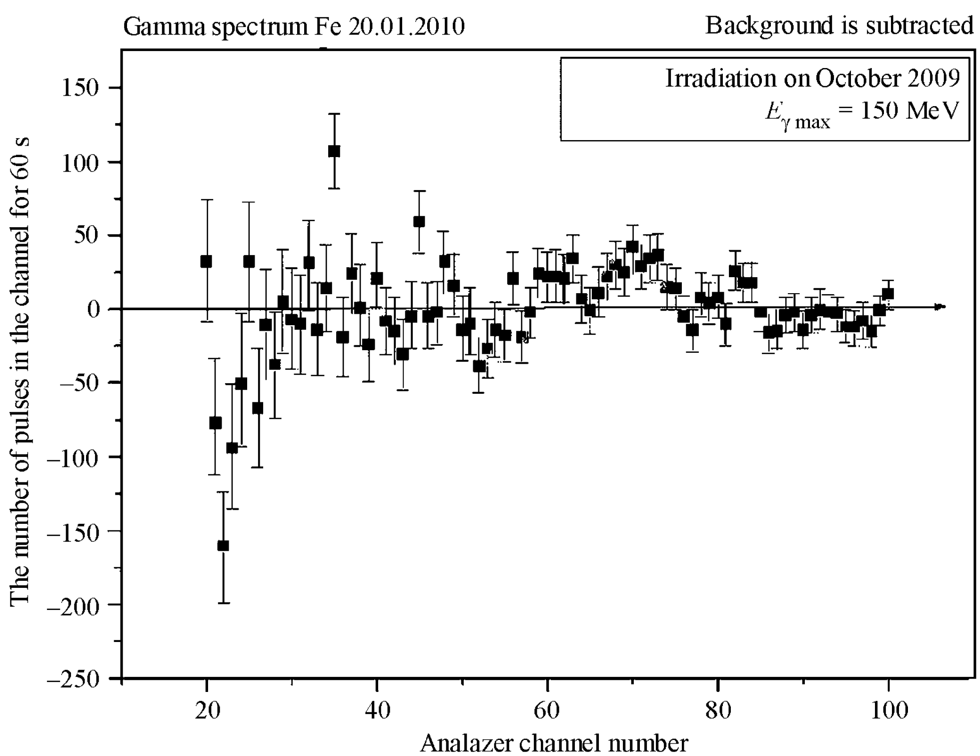

Fig. 3. Gamma spectrum of the iron target, measured in three months after irradiation in the bremsstrahlung beam with a maximum energy of 150 MeV. The irradiation end is October 2009. The background is subtracted.

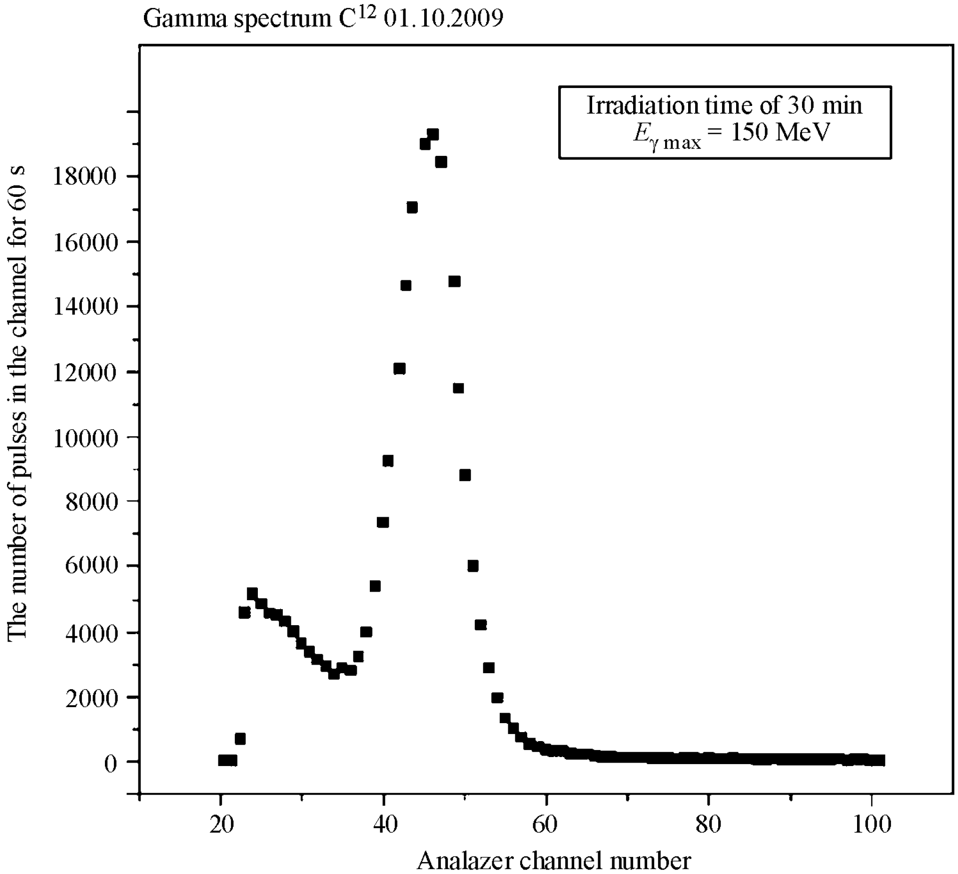

Fig. 4. Gamma spectrum of the carbon target, measured in October 1, 2009 in 10 min after irradiation in the bremsstrahlung photon beam with a maximum energy of 150 MeV. The irradiation time was 30 min.

isotopes have already decayed. Data are presented after subtracting the background counting rate of the spectrometer. Figures 4 and 5 show the gamma spectra obtained by processing the spectra from the carbon target irradiated for 30 min under the same conditions with the iron target in the bremsstrahlung beam at maximum energies of 150 and 650 MeV, respectively. The spectra were measured immediately after irradiation. We can see that the C^{11} isotope yields at the beam energy of 650 and 150 MeV differ less than twofold (this suggests that the number of photons in the low-energy region in the bremsstrahlung beam remained almost unchanged when the maximum energy changes from 150 to 650 MeV), whereas the Mn^{54} isotope yield in the iron target at the energy below 150 MeV is close to zero; but at the maximum energy of 650 MeV, its value is appreciable. This means that the neutron–proton pair production occurs mostly due to photons with energies above the π-meson photoproduction threshold.

The cross section of the reaction $\gamma + Fe^{56} \rightarrow Mn^{54} + n + p$ was estimated as $\sigma = 4 \cdot 10^{-27}$ cm^2.

This value is comparable to the cross section of the π^0-meson photoproduction by protons [8]. At the maximum, this cross section reaches $2 \cdot 10^{-28}$ cm^2. Since both protons and neutrons are involved in the isobar production, and taking into account errors, it can be considered that the presented cross sections do not contradict each other.

Conclusions. The Mn^{54} isotope yield due to the neutron–proton pair photoproduction on Fe^{56} at the maximum beam energy of 150 MeV is close to zero. Almost the entire neutron–proton pair yield is caused by photons of higher energies. At the same time, the number of photons in the beam in the low-energy region does not change significantly when the maximum energy changes from 150 MeV to 650 MeV. Hence, the neutron–proton pair production occurs mostly due to photons with energies above the π-meson photoproduction threshold. The obtained estimate of the reaction cross section does not contradict the assumption that the neutron–proton pair production occurs via the Δ_{33} isobar

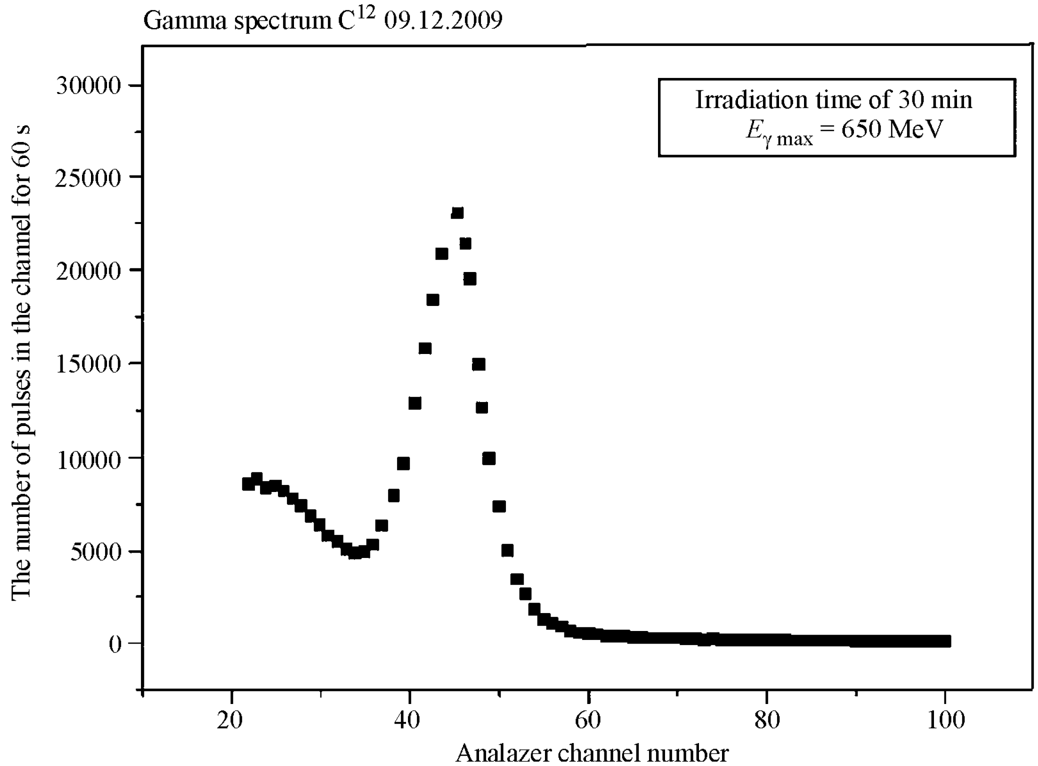

Fig. 5. Gamma spectrum of the carbon target, measured in 10 min after 30-min irradiation of December 9, 2009 in the bremsstrahlung beam with a maximum energy of 650 MeV.

photoproduction. This result can be explained the mechanism of π-meson photoproduction suppression on inner nucleons of the nucleus, proposed by R.R. Wilson.

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