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Fig. 1

Figure 1: Fig. 1

Abstract

Full Text

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PHYSICS

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DEPENDENCE OF THE CROSS SECTIONS FOR PHOTOPRODUCTION OF π^0 MESONS ON THE MASS NUMBERS OF NUCLEI

(Presented by Academician I. E. Tamm, 15.VIII.1956)

The dependence of the cross sections for production of π^0 mesons (σ_{π^0}) under the action of bremsstrahlung γ rays on the mass numbers of nuclei A was investigated in works ⁽¹⁻⁵⁾, with the maximum energy of the bremsstrahlung spectrum varying from 170 to 340 MeV, and the π^0 mesons being recorded either by one ^(2,4,5) or by both ^(1,3) γ rays emitted in their decay. Each of these methods of recording π^0 mesons has its advantages and its disadvantages. Recording a single γ ray makes it possible to greatly increase the statistical accuracy; however, elastically or inelastically scattered by nuclei γ rays may also be recorded. Recording two γ rays makes it possible to isolate the effect of π^0 -meson production against the background of other processes; however, for a given arrangement of the two counters, only π^0 mesons of a quite definite energy are observed, and this leads to a decrease in the efficiency of recording π^0 mesons from complex nuclei (for which, in inelastic photoproduction, there is no unambiguous relation between the emission angle and the energy) as compared with π^0 mesons from hydrogen.

Fig. 1. Dependence of the cross sections for photoproduction of π^0 mesons on the mass number of the nucleus, according to literature data:

a -⁽¹⁾, 260 MeV; b -⁽²⁾, 237–310 MeV; v -⁽³⁾, (265 + 15) MeV; g -⁽⁴⁾, 170–340 MeV; d -⁽⁵⁾, 260 MeV; e -⁽⁵⁾, 200 MeV

The shortcomings of the studies of the dependence $\sigma_{\pi^0} = f(A)$ carried out so far should also include the fact that the ratio of cross sections for complex

nuclei and hydrogen either was not studied at all ^(3,4), or was determined from separate measurements with paraffin and graphite targets ^(1,2,5) with rather low accuracy. A summary of the data obtained in ⁽¹⁻⁵⁾ is presented in Fig. 1.

In order to clarify the dependence of the cross sections for photoproduction of π^0 mesons over a wide range of nuclear mass numbers, we carried out a series of experiments and, in particular, an especially careful study of this dependence in the region of small A . For this purpose we compared the yield of π^0 mesons from liquid hydrogen, liquid nitrogen, and liquid oxygen, which were poured into a cylindrical target made of PS-4 polystyrene foam (inner diameter of the target 108 mm, outer diameter 208 mm, wall thickness 40 mg/cm²). The background from the empty target amounted to up to 1.6% for oxygen and up to 8-33% for hydrogen, so that it was readily possible to obtain results with a high degree of accu-

ness. To pass, in a single series of experiments, to heavier nuclei we used two graphite targets. One of them—a cylindrical one with a diameter of 106 mm—was inserted inside the polystyrene target, which made it possible to compare directly the photoproduction cross section of π^0 mesons on carbon with hydrogen, nitrogen, and oxygen. The other graphite target—a flat one, with thickness 3.3 g/cm²—was placed at an angle of 45° to the bremsstrahlung beam under the same geometrical conditions as the targets of aluminum (1.79 g/cm²), iron (1.30 g/cm²), copper (1.27 g/cm²), cadmium (0.928 g/cm²), and lead (0.541 g/cm²). Thus it was possible to refer the photoproduction cross sections of π^0 mesons on the listed complex nuclei to hydrogen.

Fig. 2. Various data on the bremsstrahlung spectrum and the efficiency of recording γ quanta in our experiments

The experiments were carried out at the 265 MeV synchrotron of the Physics Institute of the Academy of Sciences of the USSR. To reduce the overload of individual counters and coincidence circuits, such an operating mode of the accelerator was used in which, instead of an instantaneous cutoff of the accelerating voltage on the resonator, a gradual decrease of its amplitude was produced.

Table 1

Relative values of the photoproduction cross sections of π^0 mesons

Nucleus	$E_{\max} =$ 256	$E_{\max} =$ 256	$E_{\max} =$ 200	$E_{\max} =$ 200	$E_{\max} =$ 180
	MeV90°without corrections for other shielding processes	MeV135°without corrections for other shielding processes	MeV135°without corrections for other shielding processes	MeV90°without corrections for other shielding processes	
H ¹	1	1	1	1	1
C ¹²	12.7 ± 0.1	12.0 ± 0.4	22.1 ± 1.4	23.2 ± 2.2	23.9 ± 2.6

Nucleus	$E_{\max} =$ 256	$E_{\max} =$ 256	$E_{\max} =$ 200	$E_{\max} =$ 200	$E_{\max} =$ 180
	MeV90°without corrections for other shielding processes	MeV135°without corrections for other shielding processes	MeV135°without corrections for other shielding processes	MeV90°without corrections for other shielding processes	
N ¹⁴	15.1 ± 0.1	15.5 ± 0.5	23.2 ± 1.5	30.3 ± 2.9	31.4 ± 3.4
O ¹⁶	17.1 ± 0.2	16.5 ± 0.5	29.5 ± 1.9		
Al ²⁷	22.1 ± 0.2	26.0 ± 0.9	40.5 ± 2.9	55.5 ± 5.3	53.8 ± 6.2
Fe ⁵⁶	38.3 ± 0.4	39.8 ± 1.4	60.4 ± 5.2	82.5 ± 8.2	71.1 ± 8.7
Cu ⁶⁴	44.7 ± 0.5	41.0 ± 0.5	82.0 ± 6.8	88.0 ± 8.9	73.6 ± 9.2
Cd ¹¹²	62.3 ± 0.5	67.6 ± 2.6	109 ± 13	135 ± 15	101 ± 16.0
Pb ²⁰⁷	105.2 ± 1.2	91 ± 4.5	176 ± 31	234 ± 26	152 ± 28

Knowing the shape of the stretched pulses of the synchrotron, i.e., the spectrum of the electrons at the moment they struck the target, and assuming for the undistorted bremsstrahlung spectrum the form $f(E) = a/E$, we could easily estimate the form of the γ -ray spectra in our experiments, shown in Fig. 2. Curve **1** in this figure characterizes the form of the spectrum in the main experiments ($E_{\max} = 256$ MeV), curves **2** ($E_{\max} = 200$ MeV), **3** ($E_{\max} = 180$ MeV), and **4** ($E_{\max} = 97$ MeV) the form of the spectrum in additional measurements, which will be discussed below. The yield of π^0 mesons was recorded by observing one of the γ quanta from their decay with the aid of a telescope of four liquid scintillation counters filled with a solution of terphenyl in toluene (3 g/l). Two telescopes were used simultaneously, placed at equal or different (90 and 135°) angles.

Immediately after the first counter of each of the telescopes, which was connected in anticoincidence, there was a lead converter (6.2-7 g/cm²), between

between the third and fourth counters—an aluminum filter of thickness 5.4-6 g/cm². The registration threshold for γ quanta, determined by the thickness of the second and third counters and the filter, was about ~ 40 MeV for both telescopes.

The dependence of the γ -quantum registration efficiency for both telescopes on their energy E is represented, according to the relation given in [2] (where telescopes of the same type were used)

$$\varepsilon \sim 1 - e^{-\frac{E-40}{40}}$$

by curve 5 in Fig. 2.

The experimental results and statistical errors are given in Table 1. In obtaining the tabulated data, small (9-15%) corrections were introduced

Fig. 3

Figure 2: Fig. 3

Fig. 4

Figure 3: Fig. 4

Fig. 3. Dependence of the photoproduction cross sections of π^0 -mesons on the nuclear mass number (our data): $a-90^\circ$, 256 MeV; -135° , 256 MeV; -135° , 200 MeV; -90° , 180 MeV.

to account for differences in the absorption of γ quanta in liquid hydrogen, nitrogen, oxygen, and the spherical graphite target.

The main source of systematic errors could have been the registration of γ quanta from elastic scattering, whose cross section is approximately $\sim (Z^2/A)^2$, and from other shielding-effect processes.

To take these errors into account, additional experiments were carried out at

$$E_{\max} = 97 \text{ MeV},$$

and, in extrapolating the data from these experiments to higher energies, we assumed that the cross section of the various shielding-effect processes at 40–260 MeV remains constant, while their yield per effective quantum increases in proportion to the area under curves 6–9 in Fig. 2, which represent the product of the bremsstrahlung spectrum by the γ -quantum registration efficiency. The magnitude of the corrections introduced for shielding-effect processes at $E_{\max} = 256$ MeV does not exceed 9%;

for $E_{\max} = 180$ MeV the corrections are indicated in the table. Whatever screening effects there may be in the processes, it follows from the results of our experiments that for light nuclei, at least up to oxygen, the cross section for photoproduction of π^0 -mesons grows approximately as $\sigma_{\pi^0} \sim A$ (and even somewhat more strongly), and only subsequently is a dependence close to $\sigma_{\pi^0} \sim A^{2/3}$ established (see Fig. 3).

Such a dependence $\sigma_{\pi^0} = f(A)$ can be qualitatively explained by the fact that the mesons are produced throughout the entire volume of the nucleus, but then undergo reabsorption, so that only part of the mesons formed there emerge from the nucleus. A similar interpretation is given, in particular, in ^(1,4) and in paper ⁽⁶⁾, where on the basis of an optical model a formula is given for determining the reabsorption path length of π -mesons from the form $\sigma_{\pi} = f(A)$.

Fig. 4. Ratio of the charge-exchange cross sections of neutral and charged π -mesons:

$$1 - \sigma_{\pi^0 n} / \sigma_{\pi^- p}; \quad 2 - \sigma_{\pi^0 p} / \sigma_{\pi^+ p}$$

However, for a quantitative consideration of the question of meson reabsorption, three circumstances that have not hitherto been taken into account should be kept in mind:

1. The yield from photoproduction of π^0 -mesons in the energy interval under consideration is several times greater than the yield for π^{\pm} -mesons.
2. The probability of meson scattering by the nucleons of the nucleus is not only no smaller, but even greater than the probability of charge exchange (and, apparently, than the probability of reabsorption of mesons in interaction with pairs or groups of nucleons).
3. Because of the endothermic nature of charge exchange of π^0 -mesons, the cross sections of the reactions $\pi^- + p \rightarrow \pi^0 + n$ and, especially, $\pi^+ + n \rightarrow \pi^0 + p$ at low meson energies appreciably exceed the cross sections of the inverse processes (Fig. 4).

The presence of strong scattering (item 2) indicates the possibility of analyzing the question of meson reabsorption (at least for heavy nuclei) not so much by the formulas of the optical model as by a system of two diffusion equations—for π^0 - and π^{\pm} -mesons. In this case, owing to the circumstances noted in items 1 and 3, the charge-exchange processes should lead to an increase in the yield of π^0 -mesons at the expense of π^{\pm} -mesons, so that, in the absence of meson absorption, for π^0 -mesons one would observe a growth of σ_{π^0} with A stronger than $\sigma_{\pi^0} \sim A$, whereas for π^{\pm} -mesons it would be weaker than $\sigma_{\pi^{\pm}} \sim A$.

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