Interaction of π^-–Mesons with Lead, Copper, Oxygen and Beryllium Nuclei

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Measurements were made of the total cross sections σ_t for interaction of π^-–mesons with Be, C and O nuclei and of cross sections σ_{in} for inelastic collisions of π^-–mesons with Be, C, Cu and Pb in the energy range from 140 to 400 mev. Cross sections were determined by measuring the attenuation of a meson beam which passed through the scatterer, using scintillation counters. The energy dependence of the cross sections σ_t and σ_{in} for nuclei in general shape resemble the energy dependence of the total scattering cross sections of pions on hydrogen and deuterium. Results of the cross section measurements were analyzed on the basis of the optical model. It can be concluded, as a result of this analysis, that the optical model with parameters computed on the basis of the single Coulomb interaction of the mesons with the nuclei, satisfactorily describes the energy dependence of the cross sections in the energy range of 140 to 400 mev.

IN order to study interaction processes between π^-–mesons and nuclei, measurements were made of total cross sections σ_t of π^-–meson interactions with Be, C and O nuclei and of cross sections σ_{in} for inelastic collisions of π^-–mesons with Be, C, Cu and Pb nuclei in the energy range from 140 to 400 mev. Results of total cross section σ_t measurements were reported earlier. In this communication we shall first describe results of σ_{in} measurements and then discuss the results of these measurements as well as the total cross sections.

Cross sections σ_{in} were determined by measuring the attenuation of a meson beam passed through the scatterer, by the method of scintillation counters. A description of experimental conditions and equipment for meson recording is contained in Refs. 1 and 2.

Measurements of Be and C cross sections for all values of energy were carried out at a distance of 6 cm between the center of the scatterer and the last scintillator, which corresponded to an average registration angle θ for the last detector of about 40°. Experiments with Cu and Pb were carried out at $\theta = 25°$. Results of measurements are shown in Table I. In the first column are given the π-meson energies in the center of the scatterer. In columns 2 to 5 are given the "measured" cross sections. The values of these cross sections include a number of introduced corrections. These corrections account for: 1) admixture of μ-mesons, 2) chance coincidences, 3) excess counts in the recording equipment. The above-mentioned corrections were discussed previously.[1,2] The errors shown in columns 2 to 5 include statistical errors as well as the uncertainty in the corrections.

The σ_{in} for inelastic collisions were obtained from the "measured cross sections" shown in columns 2 to 5. Corrections were introduced to account for the inelastically scattered mesons within the limits of angle θ and for the secondary charged particles capable of being registered in the last detector. It should be noted that the introduction of these corrections presents great difficulties. The difficulties arise because the investigations of the processes of scattering and absorption of mesons in nuclei have been carried out basically only for elements entering into photoemulsions. Results of Refs. 3 to 5 were used in making corrections. Corrections related to inelastic scattering of mesons were different for different energies and varied from (3 ± 1.5) to (8 ± 4)% for Be and C and from (2 ± 1) to (5 ± 2)% in the case of Cu and Pb. The corrections were higher for higher energy π–mesons.

Corrections for secondary charged particles capable of being registered in the last detector were taken to be the same in all cases and equal to (3 ± 1.5)% as evaluated from the data in Ref. 4, the only available source. Besides the above corrections, corrections were also introduced connected with mesons elastically scattered at angles greater than θ. This correction was introduced only for mesons of 140 mev, where it was substantial; in all other cases this correction was too small and was neglected. The correction was evaluated on the basis of diffraction scattering theory for a "nontransparent" nucleus.

The cross sections σ_{in} obtained for inelastic collisions of π^-–mesons with Pb, Cu, C and Be nuclei are given in columns 6 to 9 of the Table. In making the above-mentioned corrections account was also taken of the uncertainties in their values.

TABLE

Energy of π^--mesons mev	"Measured" cross sections (10^{-27} cm^2)				Cross sections for inelastic collisions σ_{in} (10^{-27} cm^2)			
	Pb $\left(8{,}4\ \frac{g}{cm^2}\right)^*$	Cu $\left(5{,}3\ \frac{g}{cm^2}\right)^*$	C $\left(6{,}5\ \frac{g}{cm^2}\right)^*$	Be $\left(7{,}2\ \frac{g}{cm^2}\right)^*$	Pb	Cu	C	Be
140±7				300±17				273±20
216±7	2244±95	999±42	327±13	257±11	2356±152	1048±67	350±24	275±21
256±7	2250±93	976±44	297±15		2430±183	1054±84	326±31	
290±7	2142±90	850±41	245±13		2313±175	918±76	269±26	
350±7			150±12	137±9			166±21	150±16

*The thickness of the used scatterer is shown in parenthesis.

The energy dependence of the cross sections σ_{in} was shown in Fig. 1. The same Figure contains values of cross sections σ_{in} for energies less than 140 mev measured by means of scintillation counters.[6,10] The given values of σ_{in} include corrections for the Coulomb interaction.

As can be seen from Fig. 1, the energy dependence of cross sections σ_t and σ_{in} for all nuclei resembles in general the energy dependence of the total cross section for scattering of π^--mesons by hydrogen and deuterium. In the energy region of 100 to 250 mev, the cross section depends only slightly on energy, while at energies greater than 250 mev, the cross section decreases comparatively rapidly. The cross section also changes at a fast rate at energies less than 100 mev. The cross sections σ_t and σ_{in} go through a maximum in the energy interval ($\sim$ 190 mev) where the total scattering cross sections of π-mesons in hydrogen and deuterium reach their maximum values. When studying phenomena associated with the entrance of mesons into nuclei, it is of interest to know the average path length λ of the mesons in the nuclear matter. In order to obtain information on the energy dependence of the path, $\lambda = f(E)$, on the basis of the optical model, an analysis was made of the results obtained in cross section measurements. With the nuclear radius taken as $R = 1.42 \times 10^{-13} \times A^{1/3}$cm, values of λ were then found such that the magnitudes σ_{in} for Be and C satisfy the expression

$$\sigma_{in} = \pi R^2 \left\{1 - \frac{1}{2}\,[1 - (1 + 2R/\lambda)\exp\{-2R/\lambda\}]\,(\lambda/R)^2\right\}$$

for all energies. The obtained values of λ are shown in Fig. 2. In the same Fig. are also shown values of λ for energies less than 140 mev as obtained by a number of workers cited in Ref. 11.

If we assume that the π-mesons interact with separate nucleons in the nucleus, then the free path can be computed from the data on cross sections of π-meson interaction with free nucleons and the expression

$$\lambda' = [\rho_p \alpha \sigma_t(\pi^-, p) + \rho_n \beta \sigma_t(\pi^-, n)]^{-1},$$

where ρ_p and ρ_n denote the density of protons and neutrons, respectively, in the nucleus, $\sigma_t(\pi^-, p)$ and $\sigma_t(\pi^-, n)$ = total interaction cross sections of π^--mesons with free protons and neutrons, α and β = coefficients smaller than unity introduced to account for the Pauli principle. In computing the values of λ' for hydrogen in the energy region from 30 to 350 mev the value $\alpha = \beta = 1$ was used. On the basis of charge symmetry values of $\sigma_t(\pi^+, p)$ were used in place of $\sigma_t(\pi^-, n)$. The

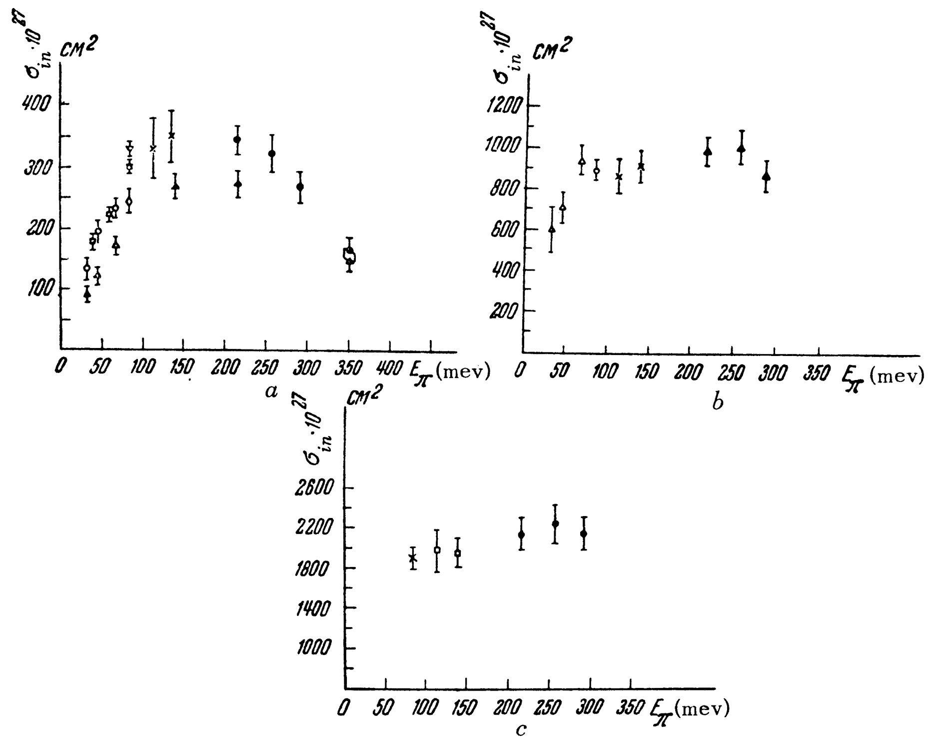

FIG. 1. Energy dependence of cross sections for inelastic collisions of π–mesons with nuclei. a – beryllium and carbon: ● – (π^-, C), this work; ▲ – (π^-, Be), this work; ▢ – (π^-, C), Ref. 7; Δ – (π^+, Be), Ref. 10; O – (π^+, C), Ref. 10; ◇ – (π^-, Be), Ref. 8; × – (π^-, C), Ref. 9; ∇ – (π^-, C), Ref. 8.

b – Copper: ▲ – (π^-, Cu), this work; × – (π^-, Cu), Ref. 9; O – (π^-, Cu), Ref. 8; Δ – (π^+, Cu), Ref. 10.

c – lead: ● – (π^-, Pb), this work; ▢ – (π^-, Pb), Ref. 9; × – (π^-, Pb), Ref. 8.

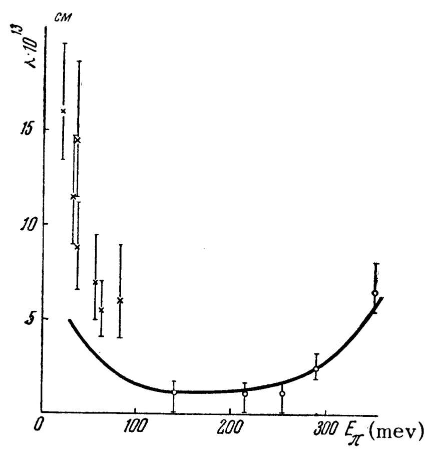

FIG. 2. Dependence on energy of the meson path λ in the nuclear matter. O–experimental points obtained by the optical model in the present work; ×– works cited in reference 11; solid curve computed without allowance for the Pauli principle from cross section data for scattering of π-mesons by nucleons.

values of $\sigma_t(\pi^-, p)$ and $\sigma_t(\pi^+, p)$ were taken from a series of published works. Results of λ' computations are shown in Fig. 2 in the form of a solid line.

As can be seen from Fig. 2, there is an agreement between the values of λ and λ' in the energy region greater than 200 mev where it is more justifiable to neglect the effect of the Pauli principle. This fact indicates directly that the initial assumption was correct, i.e., that the interaction of π-mesons in the nucleus takes place basically with its separate nucleons. This conclusion can be supplemented by making a comparison between the experimentally obtained relationships $\sigma_t = f(E)$ and $\sigma_{in} = f(E)$ and the similar relationships computed by Sternheimer on the basis of the optical model in the energy region of 100 mev to 2.5 bev.[12] This comparison is especially interesting because in computing the energy dependence of the elastic scattering $\sigma_e = f(E)$, values of the real parts of

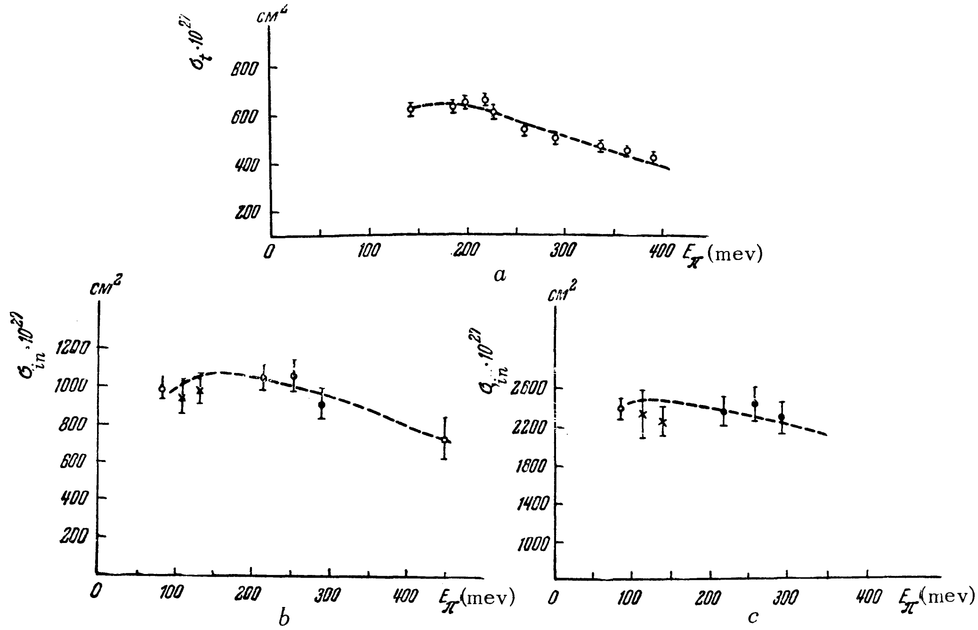

FIG. 3. Comparison of experimentally obtained energy dependence of cross sections for different nuclei computed on the basis of the causality condition.[12]

a – Total cross section for carbon [O–(π^-, C)], measured in Ref. 1.

b – Cross section of nonelastic collisions for copper: ●–(π^-, Cu), this work; ×–(π^-, Cu), Ref. 9; O–(π^-, Cu), Ref. 8; □–(π^-, Cu), Ref. 13.

c – Cross section of nonelastic collisions for lead: ●–(π^-, Pb), this work; ×–(π^-, Pb), Ref. 9; O–(π, Pb), Ref. 8.

Computed curves are shown dotted.

the forward scattering amplitudes were used, obtained in the basis of the causality condition from one data on total cross sections of meson scattering by protons. The dotted line in Fig. 3a represents the energy dependence of the total cross section for carbon obtained by the summation of the computed $\sigma_{in} = f(E)$ and $\sigma_e = f(E)$. Good agreement can be seen to exist between the computed and measured dependence of the total cross section on energy $\sigma_t = f(E)$. In Figs. 3b and 3c, where a comparison is made between the measured and computed cross sections for inelastic collisions in copper and lead, agreement between measured and computed cross sections can also be observed within limits of experimental errors.

Thus, the analysis of the results permits us to conclude that the optical model, with parameters computed on the basis of the single nucleon interaction mechanism between mesons and nuclei, satisfactorily describes the energy dependence of the total and inelastic cross sections for beryllium, carbon, copper and lead in the energy range of 140 to 400 mev.

From the cross sections σ_t and σ_{in} in the range of energies close to 190 mev (where the real part of the interaction potential between π^-–mesons and the nucleus passes through zero[12]) it is possible to derive information on the sizes of nuclei. Indeed, values of the total cross sections σ_t for beryllium, carbon, oxygen and of inelastic collision cross sections for beryllium, carbon, copper and lead in this energy region are equal to values of $2\pi R^2$ and πR^2, respectively, if the nuclear radius is taken equal to $R = 1.42 \times 10^{-13} \times A^{1/3}$cm.

In conclusion we consider it our pleasant duty to thank I. V. Popov and G. N. Tentiukov for the assistance given by them in carrying out certain computations.

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A Calorimetric Determination of the Mean Energy of the β-Spectra of P^{32}, S^{35}, Cu^{64}, W^{185} and Au^{198}

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The mean energy $\bar{E}_\beta$ of the β-spectra of P^{32}, S^{35}, Cu^{64}, W^{185} and Au^{198} were determined by the calorimetric method. The following values of $\bar{E}_\beta$ were obtained for the above isotopes, respectively: 693 ± 22; 52 ± 2; 213 ± 12; 144 ± 7 and 317 ± 15 kev.

1. THE electrons and positrons emitted during β-decay have a continuous energy spectrum. The mean energy of the β-particles

$$\bar{E}_\beta = \int_0^{E_{max}} En(E)\,dn \Big/ \int_0^{E_{max}} n(E)\,dn \qquad (1)$$

is always less than the maximum value E_{max} and for most β-active isotopes equals $0.3–0.4\,E_{max}$. The exact values of $\bar{E}_\beta$ are usually found from the spectral distribution of β-electrons, measured with the help of a magnetic or any other β-spectrograph. It should be borne in mind, however, that the experimental investigation of the shape of the whole β-spectrum is difficult, and the spectral distribution obtained can be quite incorrect. The finite thickness of the source and of the counter window, the scattering of electrons from the source mount and from the walls and baffles of the spectrograph, the diffusion of radioactive atoms into the source mount, the electrical charging of the latter, and other causes can markedly alter the shape of the β-spectrum, especially in the low-energy region. The errors of the values of $\bar{E}_\beta$ obtained by this method are in most cases not less than 3–5%

The methods of determination of $\bar{E}_\beta$ with the help of an extrapolation chamber[1] and absorption measurements[2] are as yet unsufficiently developed.

The idea of the calorimetric determination of the mean energy of the β-spectrum lies in the simultaneous measurement of the calorimetric effect Q of the β-radiation and of the number of disintegrations A of the sample. The mean energy $\bar{E}_\beta$ follows from the self-evident relation

$$\bar{E}_\beta = Q/A. \qquad (2)$$

The calorimetric method, notwithstanding its numerous advantages and relative simplicity, has almost not been used. Since the well-known experiments of Ellis and Wooster[3] who measured the mean energy of the β-electrons of RaE*, the mean energy $\bar{E}_\beta$ has been determined by the calorimetric method in the last 25 years for two cases of β-emitters only, namely, for H^3 [6] and P^{32} [7].

We determined the mean energy of the β-spectra of five β-active isotopes: P^{32}, S^{35}, Cu^{64}, W^{185} and Au^{198} using double static calorimeters having a sensitivity of 5×10^{-6} W/mm.[8] The method used is described below in short and the results are

*These classical experiments which played an important role in the formation of the modern theory of the β-decay and the neutrino hypothesis were repeated by Meitner and Ortmann[4], and also by Zlotowski[5]