SOVI ET PHYSICS JETP VOLUME 4, NUMBER 6 JULY,1957

Production of Postive π-Mesons in Various Nuclei by 660 mev Protons

A. G. MESHKOVSKII, IU. S. PLIGIN,
IA. IA. SHALAMOV AND V. A. SHEBANOV

(Submitted to JETP editor August 15,1956)
J. Exptl. Theoret. Phys. (U.S.S.R.) 31, 987-992 (December, 1956)

We measured the energy spectrum of π^+-mesons produced at 45° to the incident beam by 660 mev protons incident on Li, Be, C, Al, and Cu. The cross section $d\sigma/d\Omega$ for π^+ formation in these elements is calculated, and conclusions drawn from the fact that all the spectra are similar. The differential cross section $d^2\sigma/d\Omega dE$ for production of π^+-mesons was measured at 158 mev in Ag and Pb. Conclusions are drawn about the dependence of the π^+-mesons production cross section on atomic weight for elements between Li and Pb. For elements between Li and Al the dependence is given by $d\sigma/d\Omega = (1.17 \pm 0.05)\, A^{2/3}$. Considerably fewer π^+-mesons than indicated by this formula are produced in elements after Cu.

1. INTRODUCTION

CHARGED π-mesons are produced when high energy protons are incident on complex nuclei. The relation between the number of π-mesons produced and the number of nucleons in the nucleus has been investigated by several authors[1–6] for proton energies in the range 240–380 mev and for various elements from beryllium to lead. These investigations showed that in the energy range considered, the yield of charged π-mesons does not increase in proportion to A, the number of nucleons, but rises as $A^{2/3}$ or even more slowly.

The production of π^+ and π^--mesons in seven elements from Be to Pb by 240 mev protons has been investigated in Refs. 1,2. It was established that the yield of π^+-mesons emitted at angles of 130–150° and with energies 20–40 mev varies approximately as $A^{2/3}$ for elements from Be to Cu inclusive. The yield of π^+-mesons from heavier elements (Ag, W and Pb) is considerably smaller than indicated by the $A^{2/3}$ law. Similar statements hold for 40 mev π-mesons emitted at angles of 30–50°.[2]

The results with 340 mev protons incident on a series of elements are qualitatively the same for 53 mev π^+-mesons emitted at 0°[3] and for 33 mev π^+-mesons at 90°.[4] The yield of π^+-mesons with energies 52, 88 and 147 mev emitted at 0° from C, Cu, and Pb bombarded by 340 mev protons was also measured.[5] If these latter results are normalized relative to carbon, the π^+-meson yield from Cu and Pb is again less than would be indicated by the $A^{2/3}$ law. π-meson production at 90° by 381 mev protons incident on C, Cu and Pb has been investigated over the whole π^+-meson energy range.[6] Qualitatively, the results were the same as in the above mentioned papers.

Thus, when protons of various energies from 240–380 mev interact with complex nuclei, charged π-mesons are produced essentially by collisions with surface nucleons ($A^{2/3}$ law). Departures from the $A^{2/3}$ law in the direction of fewer π-mesons for elements after Cu is presumably due to a decrease in the transparency of the nucleus with increasing atomic weight.

The purpose of the present work was to investigate the production of π^+-mesons in complex nuclei by protons of considerably higher energy than used by previous authors.

2. PROCEDURE

Our experiments were performed with the external proton beam of the synchrocyclotron of the Institute for Nuclear Problems of the Academy of Sciences, USSR. The π-mesons were detected and their energy measured by a magnetic method we have described previously.[7]

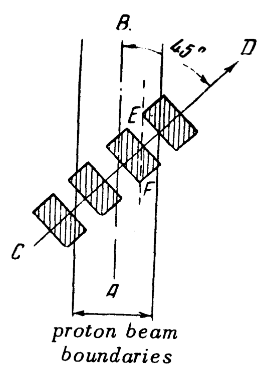

FIG. 1. Construction of the targets.

All measurements were taken at 45° to the incident beam of 660 mev protons. The angular spread in the π-mesons observed was no more than $\pm 1^{\circ}$. The solid angle defined by the scintillation counter telescope was 2.5×10^{-4} steradian. The momentum resolution varied from 4 percent at $p = 400$ mev/c to 10 percent at $p = 150$ mev/c.

As indicated in our previous paper[7], some preliminary experiments were necessary to estimate the electron background due to neutral π-mesons produced in the targets. To do this, the magnetic field was adjusted so that negative particles reached

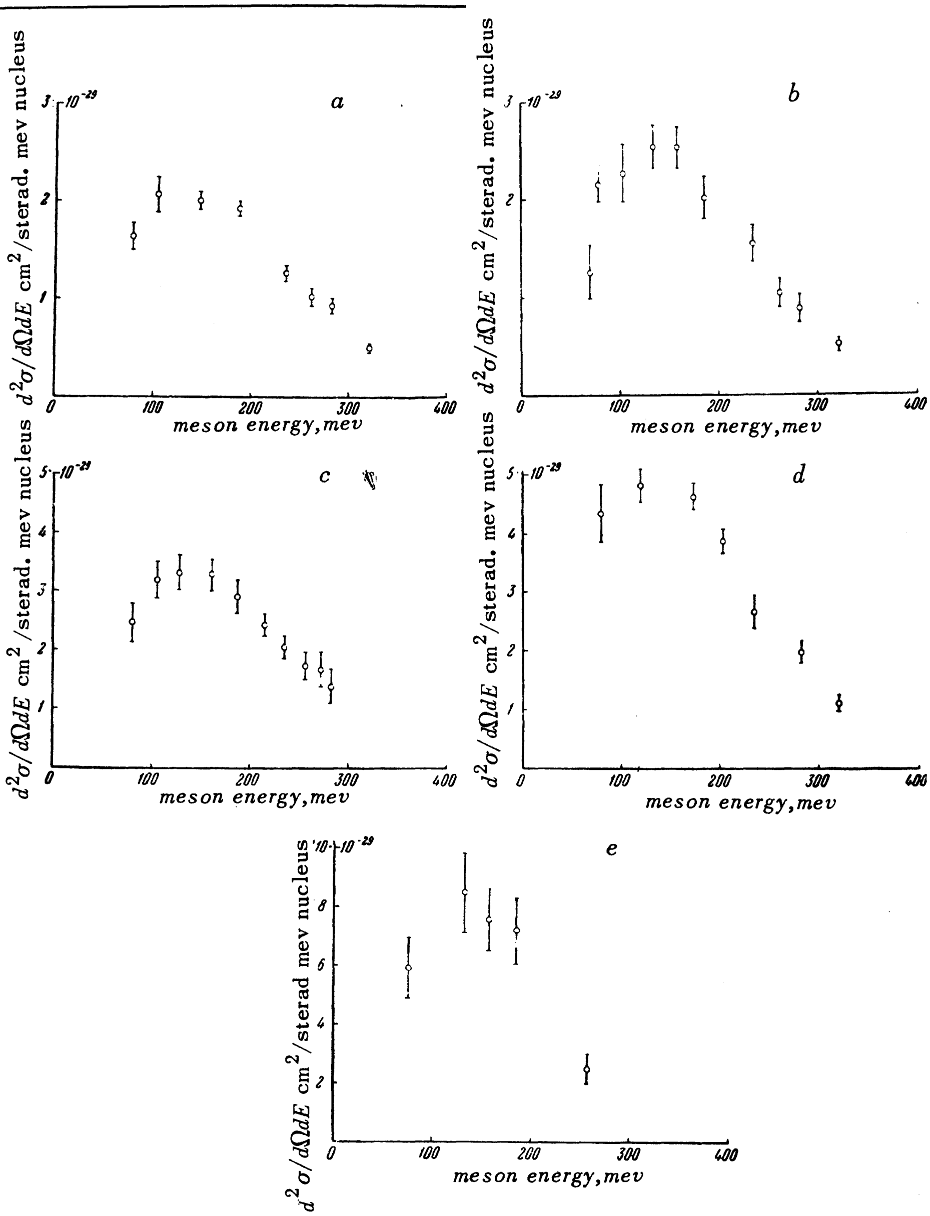

FIG. 2. π^+-meson spectra. a—lithium, b—beryllium, c—carbon, d—aluminum, e—copper.

the counter telescope, and then a paraffin target compared with a carbon one. The paraffin and carbon targets were of the same length (in atomic units) along the direction in which the π-mesons to be counted would be moving. We concluded that the electron background in our apparatus could not be larger than 2–3%. In order that the electron background be no larger during the actual experiments, the target thicknesses (in atomic units) along the direction in which the π-mesons to be counted were going were made the same as the thickness of the paraffin target in the control experiments.

TABLE I

Lithium		Beryllium		Carbon	
Meson energy, mev	$\frac{d^2\sigma}{d\Omega dE}\cdot 10^{29}$	Meson energy, mev	$\frac{d^2\sigma}{d\Omega dE}\cdot 10^{29}$	Meson energy, mev	$\frac{d^2\sigma}{d\Omega dE}\cdot 10^{29}$
79	1,65 ± 0.13	71	1.25 ± 0,27	80	2,49 ± 0.33
104	2,07 ± 0,18	79	2.15 ± 0.18	105	3,21 ± 0,29
146	2.00 ± 0,09	104	2,26 ± 0,29	128	3,32 ± 0,30
186	1.92 ± 0,07	134	2.53 ± 0.22	161	3.31 ± 0.27
234	1,26 ± 0.08	159	2,52 ± 0.21	187	2.94 ± 0.30
261	1,02 ± 0,09	186	2,01 ± 0.22	215	2,47 ± 0.18
282	0.93 ± 0,08	234	1,54 ± 0.19	235	2.10 ± 0,20
320	0.50 ± 0.04	261	1.04 ± 0.15	257	1.78 ± 0.24
—	—	282	0,88 ± 0,14	272	1.72 ± 0,31
—	—	320	0.51 ± 0,06	283	1.43 ± 0.30

Aluminum		Copper	
Meson energy, mev	$\frac{d^2\sigma}{d\Omega dE}\cdot 10^{29}$	Meson energy, mev	$\frac{d^2\sigma}{d\Omega dE}\cdot 10^{29}$
78	4,34 ± 0,50	77	5,92 ± 1.04
119	4,80 ± 0,28	133	8.47 ± 1,38
172	4.62 ± 0,26	158	7.56 ± 1,13
202	3,84 ± 0.23	185	7.14 ± 1,18
234	2.65 ± 0.29	257	2.49 ± 0.50
282	1.98 ± 0,20	—	—
320	1.02 ± 0,13	—	—
—	—	—	—
—	—	—	—
—	—	—	—

TABLE II

Element	Li	Be	C	Al	Cu
Cross section for production of π^+-mesons $(d\sigma/d\Omega)\times 10^{27}$ in cm^2 sterad^{-1}, calculated per nucleus	4,24±0,32	4,91±0,45	6,77±0,62	9,79±0,85	14,45±1,86

Seven elements were used as targets: lithium, beryllium, carbon, aluminum, copper, silver and lead. The lithium target was in the form of a solid slab 1 cm. thick. Targets of the other elements were made of several layers, as shown in Fig. 1. *AB* is the direction of the collimated proton beam, *CD* the direction in which π-mesons had to move to be counted in the telescope The plane of the drawing was horizontal and the cross-hatched rectangles represent the cross sections of the layers. The distance between layers was adjusted so that the dotted line *EF* was parallel to *AB*. This arrangement ensured that all protons travelled the same distance in the target, irrespective of where they hit it. The number of layers and the thickness of each was chosen so that the number of radiation lengths in the direction *CD* was the same for targets of each element.

The condition that all targets have the same number of radiation lengths in the direction *CD* limited the amount of matter exposed. As a result for the heavier elements relatively few π-mesons were counted in our apparatus. Hence in the runs with silver and lead, we measured the π^+-meson yield at only one meson energy. For the other elements, differential spectra were obtained for π^+-mesons in the energy range 70 to 320 mev.

3. RESULTS

Table I shows our results on the differential cross section for production of π^+-mesons at 45° in Li, Be, C, Al, and Cu by 660 mev protons. For each π^+-meson energy, in mev, the Table gives the corresponding differential cross section $d^2\sigma/d\Omega dE$ in cm^2 sterad^{-1} mev^{-1} per nucleus.

The π^+-meson yield from Ag and Pb was measured at a meson energy of 158 ± 5 mev. $d^2\sigma/d\Omega dE$ (per nucleus) was (7.90 ± 1.33) × 10^{-29} cm^{2}sterad mev^{-1} for Ag and (7.62 ± 1.43) × 10^{-29} cm^{2}sterad^{-1}

mev^{-1} for Pb.

The data of Table I are plotted in Fig. 2. The errors shown in both figure and Table are only the statistical errors. Systematic errors, amounting to $\pm 5\%$, are taken into account in integrating the spectra, i.e., in calculating $d\sigma/d\Omega$.

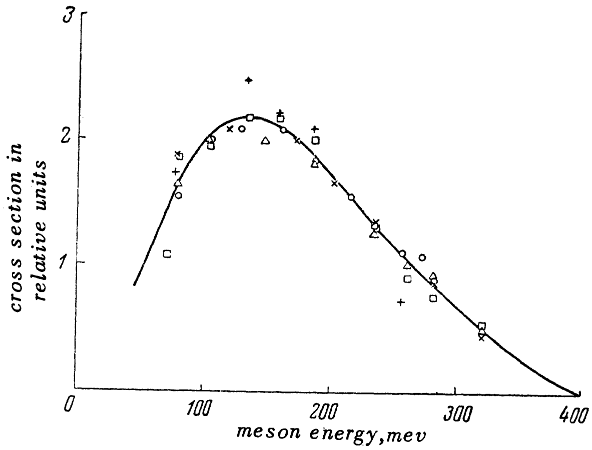

FIG. 3. Results for Li,Be,C,Al and Cu, all drawn to the same scale. Δ–Li, $\square$–Be, O–C, $\times$–Al, +–Cu.

Table II gives the integrated spectra. In calculating the entries in Table II, the high energy cut off for the spectra was taken to be 390 mev. This was the maximum energy a π-meson could have under our experimental conditions, and was calculated on the assumption that nucleons in a nucleus have an energy of 25 mev.

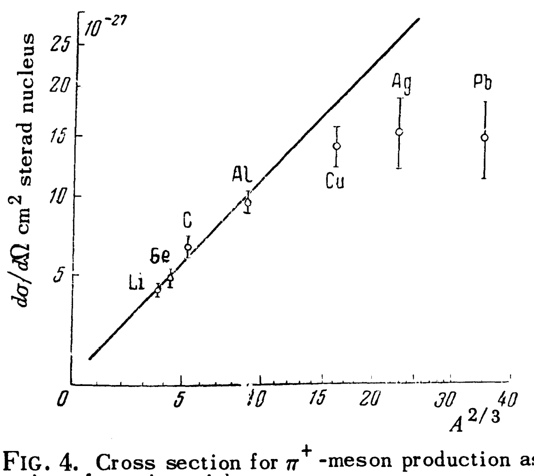

FIG. 4. Cross section for π^+-meson production as a function of atomic weight.

4. DISCUSSION OF RESULTS

The fundamental point about our spectra is that they are similar, as is evident from Fig. 2. This is particularly clear if the spectra are all plotted on the same scale, as is done in Fig. 3. The curve in Fig. 3 is drawn to fit all the experimental points best. This it does quite well, for no experimental point deviates from the curve by more than the statistical error associated with the point. The latter are not shown on the Figure to avoid confusion.

As mentioned in Sec. 3, the maximum meson energy in our set-up was calculated to be 390 mev. Extrapolation of the curve in Fig . 3 to high energies agrees well with this value.

Figure 3 shows that when the elements we investigated are bombarded by 660 mev protons, the cross section for π^+-meson production at 45° reaches a maximum at about 140 mev. Under similar experimental conditions the yield of π^+-mesons from the reaction $p + p \to \pi^+ + p + n$ attains a maximum at about the same energy (in the laboratory system). This was shown by us in a previous paper.[7]

If we assume that the meson spectra are about the same in Ag and Pb as they are for the lighter elements, then we can use our measured values of $d^2\sigma/d\Omega dE$ at 158 mev for Ag and Pb to calculate the cross section at 45° for these elements. The value turns out to be $(16.05 \pm 3.39) \times 10^{-27}$ cm^2 sterad^{-1} for Ag and $(15.48 \pm 3.52) \times 10^{-27}$ cm^2 sterad^{-1} for Pb.

The dependence of the π^+-meson production cross section on atomic weight is illustrated in Fig. 4. Here the abscissa is $A^{2/3}$, while the ordinate is the cross section $d\sigma/d\Omega$. The relation $d\sigma/d\Omega = kA^{2/3}$ corresponds to the straight line, which was drawn to give a least squares fit to the first four points. The slope of this line is $k = 1.17 \pm 0.05$. Figure 4 also shows the points for Ag and Pb, calculated by the method described above. If the meson spectra for Ag and Pb were not really similar to the other spectra, as we have assumed them to be, then it is possible that our values for $d\sigma/d\Omega$ differ from the true ones. In this case the points for Ag and Pb indicated on the graph give the dependence of the π^+-meson yield on atomic weight for a definite meson nnergy (158 mev in our case).

From the above discussion it appears that the dependence of π^+-meson yield on atomic weight is generally the same at 660 mev proton energy as at lower proton energies (240–380) mev. Since the first four points (Fig. 4) lie on the straight line $kA^{2/3}$, we can conclude that in the elements from Li to Al π^+-mesons are produced on the surface of the nucleus. At larger atomic weights, the π^+-meson yield is less than that given by the $A^{2/3}$ law (cf. the points for Cu, Ag and Pb). This is presumably due to an increase in the absorption of protons and charged π-mesons by nuclear matter.

1 D. Clark, Phys. Rev. **81**, 313 (1951).
2 D. L. Clark, Phys. Rev. **87**, 157 (1952).
3 Hamlin, Jakobson, Merritt and Schulz, Phys. Rev. **84**, 857 (1951).
4 R. Sagane and W. Dudziak, Phys. Rev. **92**, 212(1953).
5 J. Merritt and D. A. Hamlin, Phys. Rev. **99**, 1523 (1953).
6 Block, Passman and Havens, Phys. Rev. **88**, 1239 (1952).
7 Meshkovskii, Pligin, Shalamov and Shebanov, J. Exptl. Theoret. Phys. (U.S.S.R.) **31**, 560 (1950); Soviet Phys. JETP **3**, 426 (1956).

Translated by R. Krotkov
212