INELASTIC INTERACTIONS OF π^+ MESONS WITH LIGHT NUCLEI IN THE ENERGY REGION 80—300 Mev

A. G. MESHKOVSKIĬ and Ya. Ya. SHALAMOV

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The cross sections for the inelastic interactions of π^+ mesons with a mixture of C, F, and Cl nuclei were measured at ten values of the pion energy in the 80 — 300 Mev region. The results are compared with curves calculated by the optical model assuming alternately a uniform charge density distribution in the nucleus and a Fermi-type distribution. It is shown that the experimental results satisfy the second assumption. The pion inelastic scattering cross sections were measured.

A paper by Blinov and others[1] described experiments on the interaction of 80 — 300 Mev π^+ mesons with the mixture of the elements C, F, and Cl which made up the working liquid in a 17-liter freon bubble chamber.[2] The analysis of the photographs taken with the aid of this chamber in π^+-meson beams from the synchrocyclotron of the Joint Institute for Nuclear Research determined the cross sections for exchange scattering and for star formation and the sum of the π^+-meson elastic and inelastic scattering cross sections.

In the present work an analysis of the photographs was done for the purpose of separating out all the inelastic interaction processes from the elastic. We found and analyzed 7400 events of various forms of interaction.

RESULTS OBTAINED

The numbers of events counted of the different interactions are given in Table I as a function of energy.

The number N_1 includes not only the stars seen on the exposures but also the positive-pion stoppings not accompanied by tracks of products from a pion-nucleus interaction. Such events can be related either to stars with outgoing neutrons or to stars with low-energy protons, since protons with energy less than about 10 Mev did not make visible tracks in our chamber. Since not only positive-pion absorption but also charge exchange ($\pi^+ \rightarrow \pi^0$) can take place in star formation, the number N_1 includes also the detected charge exchange events, that is, star events accompanied by an electron-positron pair pointing toward the point of interaction (conversion of a γ quantum from π^0 decay).

TABLE I. Number of events found

π^+-meson energy in Mev, E_π	Absorption of π^+ mesons and charge exchange, N_1	π^+-meson scattering		
		Inelastic, N_2	without visible tracks for nuclear transformation products	
			forward, N_3	back, N_4
67—91	98	14	58	33
91—115	150	29	143	38
120—144	178	108	165	24
144—165	267	120	266	35
165—185	327	191	348	45
185—205	447	286	447	37
210—230	226	138	224	18
230—251	251	171	308	17
251—273	341	218	434	13
273—291	399	281	439	16

We attributed to the inelastic scattering (N_2), first, those events where the positive-pion scattering was accompanied by charged particles (visible on the plate) outgoing from the nucleus and, second, those scattering events without accompanying particles when a noticeable decrease of the pion energy after scattering could be established. An estimate of the π^+ energy after scattering, in these cases, was carried out from the range or from the characteristic formation of ions along the track.

The number of pion forward scattering events without visible charged particle tracks (N_3) was obtained only in scatterings where the sum of the scattering angle projections for two stereoscopic exposures was greater than 10°. These events were fundamentally related to the elastic scattering of positive pions on a nucleus. Obviously the number N_3 includes also pion inelastic forward scattering events not accompanied by visible tracks of nuclear transformation products.

As will be shown below, the pion elastic backward scattering was relatively small in our energy region. Therefore the number of events N_4 is fundamentally attributed to the pion inelastic backward scattering, although tracks of interaction products were not visible on the plate.

Calculation of the cross section for all inelastic processes σ_u was carried out using the number of interactions $n = N_1 + N_2 + (1+\alpha)N_4$ where α is the forward/backward ratio calculated in each energy region for pion inelastic scattering. It is evident that αN_4 is the number of inelastic events which are included in the number N_3 if it is taken that the quantity α is the same for scattering with and without visible interaction tracks.

The value of the cross section σ_u calculated with n included a small correction connected with the fact that N_4 actually included elastic scatterings, since backward elastic scattering always gave some contribution, even though small. This contribution could be estimated with enough accuracy for our purposes from the results of recent work by other authors. For π energies of 80 Mev there exist data for elastic scattering on carbon and aluminum at angles up to 110° (reference 3). Elastic scattering on carbon at 150 Mev has been measured up to 140° (reference 4). One can judge from the results of these two papers that the backward elastic scattering cross section comprises about 5% of the inelastic processes cross section at a pion energy of 80 Mev and fall to 1% at 150 Mev.

The results of the calculation of σ_u are given in Table II. The results of calculating the inelastic cross section σ_i according to the number of interactions $N_2 + (1+\alpha)N_4$, with a correction for elastic backward scattering are also given there. All cross sections are calculated for the mixture of C, F, and Cl which we had in our chamber (20% carbon, 49% fluorine, 31% chlorine). The average geometrical cross section of this mixture is 485 mb, assuming that the nuclear radius is $1.4\,A^{1/3}\,10^{-13}$ cm.

Let us compare the data we obtained with the results of other authors. The cross sections for the inelastic interactions of π^+ and π^- mesons at energies close to ours have been measured for light elements, chiefly carbon, by the methods of scintillation telescopes,[5,6] Wilson chambers in a magnetic field,[7] and propane bubble chambers.[8] The comparison of the data for total inelastic scattering cross sections is given in Table III.

TABLE II

π^+-meson energy, Mev	σ_u, mb	σ_u in units of the average geometrical cross section	σ_i, mb	σ_i in units of the average geometrical cross section
79	344±44	0.71±0.09	125±32	0.26±0.07
103	415±44	0.86±0.09	140±30	0.29±0.06
132	525±49	1.08±0.10	229±36	0.47±0.07
154	568±48	1.17±0.10	223±33	0.46±0.07
175	567±43	1.17±0.09	255±34	0.53±0.07
195	573±40	1.18±0.08	250±31	0.52±0.06
220	505±43	1.04±0.09	215±30	0.44±0.06
241	464±37	0.96±0.08	206±27	0.42±0.06
262	462±34	0.95±0.07	191±23	0.49±0.05
282	442±31	0.91±0.06	196±24	0.40±0.05

TABLE III

Pion energy, Mev	Element	σ_u in millibarns	σ_u in units of the geometrical cross section	Reference
216	C	350±24	1.08±0.07	[5]
225	C	346±21	1.07±0.07	[6]
225	Al	596±30	1.07±0.05	[6]
230	C	307±37	0.95±0.11	[7]
256	C	326±31	1.01±0.10	[5]
260	C	296^{+35}_{-28}	$0.92^{+0.11}_{-0.09}$	[8]
290	C	269±26	0.83±0.08	[5]

Comparing the cross sections given in Table III with our data for nearby energy points (Table II), we see a good agreement of the results for the total cross sections for inelastic interactions as expressed in units of the geometrical cross section. In the work of Wang Kan-Chang et al.[8] there was also measured the cross section for inelastic scattering for carbon at a pion energy of 260 Mev, which turned out to be 120^{+38}_{-19} mb or $(0.37^{+0.12}_{-0.06})\,\sigma_g$ (σ_g is the geometrical cross section). This quantity agrees within the limits of error with our value, $\sigma_i = (0.49 \pm 0.05)\,\sigma_g$ measured at 262 Mev (Table II).

COMPARISON OF THE EXPERIMENTAL RESULTS WITH THEORY

To compare our results with theory we shall use the optical model of the nucleus. Here one must bear in mind that in the basic work on the optical model,[9] the expressions for the cross sections of inelastic and elastic processes were obtained under the assumption of a uniform distribution of charge in the nucleus. It is well known, however, that experiments on high-energy electron scattering[10] agree best with the nuclear model in which the charge density ρ is described by the Fermi function

$$\rho(r) = \rho(0) \Big/ \left[1 + \exp\left(\frac{r-c}{z}\right)\right], \tag{1}$$

where $c = 1.08\,A^{1/3}\,10^{-13}$ cm and $z = 0.53 \times 10^{-13}$ cm. Expressions for the interaction cross sections using distribution (1) were obtained in the work of Cronin et al.[11] It is evidently interesting; in comparing the experimental values of the cross sections with theory, to carry out calculations for the two cases: for a homogeneous distribution and for the Fermi distribution.

For a homogeneous charge distribution in the nucleus we have[9]

$$\sigma_u = \pi R^2 \left[1 - \frac{1-(1+2kR)\,e^{-2kR}}{2k^2R^2} \right], \qquad (2)$$

where R is the radius of the nucleus and k is the coefficient of absorption. For positive pions the quantity k is connected with the cross sections for the interaction of pions with nucleons in the following way (without taking into account the Pauli principle)

$$k = \frac{\rho}{A}\left[Z\sigma^{+}_{\pi p} + (A-Z)\,\sigma^{-}_{\pi p}\right], \qquad (3)$$

where $\sigma^{+}_{\pi p}$ and $\sigma^{-}_{\pi p}$ are the total cross sections for the interaction of positive and negative pions with protons.

If the charge density in the nucleus follows the Fermi distribution, we get the expression[11]

$$\sigma_u = 2\pi \int_0^\infty \{1 - \exp[-2\bar{\sigma}\rho(0)\,S(b)]\}\,b\,db, \qquad (4)$$

where $\bar{\sigma} = [Z\sigma^{+}_{\pi p} + (A-Z)\sigma^{-}_{\pi p}]/A$, and the function S(b) is calculated in the paper by Cronin et al. for various values of the parameter c.

The experimental values of the cross sections $\sigma^{+}_{\pi p}$ and $\sigma^{-}_{\pi p}$, necessary to calculate k and $\bar{\sigma}$, were taken by us from the work of Anderson.[12] In calculating σ_u by (2) we set $R = 1.4\,A^{1/3}\,10^{-13}$ cm; σ_u was calculated by (4) with the parameter value $c = 1.08\,A^{1/3}\,10^{-13}$ cm, which follows from the electron scattering experiments.[10] In addition, the values of σ_u were increased by the factor $(1 - Ze^2/RE_\pi)$ in order to take into account the Coulomb interaction of the π^+ mesons with the protons inside the nucleus.[13]

The results of the σ_u calculations are shown in the figure. The experimental values of σ_u found in our work (Table II) are also shown there. As follows from the figure, these values satisfy the theoretical curve I, using the Fermi distribution, much better than curve II, calculated assuming a homogeneous charge density in the nucleus.

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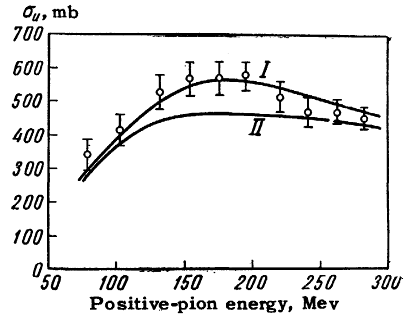

Dependence of the positive-pion inelastic scattering cross section on energy. Theoretical curves: I – Fermi distribution, II – homogeneous charge distribution.

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192