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I.M.VASILEVSKY, Yu.D.PROKOSHKIN

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INVESTIGATION OF THE ENERGY CHARACTERISTICS OF THE 6 METER SYNHROCYCLOTRON EXTERNAL PROTON BEAM

Measurements were made of the energy spectrum and the mean energy of the external proton beam of the Joint Institute for Nuclear Research 6 meter synchrocyclotron at various acceleration rejimes. The spectrum is described by the Gaussian curve with the dispersion (2.8 ± 0.3)Mev. The mean energy was determined with the acouracy of 0.I%.

Introduotion

The intensive proton beam extracted from the Joint Institute for Nuclear Research synchro-oyolotron[I] made it possible to oarry out experiments in which the accuracy of measurements of the partiole interaction cross sections could be made equal to some per cent. However, to reaoh such an accuraoy is possible only in the case when the thorough measuring of proton beam energy is made simultaneously with determination of the cross seotion values. The reason of this is the rapid increase of cross seotions with energies especially in the region close to the "threshold" of the investigated reaotions. Thus, the oross section of meson produotion in nucleon-nucleon collisions at the proton energy of 650 Mev is changed as fast as 0.7%/Mev, and at the energy of 350 Mev as 3%/Mev. Because of suoh rapid inorease of the cross seotions at the low proton energies it is neoessary to have information not only about the mean energy but also about the energy spectrum of a beam. The latter is espeoially desirable in the case when the deorease of the proton beam energy is reaohed by slowing down the protons since this is aooompanied by the essential inorease of the beam energy spread. The purpose of this work was to investigate the energy speotrum of the proton beam at several proton energies in the region of I50 ÷ 670 Mev. Besides, the measurements were made of the mean proton energy at various operation rejimes of the aocelerator.

2. The energy spectrum of protons

For measuring the proton speotrum the magnet with the pole diameter of I00 om and the field in a gap of I6000 Oe was used. The magnet was plaoed on the pass of the external proton beam (see Fig.I) and oould deflect it at the angle 20°. A number of brass collimators having a form of vertioal slit were placed before the magnet and oould form the flat proton beam 0.I ÷ 0.7 om wide and 2 om high. At the exit of a speotrometer the protons were registered by a deteotor oonsisting of thin (0.I ÷ 0.2 om) plastio scintillator, and the photomultiplyer FEU-I9M placed

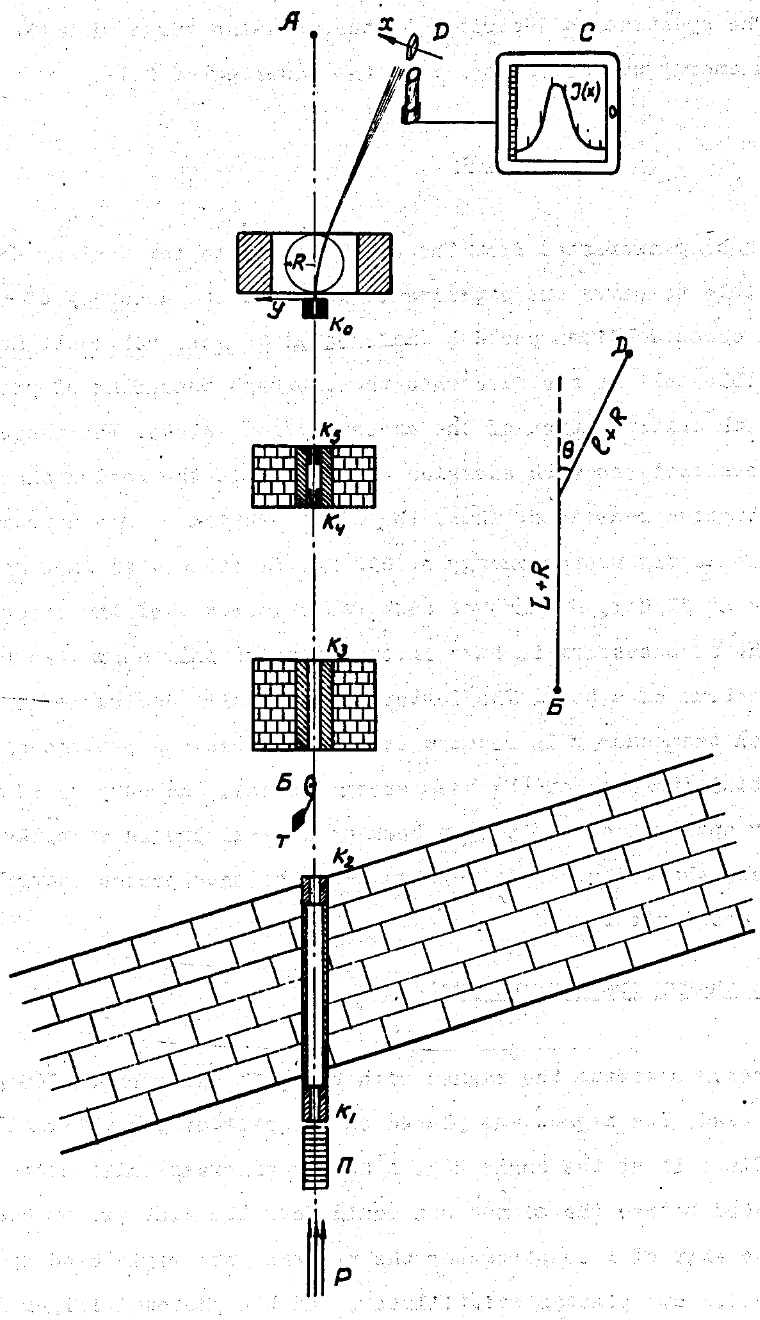

Fig.I. Experimental arrangement

P = the proton beam, П = polyethelene absorber, $K_0 \div K_5$ = collimators,

D = the proton detector, C = the recording potentiometer, Б = the block for stretching the thread.

below it. The output impulses of the photomultiplier were integrated by RC-unit and the current ($10^{-9} \div 10^{-7}$a) was measured by recording potentiometer EPPV-51. With the help of synchronous motor the detector could be moved perpendicularly to the proton beam, and the change of the beam density J with the change of coordinate x (see Fig.1) was registered on the recorder tape. The characteristic curve $J(x)$ is given in Fig.2. Simultaneously the coordinate marks were made on the recorder tape so that the coordinate x could be determined with the accuracy of 0.02 cm. Another detector used in the device and similar to that described above could register the change in the proton beam intensity with time. The whole measuring cycle of a curve $J(x)$ lasted for 5 minutes. During this period the value of the deflecting magnet field changed by no more than 0.05 per cent.

As is seen from Fig.2, the function $J(x)$ is well described by the Gaussian curve. The dispersion of this curve σ is due to several factors: energy spread of a beam, the scattering of protons in the air, collimator width and the scintillator thickness. Each of the factors mentioned above is characterized by the corresponding dispersion σ_i, contributing to the total dispersion σ. Preliminary experiments performed with the differential ionisation chamber[2] showed that the mean energy spread of a beam was equal to about 3 Mev. The dispersion $\sigma_E = 0.1(1 + l/R)$cm corresponds to this value at the maximum current of the spectrometer magnet (R and l are shown in Fig.1). The least dimention of the collimators (d_1) and the scintillator (d_2) in the experiments described was equal to 0.1 cm. As the inequality $d_1, d_2 \ll \sigma_E$ must be fulfilled, the lower limit of l is equal to 2R. The distance l cannot be also taken too large because the scattering in the air behind the collimator K_0 is growing quickly with increasing l : $\sigma_s' \approx 0.12(l + l/2R)^{3/2}$ cm. When l is large the ratio σ_E/σ_s' decreases as $l^{-1/2}$. However, in the interval $l < 10R$ this ratio is practically constant. Thus, l must lie within $2 < l/R < 10$. The distance l was taken equal to 4 meters; this gave the spectrometer resolution dE/E dx ≈ 1%/cm. The ratio σ_E/σ_s' was equal to 0.7. Besides the proton scattering in the air behind the collimator K_0, one should take into account also the scattering in the air between the collimators. The estimation of the corresponding dispersion σ_s'' (it is proportional to the value $l + l/2R$) shows that in our case $\sigma_E/\sigma_s'' = 0.7$. Thus, the scattering in the air makes the main contribution to the total dispersion σ. To decrease σ_s, a thin polyethelene tube filled with helium was placed on the pass of the beam. This helped to weaken the scattering several times.

The energy spectrum of protons can be found by comparing curves $J(x)$ measured with the magnetic field / $J_H(x)$ / and without it / $J_0(x)$ /. In order to measure $J_0(x)$ the detector was moved to the point A (see Fig.1). Dispersion σ_E was determined as a difference $(\sigma_H^2 - \sigma_0^2)^{1/2}$, where σ_H and σ_0 are the dispersion of the functions $J_H(x)$ and $J_0(x)$. In

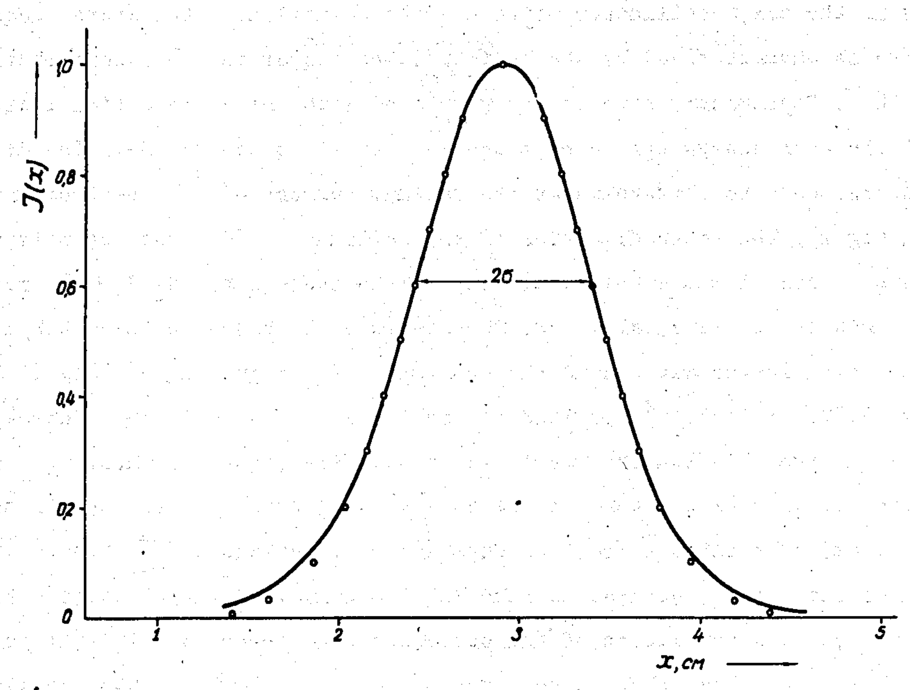

Fig.2. The measured dependence J (x) (solid ourve). The circles indicate the Gaussian funotions with the standard б .

experiments carried out with no helium tube the ratio σ_E/σ_0 was equal to 0.5. The value of the mean energy spread of the beam in this case was determined with the accuracy $\approx$ 0.6 Mev, but of the form of the energy spectrum it was impossible to say something definite. The application of helium increased the ratio σ_E/σ_0 by a factor of 2.5; this made it possible to determine rather accurately both the dispersion σ_E and the form of the spectrum. The function F(x) describing the spectrum can be found by solving the relation:

$$J_H(x) = \int_0^\infty J_0(x-\xi)\, F(\xi)\, d\xi. \qquad (I)$$

The energy spectrum of the beam protons was found to be symmetrical. It is well described by the Gaussian curve:

$$\Phi(E) \sim \exp\left\{-(E-\bar{E})^2/2\Delta_E^2\right\} \qquad (2)$$

At the proton energy $\bar{E}$ = 665 Mev, the value Δ_E is found to be equal to (3.0 ± 0.6) Mev. (measurements performed without helium) and (2.7±0.3)Mev (with helium). The weighed mean is equal to

$$\Delta_E = (2.8 \pm 0.3) \text{ Mev}.$$

The spectrometer calibration (that is, determination of $\bar{E}$ and dE/dx) was made by the method of current carring thread (see below).

Dispersion value Δ_E found in this work differs from the estimation $\Delta_E \approx 4$ Mev obtained in[3] by the ionization chamber method[4]. The reason of this divergence (as shown in[2]) is the increase of Δ_E in the work[4], the authors of which did not take into account the effect of proton scattering.

The above method was used to measure proton spectra at lower energies as well, when the beam passing through polyethelene absorber was slowed down (see Fig.I). When the proton energy decreases the energy spread of the beam grows due to the increase of the ionisation losses and the dispersion of the "straggling" type, arising because of fluctuations of ionisation losses. Therefore the relative dispersion Δ_E /E is growing very quickly with the proton slowing down; this makes the performents of measurements easier. So. at $\bar{E}$ = I85 Mev helium is not applied already and wide collimators (0.7 cm) should be used since even in this case σ_E/σ_0=2.5. The functions $J_H(x)$ and $J_0(x)$ measured at low proton energy are in a good agreement with the Gaussian curve. From this follows that the proton spectra Φ(E) at low energies has the form of the Gaussian curve (2). At the same time this confirms the above conclusion that the spectrum of unmoderated beam is described by the Gaussian curve.

Dispersions Δ_E measured by means of the spectrometer are given in Fig.3. The data on the relative change of Δ_E with energy obtained by means of the chamber described in[2] are also shown in Fig.3. The results of the experiments agree with the theoretical dependence calculated

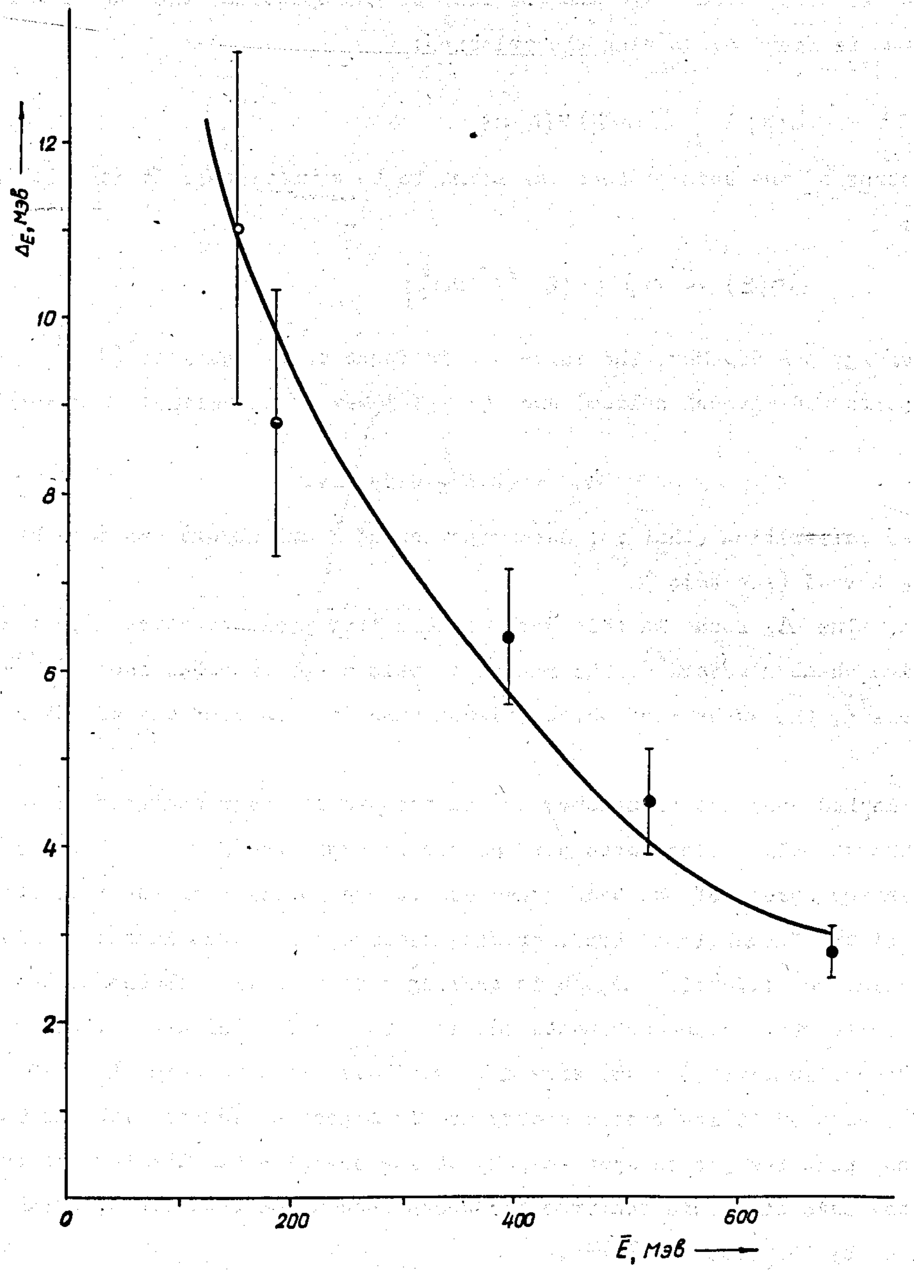

Fig.3. Dispersion of the beam Δ_E at different proton energies $\bar{E}$. ɸ is measured by a spectrometer, ϕ is measured by means of the differential ionization chamber. The solid curve represents the theoretical energy dependence of dispersion.

by taking into acoount the increase of ionization losses and the dispersion of the "straggling" type.

3. Mean proton energy

The most popular method for determining the mean energy of the external beam is the measurement of the proton range by means of ionization chamber[4]. However, this method in a form described in[4] leads to systematic error (2 ÷ 3 Mev for $\bar{E} \approx 650$ Mev) due to the faot that in treating the Bragg curve the proton scattering is not taken into account. This error oan be removed by the proper correction, but even in this case the ionization chamber method oannot give the energy measurement aocuracy better than 5 Mev at $\bar{E} \approx 650$ Mev as the ionization potential inoluded into the "range-energy" relation is not known well.

The method of measurement of the Čerenkov radiation angle[4,3] makes it possible to determine directly the velocity and energy of protons. This method is the most acourate at small proton energies. Its acouraoy decreases with inoreasing energy and at $\bar{E} \approx 650$ Mev it is equal to 2 Mev. The optical device for measuring the Čerenkov radiation angle is oomplioated one and this prevents the method from wide practical applioation.

To measure the mean proton energy we used the method of ourrent oarring thread[5]. It is desoribed in detail in[6] and in this work we only disouss briefly some questions on the application of this method for measuring the proton energy with acouracy better than I Mev at $\bar{E} \approx 650$ Mev. The soheme of measurements is given in Fig.I. The thin flexible wire-thread is fixed with its one end in the center of the deteotor (in front of the scintillator) and passes through the magnet and collimators following the direction of the proton beam. In B the blook is placed to stretch the thread with the help of the load T. The ourrent i passes through the thread. If T, i and mean momentum of the proton beam P satisfy the relation

$$P = cgT/i \qquad (3)$$

where o is the velocity of light, g is the aooeleration of gravity*), the horisontal projection of the thread and that of the beam ooinoide. Plaoing the deteotor so that the sointillator should be in the maximum of the ourve J(x), matohing together the thread and the center of the oollimator K_0 slit, and measuring the current i we oan find the value P with great aoouraoy.

The relation (3) is valid if the thread is absolutely flexible and weightless. As the real thread is elastic a momentum appears opposing the magnetic-eleotrioal forces. The momentum oalculated by the formula (3) differs from the real one by

$$5 \times 10^3 P d^4 / T \qquad (4)$$

(for oopper wire).

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*) og in the latitude of Dubna is equal to 2.9426, T being measured in gramms, i in apperes, and P in Mev/c.

Here d is the diameter of the thread in cm. The sign of this correction is determined by the direction of the thread motion to the equilibrium position, and as the thread oscillates slightly with respect to equillibrium position due to the accidental changings of current and magnetic field, the factor (4) plays the role of accidental error and must be included into the total error of a single measurement of the impulse P. The error (4) decreases by the factors 2 or 3 if before measuring the wire is annealed by passing the high current through it.

Besides the error (4) one must take into account also the sagging of the thread under its own weight which is characterized by the factor

$$d^2 l_o^2 / T \qquad (5)$$

Here l_o is the length of the thread. The thread is placed therefore below the beam trajectory. This is essential if the magnetic field is inhomogeneous. The corresponding correction can be determined experimentally by moving the thread up and down. In our case this correction did not exceed 0.05%.

From (5) follows that the thread length l_o must be chosen as small as possible. However the accuracy of measurements decreases with decreasing the thread length since

$$\Delta y / \Delta P \approx L(l_o - L - R)\sin\theta / P l_o \qquad (6)$$

(see Fig.I). The minimum length l_o is determined by the accuracy Δy_{min} with which the thread can be fixed in the center of the collimator K_o slit. In our case l_o=I6 m, L=9m and Δy_{min}=0.03 cm. The thread is mounted automatically in the center of the slit by means of the contact device. The error $\Delta P/P$ determined by the ratio (6) is equal to 0.03%.

As is seen from (4,5) corrections decreases quickly with decreasing the thread diameter. So, the correction (4) measured at T=I00 g and d= 0.0I cm turned out to be 0.4% (for P=I300 Mev/c) and at d=0.0I3 cm the correction is equal to I.0% (copper wire). To use the wire less than 0.005 cm in diameter and the length $l_o \approx$ I0 m is practically very difficult. The further decrease of corrections (4,5) can be reached only at the expence of decreasing the load weight T. Simultaneously, it is necessary to increase the current i in accordance with the relation (3). The values T and i are limited by the mechanical strength of the wire. Fig.4 gives the current i as a function of the load T at which the wire cuts off. For copper wire the border of the area of the admissible values T and i is described roughly by the circle (see Fig.4):

$$(T/d^2 \times 10^4)^2 + (i/d \times 10)^2 = 2^2 \qquad (7)$$

which could be used in choosing the optimum values T, i and d (T is measured in gramms, i in amperes and d in millimeters).

In the present work the measurements were carried out at d=0.0I cm., T = I00 g. The current i changed within 0.2 + I.0 a. T and i were measured with the accuracy better than 0.05%; this made it possible to determine the mean energy of the beam E with the error less than I Mev:

$$\bar{E} = (667.1 \pm 0.7)\,\mathrm{Mev}$$

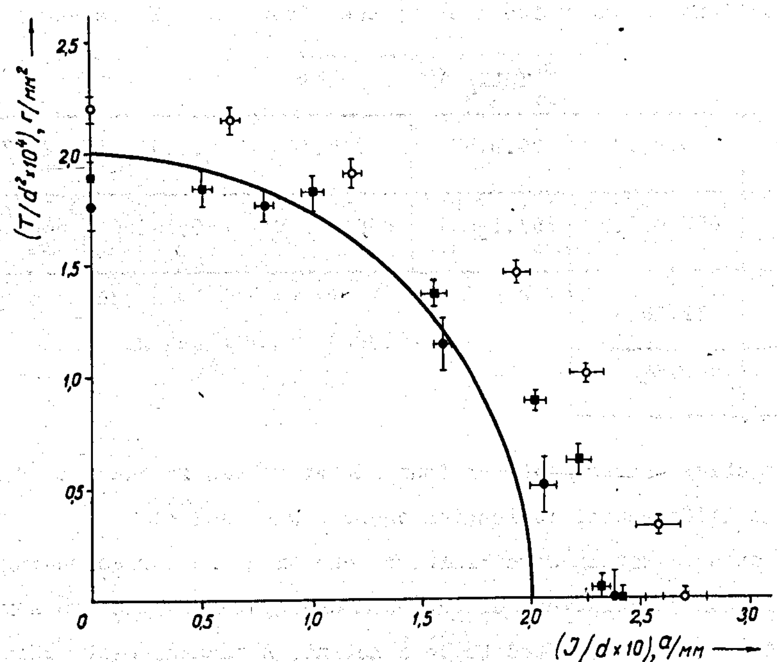

Fig.4. The maximum current passing through the thread i as a function of the load T causing the cut off of the thread. ●, ○, ○ are measured for a copper wire 0.0063, 0.0099 and 0.0155 cm in diameter, respectively. The solid curve represents the circle (7).

(at the exit of the accelerator chamber).

The indicated accuracy of measurements can be reached within the limited energy regions of protons (E > 250 Mev). At lower energies one has to use the small load T, to pass high current through the thread and use the thick wire; this reduces the accuracy of measurements.

4. The beam energy at various rejimes of proton acceleration

The value of the mean energy of the beam $\bar{E}$ depends upon the accelerator magnetic field, the character of the spectra of the radial oscillation amplitudes, and the conditions of the beam extraction, that is, it is the function of a large number of parameters characterizing the operation of the accelerator. Due to this fact the beam energy is not constant and changes within small limits because of uncontrolled changes of the number of the accelerator's parameters. These fluctuations of the value E as is seen from Table I are equal to some Mev.

Table I

Data of measurements	5.7.57	3.8.57	20.8.57	3.5.58	5.6.58	29.7.58	
E Mev	67I.0±I.5	667.8±I.0	667.I±0.7	658.8±I.0	669.3±I.0	666.3±I.0	
Data of measurements	20.8.58	I2.I0.58					
E Mev	665.3 ±I.0	663.2±I.0					

The error of the relative measurements of four latter values is equal to 0.5 Mev (in relative measurements the differential ionization chamber was used[2]).

The value $\bar{E}$ can be changed within some limits by choosing the corresponding acceleration rejime. The necessity of such "regulation" of the beam energy takes place in some experiments in which the proton beam energy is required to be constant. As measurements showed (see Fig.5) the energy $\bar{E}$ depends essentially upon the accelerator magnetic field. The "regulation" of the value $\bar{E}$ within small limits can be reached also by changing the conditions of the beam extraction. (see Fig.6). The application of the indicated methods makes it possible to increase the proton energy up to the value

$$\bar{E}_{max} = 683 \text{ Mev}$$

Here the intensity of the external proton beam reduces by the factor of 10^3.

As it was previously pointed out the measurements of the proton energy are especially important if in experiments the slowing down of protons is used (this method is widly spread

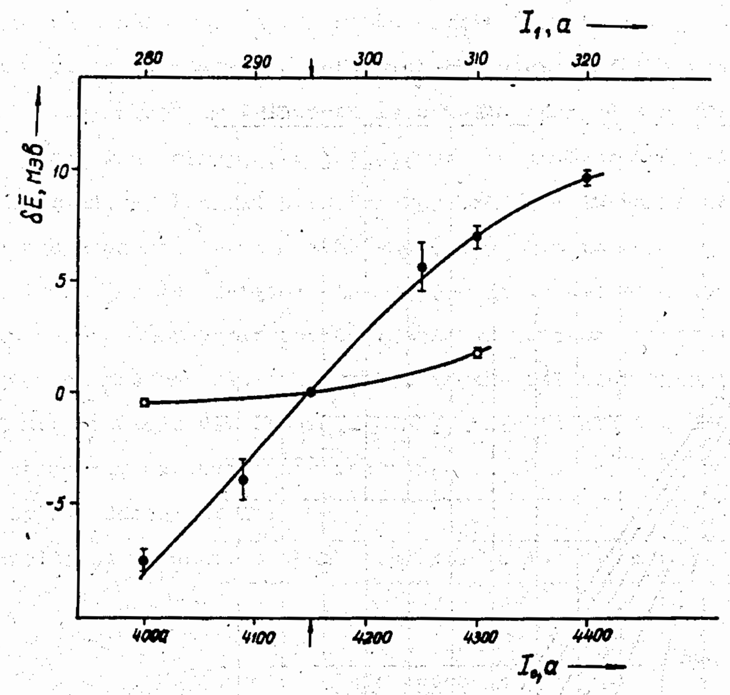

Fig.5. The changing of the mean energy of the proton beam with the change of the accelerator magnet current I_0(ɸ), and current I_1 passing through the winding, correcting the position of the median plane of the magnetic field (ϙ). Arrows indicate I_0 and I_1 in the usual working rejime.

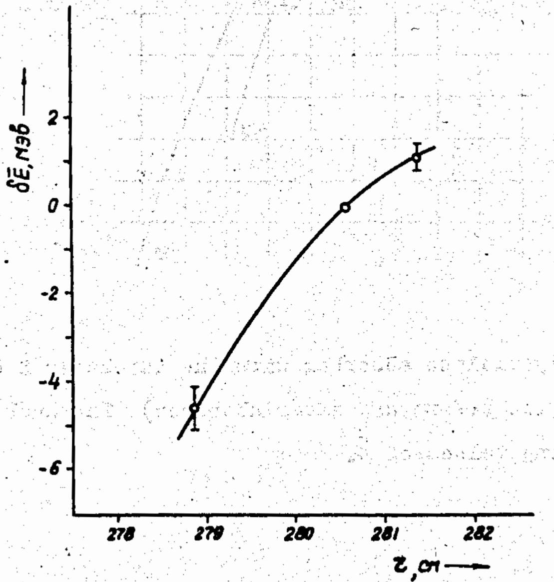

Fig.6. The changing of the mean proton beam energy with the change of regenerator position z (the part of the device for the beam extraction[1]).

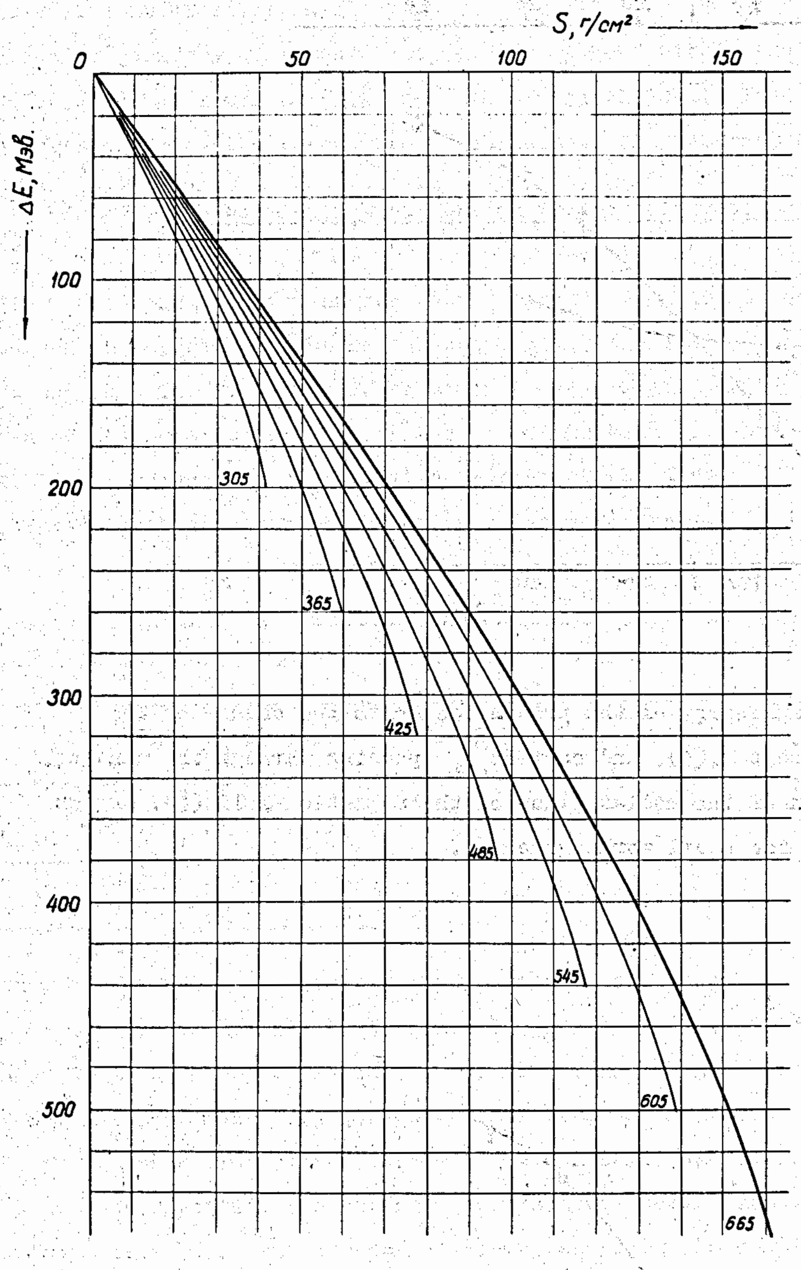

Fig.7. The energy loss $\Delta E = \bar{E} - \bar{E}'$ in polyethelene absorber with the thickness S (Here $\bar{E}$ and $\bar{E}'$ are the proton beam energies before and after absorber). The numbers of the curves show the corresponding values of $\bar{E}$.

and was used in a number of experiments carried out in laboratories of different oountries). In this oase it is necessary to determine the energy of the moderated beam (whioh is not oonvinient as the absorber thickness is usually changed several times during the experiments) or to make precision energy measurements of the unmoderated beam using for determining the moderated beam energy the relation "energy decrease in the absorber - filter thickness". This dependenoe was measured for polyethelene $(CH_2)_n$ (it is valid also for the paraphine) in the region I50 + 665 Mev and is given in Fig.7. It should be noted that the application of the usual ratio "range-energy" is not desirable as it leads to great errors especially in the low energy region of the moderated beam. So, if the relation "range-energy" is known with the accuracy 2 Mev at E=650 Mev (that is 0.4%), then in slowing down the beam up to IOO Mev the error in the energy determination increases up to 6 Mev and is equal already to 6%, that is increases by the factor of I5.

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References

I. V.P.Dmitrievsky, V.I.Danilov, Yu.N.Denisov, N.L.Zaplatin, V.S.Katyshev, A.A.Kropin, A.V.Chestnoy, Pribory i techn. eksperim. I,II,I957.
2. I.M.Vasilevsky, Yu.D.Prokoshkin, Pribory i tehnika eksperim. (to be published)
3. V.P.Zrelov, G.D.Stoletov, The aocount of the JINR,I958.
4. R.Mather, Phys.Rev. 84,I8I,I95I; R.Mather, E.Segrè, Phys.Rev.84,I9I,I95I.
5. J.J.Thomson, Phil.Mag.,Ser.6,I3,56I,I957.
6. M.S.Kozodaev, A.A.Tyapkin, Pribory i tehnika eksperim. I,2I,I956.

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