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MEASUREMENT OF TOTAL CROSS SECTION FOR CHARGED PION PRODUCTION IN (n-p) COLLISIONS AT NEUTRON ENERGY 586 MEV

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A B S T R A C T

The total yield of the charged pions produced in (n-p) collisions at the effective neutron energy 586 MeV has been measured in the laboratory angle range from 15^o up to 120^o. The total cross section for positive and negative pion production which was found from the obtained data under the assumption of charged symmetry of nuclear forces is

$$\sigma(np \to \pi^+) = \sigma(np \to \pi^-) = (2,20 \pm 0,44) \cdot 10^{-27} cm^2 .$$

The process of charged pion production in neutron-proton collisions has not been studied in detail. The sufficiently complete investigation has been carried out only at the neutron energy 409 MeV[1/]. At the energy close to 600 MeV only one research has been performed earlier.[2/] In this research the method of nuclear emulsions was used. The spectra and yields of positive and negative pions outgoing at the angle $\phi = 90^{o*}$ (lab.system) from the liquid hydrogen target irradiated by the neutrons from the 670 MeV proton "charge-exchange" have been measured. The comparatively small cross section for meson production, three particles in the finite state of the reactions under investigation, and the non-monoergic neutron beam used in the experiments create great difficulties in the study of the positive and negative pion production in (n-p) collisions. Nevertheless, the detailed study of (n-p) collisions at the nucleon energies which considerably exceed the threshold for meson production requires the investigation of these prodess. The study of meson production in neutron-proton collisions is also of interest from the standpoint of in-

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* The angle ϕ is measured with respect to the direction of neutron beam incident on the target.

vestigating the nucleon-nucleon interaction in different isotopic spin states (T = 0 and T = 1).

EXPERIMENTAL ARRANGEMENT

The measurements were made at the synchrocyclotron of the Joint Institute for Nuclear Research. The neutron beam used in these experiments was obtained by the charge exchange scattering of the 680 MeV protons on the berrilium target. The energy distribution of neutrons in the beam has the maximum at the energy 600 MeV and the half-width 130 MeV.[3]

To determine the diffrerential cross section for the charged pion production in (n-p) collisions the ratio of the total number of positive and negative pions N_π to the number of the recoil protons N_p emerged from the polyethelene target at the given angle φ as a result of (n-p) collisions has been measured. Then the differential cross section for pion production has been found by the obtained ratio and by the differential cross section of elastic (n-p) scattering measured by the authors earlier.[4]

To measure the pion yield the polyethelene and graphite targets were placed in the neutron beam. The charged particles emerged from the targets were detected. The diffrence of the numbers of particles detected from the polyethelene and graphite targets gives the total flux of the charged particles emerged from the target as a result of (n-p) collisions. The estimate has shown that this flux is mainly determined at the given neutron energy by the number of the recoil protons and pions incident on the detector.

It turned out that the admixture of muons and β-particles which appear as a result of pion decay under the experimental conditions does not exceed 10-15% of the number of pions. This made it possible to neglect the admixture of μ and β-particles and to regard in the first approximation all the particles different from the recoil protons to be pions. The corresponding corrections are introduced into the results of the measurements further.

The separation of pions and recoil protons was made either by the ranges or by the velocities. The range separation was used at the angles $\phi \gg 60^{\circ}$

At the angles $60<\phi<15^{\circ}$ the pion separation was made by velocities.

In accordance with the two above-mentioned ways of pion separation two types of detectors were used (Table 1). The usual telescope of three scintillation counters in coincidence was used as a detector, at large angles $\phi \geqslant 60^{\circ}$. The estimates made by the data[2/] have shown that at the angles $\phi \geqslant 60^{\circ}$ this detector counted the overwhelming majority of pions even if the threshold of the telescope was increased up to the maximum energy of the recoil protons by means of the absorber.

To measure the yield of the charged mesons at the angles $\phi < 60^{\circ}$ the separation of pions was made by velocity selecting. For this the second counter of the telespope was replaced by a Cerenkov counter. (Fig. 1). Other counters were scintillation ones. To determine the total yield of the charged particles it became necessary to replace the Cerenkov counter of the detector for the scintillation one. Jn order that the geometry of the detector does not change when replacing the counters and the replacement may be done quickly both counters had only one photomultiplier FEU-19-M. The phosphorus of the scintillation counter was placed before the photocathode just behind the radiator of the Cerenkov counter. At the angle ϕ = 15^{0} the recoil protons of the maximum energy may be detected by the Cerenkov counter. In this case the correction which takes into account the fraction of the detected protons was introduced. The geometry of the detector provided for the angular resolution 3^{0}. The energetic thresholds of the detector at different angles are given in Table 1.

Table I

Angle of pion output (lab.sys). ϕ	Energetic threshold of the detector for pions (MeV)	Notes
15^{0}	78,0	The detector is a Čerenkov counter (water) and two scintillation counters in concidence
30^{0}	78,0	
45^{0}	78,5	The detector is a Čerenkov counter(plexiglass) and two scintillation counters connected in coicidence.
60^{0}	65	The detector is three scintillation counters connected in concidence.
90^{0}	37	
120^{0}	37	

The polyethelene and graphite disks with the equal stopping power served as scatterers. The polyethelene scatterer was 0.9 g/cm^2 thick at the angles $\phi > 45^\circ$ and 3.2 g/cm^2 at the angles 45°. Copper and tungsten plates were used as absorbers.

In accordance with the above-mentioned the measurements were made in the following way. First of all under the conditions of the experiments on the measurement of the differential elastic (n-p) scattering cross section[4/] the total flux of charged particles which were incident on the detector at the given intensity of the beam as a result of (n-p) collisions has been determined. A usual difference experiment CH_2 -C was arranged. Then the detector was placed under the conditions when the recoil protons were not detected and the total pion yield was measured. The regime of the detector necessary for this was achieved as it was mentioned above either by increasing the telescope threshold up to the maximum energy of the recoil protons (the measurements at the angles $\phi > 60^\circ$), or the replacement of the second telescope counter for the Čerenkov counter. When determining the pion yield at the angles 15°, 30°, 45°, a special attention in the experiment was paid to the measurement of the background. Except the usual measurments of the background from the real and accidental coincidences it became necessary to measure the background which was due to the fact that the detector detected an appreciable fraction of the recoil protons incident just on the photocathode of the photomultiplier of the Cerenkov counter. At the angle of 60° the general background was less than 5% and grew up to 20% of the number of mesons incident on the detector from the polyethelene target at the angle of 15^{o}.

The constancy of the neutron beam intensity during the measurements was controled with the help of the ionization chamber placed in the beam and connected with the integraing circuit. (Fig.1).

RESULTS AND THEIR TREATMENT

The determination of the total cross section. Before the results of the measurements might be used for the determination of the total cross section for pion production, the following corrections are necessary:

I. The correction for the admixture of μ -mesons and electrons. As was pointed out earlier, among the charged particles incident into the detector besides protons and pions there were present μ -mesons and electrons in small quantity. The number of electrons detected by the detector together with pions was determined by computing in accordance with the data[5] under the assumption that the angular distribution of π^{o}-mesons in the c.m.s. of the colliding nucleons is $0,2 + \cos^2\vartheta$. It was also taken into account that about 1.5% of the total number of π^{o}-mesons decays according to the second mode of decay. The admixture of μ -mesons was evaluated according to the known pion yield and to the calculated angular distribution of μ -mesons.

2. The correction for the proton admixture. It was introduced only at the angle of 15^{o} where the most energetic recoil protons may be detected by the Cerenkov counter. The correction

was determined by the known neutron spectrum and by the found dependence of the Cerenkov counter efficiency upon the velocities of particles. (Fig. 2).

3. The corrections for the presence of particles in pion spectrum the energies of which are below the detector threshold. These corrections were determined by the pion spectra calculated according to the data[2] under the assumption that the pion spectrum in the c.m.s. of the colliding nucleons does not depend upon the angle of the meson output. The calculated correction coefficients are given in the third line of Table 2. These coefficients were calculated again also under the assumption that the pion spectra from the reactions $P + P \rightarrow \pi^{+} + n + p$ and $n + p \rightarrow \pi^{+} + 2n$, $n + p \rightarrow \pi^{-} + 2p$ are identical.* The magnitudes practically coinciding with those given in Table 2 have been obtained.

4. The corrections for the recording efficiency due to the different absorption of pions and protons in the detector absorber and to the inefficiency of the Cerenkov counter. The magnitudes of the corrections were determined experimentally on the beams of pions and protons of the corresponding mean energies.

5. The corrections for $/\pi - \mu/$ decay. The correction coefficients are calculated according to the known pion lifetime, the spectra found under the above-mentioned assumptions in 3 being taken into account.

Strictly speaking, when considering the results of the measurements it would have been necessary to take also into account

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* This is likely to occur at the energies considerably exceeding the meson production threshold, see, e.g. /6/

the error which is due to somewhat different probability of the absorption of positive and negative pions in matter. The estimate made by the data|7|, however, shows that the error due to the above mentioned circumstance is very small under the conditions of the experiment and may be neglected.

The corrected results after the integration over angles provided the charge symmetry of the nuclear forces give the value

$$\sigma(np \rightarrow \pi^{+}) = \sigma(np \rightarrow \pi^{-}) = (2{,}0 \pm 0{,}5)\,10^{-27}\,cm^{2}$$

for the total cross section of positive and negative pion production in (n-p) collisions

T a b l e 2.

Angle φ^{o}	15	30	45	60	90	120
Correction for admixture of muons and electrons	0,9	0,9	0,9	0,92	0,90	0,88
Correction for proton admixture	0,15					
Correction for pions with the energy below the detector threshold					1,25	1,95
Correction for recording efficiency	1,21	1,21	1,20			
Correction for decay	1,03	1,03	1,03	1,04	1,06	1,1
N_{π}/N_{p} % %	8,6±3,5	19±2,3	13,7±2,7	9,7±0,5	44±1,3*	4,3±±0,9*

* Pion yield is determined with respect to the yield of the recoil protons at $\varphi = 60^{o}$.

Apart from this, the total cross sections of the reactions under investigation may be determined also by the pion yield found for the so-called "isotropic" angle[8], i.e., the angle for which there exist the ratio

$$\sigma_{\pi}(\vartheta_{i}) = \frac{1}{4\pi}\,\sigma_{np}(np \to \pi^{+})$$

between the differential cross section $\sigma_{\pi}(\vartheta)$ and the total cross section. The "isotropic" angle ϑ_{i} may be easily found if one takes into account according to the obtained data that the angular distribution of pions (in the c.m.s.) is unlikely to involve the terms higher than $\cos^{2}\vartheta$ and may be written in a form:

$$\sigma_{\pi^{+}}(\vartheta) = \sigma_{\pi^{-}}(\vartheta) = a + b\cos^{2}\vartheta$$

where ϑ is the angle of outgoing meson, a and b are the constants, ϑ_{i} is known to be equal to arccos $\frac{1}{\sqrt{3}}$ and corresponds in our case to the angle $\varphi = 30^{0}$ (lab.sys). If onemakes use of the magnitude $\frac{N_{\pi}}{N_{p}}$ for this angle given in Table 2, then the total cross section is found to be equal to

$$\sigma(np \to \pi^{+}) = \sigma(np \to \pi^{-}) = (2,20 \pm 0,44)\,10^{-27}\,cm^{2}$$

The obtained galues of the cross sections are rather close to each other. This is very likely to point out that the assumtpions under which the above-mentioned values have been obtained do not introduce any serious distortions into the pion angular distribution.

<u>The determination of the effective energy.</u> In the method of the measurments employed the detector detected the pions produced in collisions of particles the energies of which

changed in a rather wide energy range from 300 up to 670 MeV. The problem about the determination of the mean effective energy. E_{eff} was therefore of special interest. To determine E_{eff} its dependence upon the form of the excitation function of the investigated reaction at the given form of the energetic neutron spectra has been found. The excitation function was taken in the form[9].

$$\sigma(np \rightarrow \pi^+) \sim \eta_{max}^{n} \tag{9}$$

where η_{max} is the maximum value of the pion momentum in the c.m.s. It has been found that under the given conditions the mean effedtive energy for the exponents $n > 3$ in Eq. 1 is practically constant and does not depend upon n (Fig. 2). Taking this into account by the known value of $\sigma(np \rightarrow \pi^+)$ at the neutron energy 409 MeV we have found that in our case the mean effective energy is equal to (586 ± 15) MeV.

DISCUSSION OF THE RESULTS

The comparison of the obtained value $\sigma(np \rightarrow \pi^+) = (2,2 \pm 0,44)\, 10^{-27}\, cm^2$ with the cross section found at the energy 409 MeV[1] $\sigma(np \rightarrow \pi^+) = (0,16 \pm 0,04)\, 10^{-27}\, cm^2$ shows that the total cross section for positive and negative pion production in (n-p) - collisions increases more than ten times with the energy increase from 409 up to 586 MeV. It turnes out that the dependence of the cross section upon the maximum pion momentum η_{max} may be written in the form

$$\sigma(np \rightarrow \pi^+) \sim \eta_{max}^{5 \pm 0,6}$$

This dependence is in good agreement with the dependence $\sigma(np \to \pi^+) \sim \eta_{max}^{4+1}$ found in/10/ which was obtained on the basis of the values of the cross sections calculated in a wide energy range by the known cross sections $\sigma(np \to \pi^+)$, $\sigma(pp \to \pi^0)$ and $\sigma(pn \to \pi^0)$ under the assumption of charge independence of nuclear forces. It is to be noted, however, that for $\sigma(pn \to \pi^+)$ at 580 MeV the authors/10/ give somewhat low value $(0,8 \pm 1,1)\ 10^{-27} cm^2$ which, nevertheless, within the above-mentioned errors does not contradict to the magnitude obtained in this paper.

The value determined is also in satisfactory agreement with the hypothesis of isotopic invariance. Really, according to this hypothesis

$$\sigma(np \to \pi^+) = \sigma(np \to \pi^0) + \sigma(pp \to \pi^0) - \tfrac{1}{2}\sigma(pp \to \pi^+)$$

(##)

If assume $\sigma(np \to \pi^0) = (5,7 \pm 1,5)\ 10^{-27} cm^2$ /5/

$\sigma(pp \to \pi^0) = (1,6 \pm 0,2)\ 10^{-27} cm^2$ /10/ and $\sigma(pp \to \pi^+) = (8,5 \pm 0,7)\ 10^{-27} cm^2$ /11/.

then it turnes out that $\sigma(np \to \pi^+) = (3 \pm 1,6)\ 10^{-27} cm^2$ what within the limits of the above-mentioned accuracy coincides with the measured magnitude.

As is known/9/ according to the hypothesis of charge independence ~~according to~~ the cross sections of all the processes of pion production in nucleon-nucleon collisions are experessed in terms of the three partial cross sections σ_{10}, σ_{11}, σ_{01} x/. σ_{11} and σ_{10} and in the wide energy range have been studied in/10/. The obtained magnitude of the cross section $\sigma(np \to \pi^+)$ makes it possible to determine σ_{01} at the energy 586 MeV:

$$\sigma_{01} = 2\sigma(np \to \pi^+) - \sigma_{11} = (2,8 \pm 0,9)\, 10^{-27}\ cm^2$$

It is also known[10] that at 409 MeV $\sigma_{01} = (0,23 \pm 0,09) \times 10^{-27}\ cm^2$

Thus, σ_{01} sharply increases with the energy increase whereas the dependence σ_{01} upon the maximum meson momentum is given by

$$\sigma_{01} \sim \eta_{max}^{4,7 \pm 0,8}.$$

The total cross section for pion production in (n-p)- collisions at 586-590 MeV is $\sigma(np \to \pi^{\pm,0}) =$

$$= \sigma(np \to \pi^0) + 2\sigma(np \to \pi^+) = (10,1 \pm 1,7)\ 10^{-27}\ cm^2$$

The total cross section of (n-p) - interaction is equal to $(36 \pm 2)10^{-27}$ cm^2. Therefore, in approximately 30% of the cases the collision of a neutron with a proton leads to the production of a pion.

In conclusion making use of the obtained magnitude and of the data from[5,10,11] let us compare the probabilities of pion production in the nucleon-nucleon interaction in different isotopic spin states. ~~It may be~~ It may be shown[12] that the total cross section for pion production in (n-p) collisions

$$\sigma(np \to \pi^{\pm,0})$$

may be written in the form

$$2\sigma(np \to \pi^{\pm,0}) = \sigma_\pi^1 + \sigma_\pi^0 \qquad (3)$$

where σ_π^1 and σ_π^0 are the cross sections for pion production in nucleon-nucleon collision in the states with the isotopic spin T = 1 and T = 0, respectively. Assuming from the values given earlier

$$\sigma_{n} = \sigma(pp \to \pi^{0}) + \sigma(pp \to \pi^{+}) = (10,1 \pm 0,73)\ 10^{-27}\ cm^{2}$$

$$\sigma(np \to \pi^{\pm,0}) = 2\sigma(np \to \pi^{+}) + \sigma(np \to \pi^{0}) = (10,1 \pm 1,82)\ 10^{-27}\ cm^{2}$$

from (3) one may obtain that

$$\sigma_{\pi}^{0} = (10,1 \pm 3,7)\ 10^{-27}\ cm^{2}$$

So, in the nucleon interaction in the states with T = 0 and T = 1 pion production occurs with approximately equal probability and, thus, the nucleons in these states interact in this sense with identical intensity.

The approximate equality of σ_{π}^{0} and σ_{π}^{1} indicates also that in the processes investigated at the energy close to 600 MeV the transitions as a result of which the pion-nucleon system turns out to be in the states with the total isotopic spin T = 3/2 and T = 1/2 occur with approximately equal probability. The latter circumstance is very likely to be the main reason that the ratio $\frac{\sigma(pp \to \pi^{+})}{\sigma(np \to \pi^{+})}$ which in our case is equal to to 3.9 ± 1 is considerably less than ten. The value of the ratio equal to ten may be predicted according to the hypothesis of the isotopic invariance under the assumption that the pion-nucleon system is always found only in the state T = 3/2.[12] It should be noted however, that the value of this ratio in [12] has been obtained under some simplifying assumptions and may be in fact somewhat different.

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F i g u r e s

Fig. 1. The set up of the experiment. n - is a neutron beam. M is a monitor (ionization chamber). 1,2,3 are schintillation counters. 4. is the radiator of the Čerenkov counter. Ф is a filter. P is a scatterer.

Fig. 2. The dependence of the Čerenkov counter efficiency upon the velocities of the detected particles.
a) - the radiator made of plexiglass, B) - made of water.

Fig. 3. The dependence of the effective neutron energy upon the exponent of the maximum pion momentum in Eq. (1).

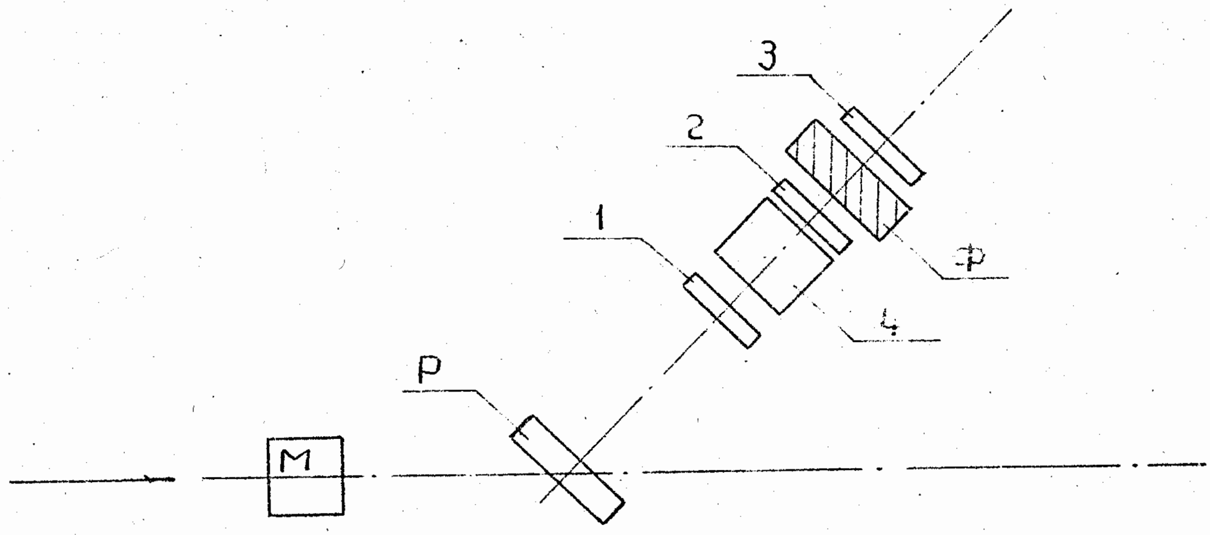

Fig. 1

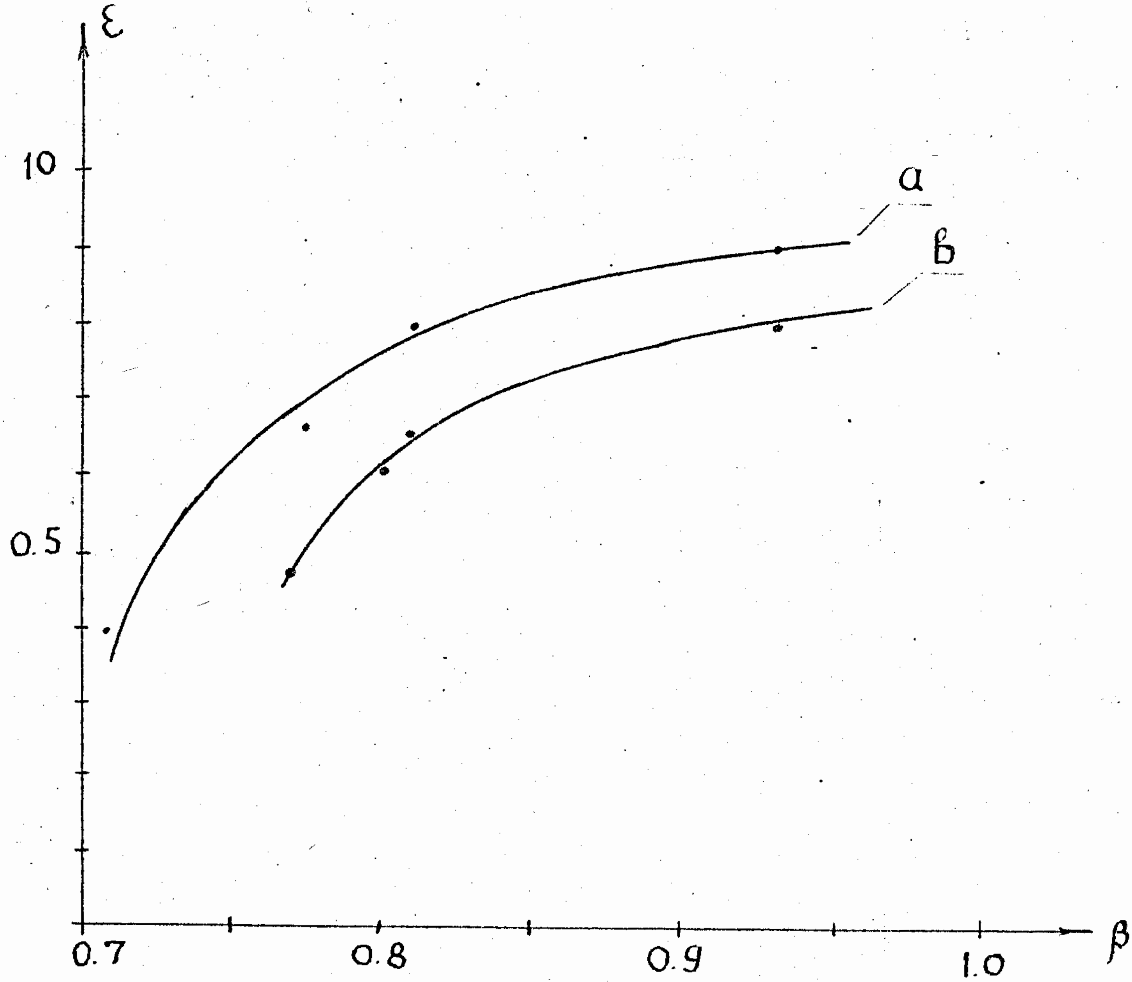

Fig. 2

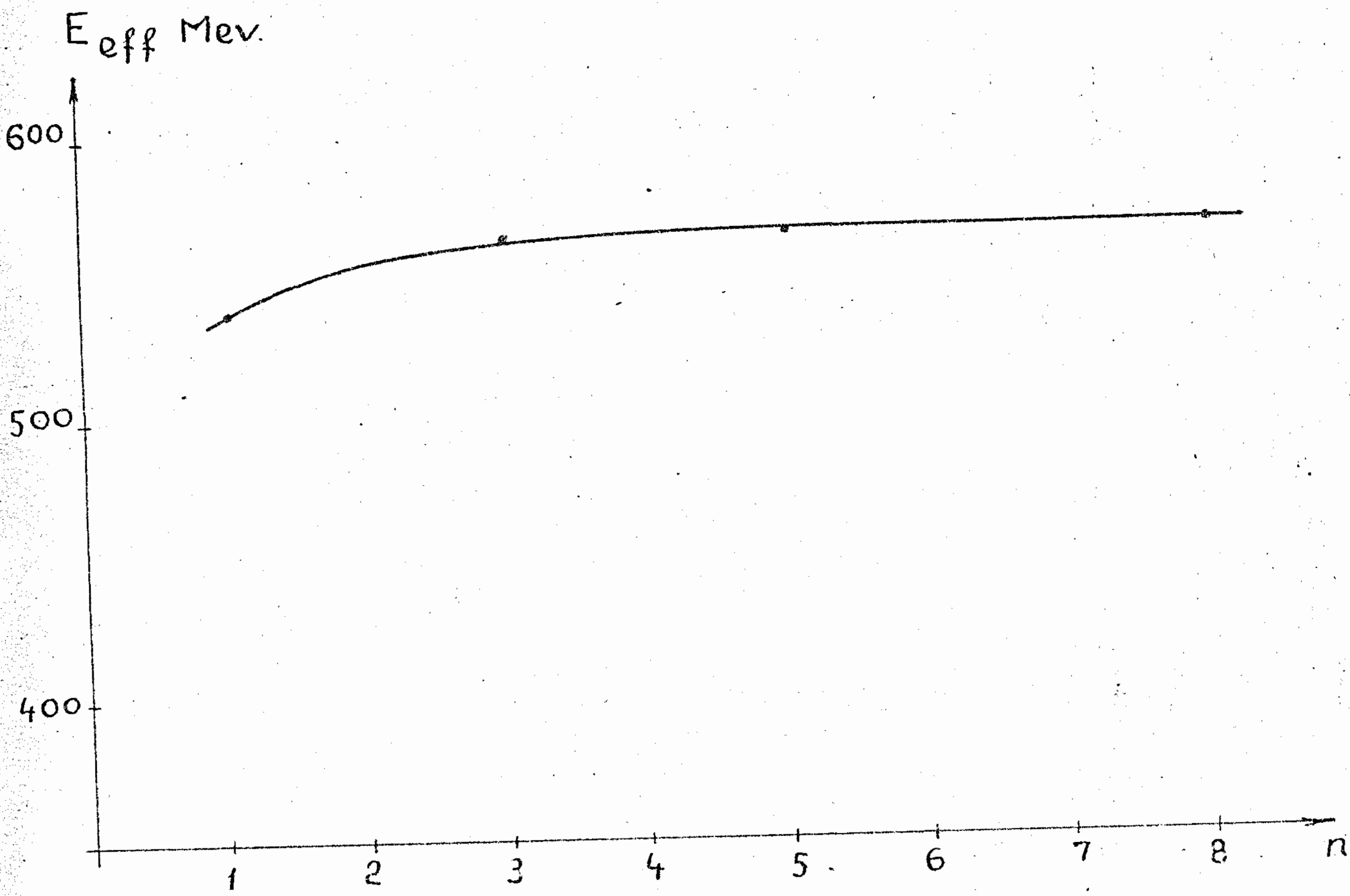

Fig. 3

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