HIGH-ENERGY PARTICLE BEAMS FROM THE 6 METRE SYNCHROCYCLOTRON AND THEIR UTILIZATION

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(presented by V. P. Dzhelepov)

Introduction

Particle accelerators up to and over the energies of several hundred Mev offer wide opportunities of investigating some of the most urgent problems of modern nuclear physics, such as the structure and properties of elementary particles, the nature of their interaction, the pattern of their mutual transformations, etc.

Powerful accelerators are huge industrial structures entailing considerable expenditure on construction and operation. A consideration of how best and most effectively to use them is therefore of special importance.

The present paper gives a brief description of how this problem was solved on the 6 m. synchrocyclotron of the Institute of Nuclear Problems of the USSR Academy of Sciences which accelerates protons to an energy of 680 Mev.

Main ways of increasing the utilization efficiency of the accelerator

The scientific investigations carried out on the synchrocyclotron were mainly directed towards studying the processes of elastic and inelastic collisions of 300-680 Mev nucleons with nucleons, and the scattering of π mesons by nucleons and deuterons. Since the cross-sections of most of these processes range from several units to several tens of millibarns, considerable time expenditure is involved in operating the accelerator if exact quantitative results are to be obtained.

Under such conditions, the efficiency and the degree of exploitation of the synchrocyclotron for nuclear investigations with high-energy particles depend largely on the rational solution of two problems :

1. The ejection from the accelerator vacuum chamber of intensive beams of different kinds of high-energy particles.

2. A radial reduction of the background due to accompanying radiations. The following measures were accordingly carried out on the synchrocyclotron :

(*a*) beams of high-energy protons, neutrons and π mesons were ejected from the accelerator chamber past the shields in thirteen directions;

(*b*) an experimental room for measurements and a special laboratory for work with beams of π mesons, both shielded from background radiations, were built;

(*c*) experiments were carried out simultaneously on several beams of similar and different particles; the apparatus was set up in echelon arrangement;

(d) automatic and remote control of the experimental apparatus was used ;

(*e*) multiple-channel electronic systems were used for registering the nuclear processes.

High-Energy particle beams

In principle, the synchrocyclotron makes it possible to obtain high-energy particle beams from any point of the trajectory of the accelerated protons. The successful realization of this possibility, however, depends essentially on the accelerator design.

It is important that the greater part of the internal volume of the accelerator vacuum chamber and a considerable part of its lateral surfaces be free from any devices which might hinder free ejection on the particle beams. Figs. 1 and 2 are an illustration of how these conditions are obtained in the synchrocyclotron.

The first figure gives a view of the front wall of the chamber. Ejection windows for the passage of the beams of particles and covered with dural diaphragms about one mm. thick have been fitted along practically the entire length of the wall on the level of the trajectory of the accelerated protons. On the right can be seen the vacuum valve of one of the probe-holders.

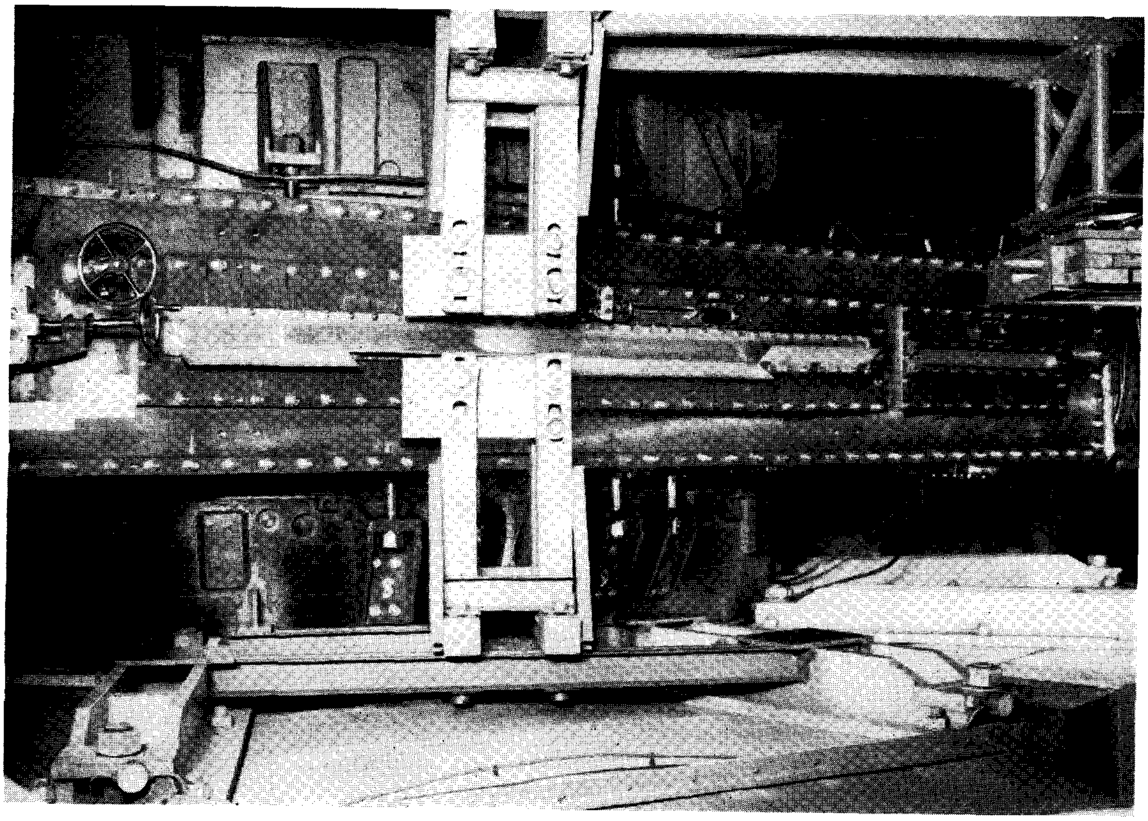

Fig. 1.

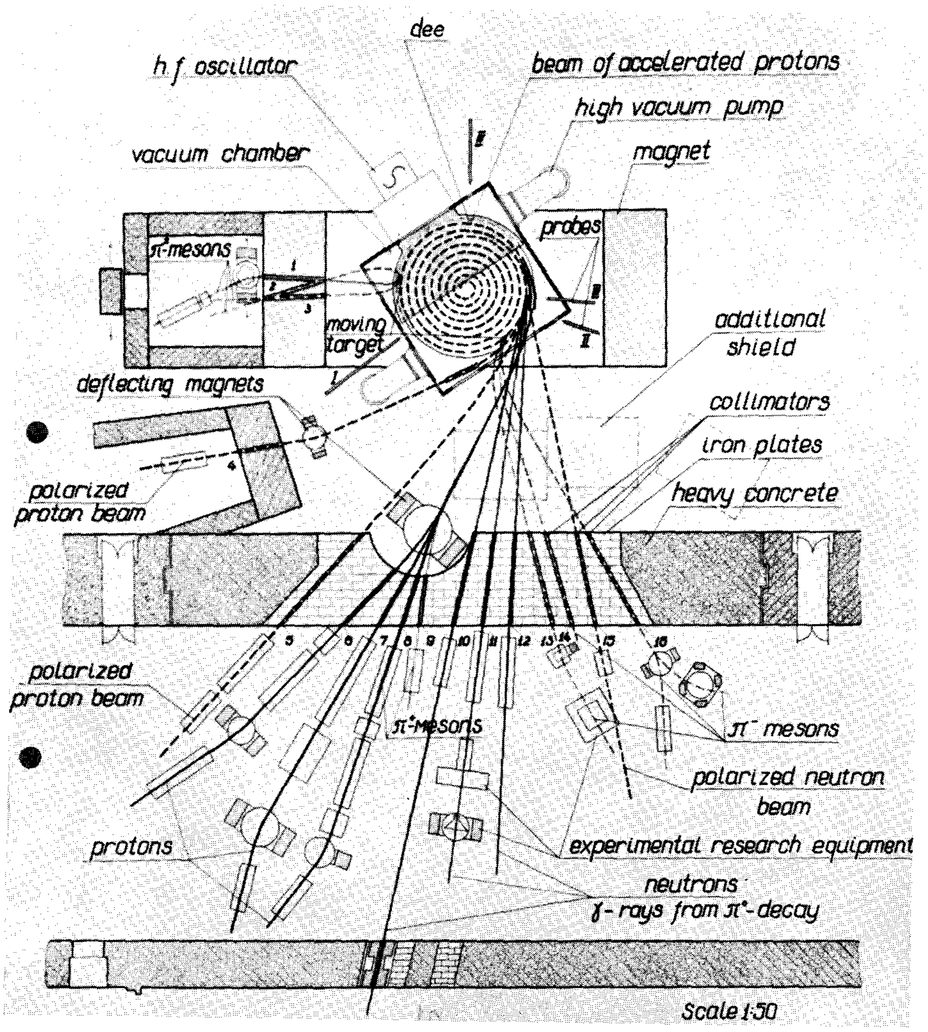

Fig. 2. Beams of high-energy particles from the 6-metre synchrocyclotron.

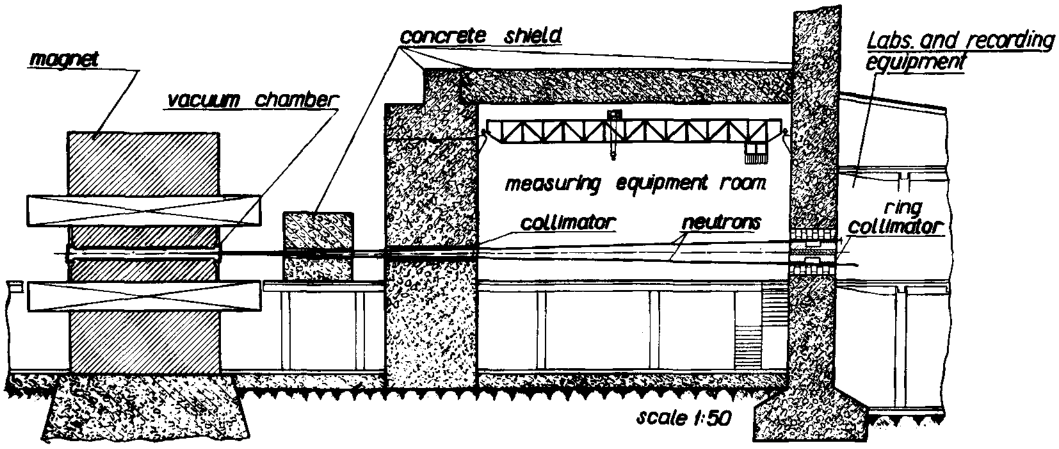

Fig. 3. Shielding from 6-meter synchrocyclotron radiation.

Fig. 2 shows the general diagram of the synchrocyclotron chamber, the trajectories of the emerging beams of particles and the distribution of the shielding constructions and measuring appliances.

The greater part of the high-energy particle beams are ejected from the synchrocyclotron into the atmosphere and directed into the experimental room containing the experimental apparatus. The 4 m. heavy concrete wall can be seen with the collimators in its embrasure. The latter are steel slugs of square cross-section and 3.6 m. in length containing a centre opening the diameter of which can be varied from 150 to 10 mm. The space between the collimators is plugged with cast-iron slabs which make for good shielding of the embrasure, and also allow the position of the collimators to be readily changed. Fig. 3 shows a longitudinal section of the synchrocyclotron building. The additional local shielding of concrete blocks placed in front of the 4 m. wall of the experimental room can be seen in fig. 2; it is indicated by dotted lines. A ring-collimator set in one of the neutron beams and designed for work with ring-shaped scatterers is shown in the same figure (and in fig. 2).

Efficiency of protection of synchrocyclotron labs from radiation

The efficiency of protection of the experimental room and the room containing the recording equipment against radiation is characterized by the level of such radiation in the rooms. The relevant figures are as follows: The level of total radiation in the experimental room for a 0.2-0.3 μA current of 680 Mev protons impinging on the internal target varies from 0.1-2 μr/sec (right-hand side of the room) to 1.5-2 μr/sec (left-hand side of the room where a trapdoor is built in the ceiling for the operation of the crane); the flux of fast neutrons varies from 1-2 to 60/cm^{2}sec respectively. The number of neutrons with an energy greater than 50 Mev does not exceed 5n/cm^{2}sec[1].

In the recording equipment room, the level of background radiation is insignificantly small. This is evident from the fact that with the accelerator working at maximum intensity the count registered by a Geiger counter in any part of the room does not exceed twice the background due to cosmic radiation[1].

Characteristics of high-energy particle beams ejected from the accelerator chamber. Unpolarized proton beam

It is understandable that special attention was paid to increasing the intensity of the proton beam obtained from the accelerator. To this end, an earlier method of ejecting the protons into the atmosphere based on their scattering in a uranium target was discarded for a new method[2] which has been developed experimentally at

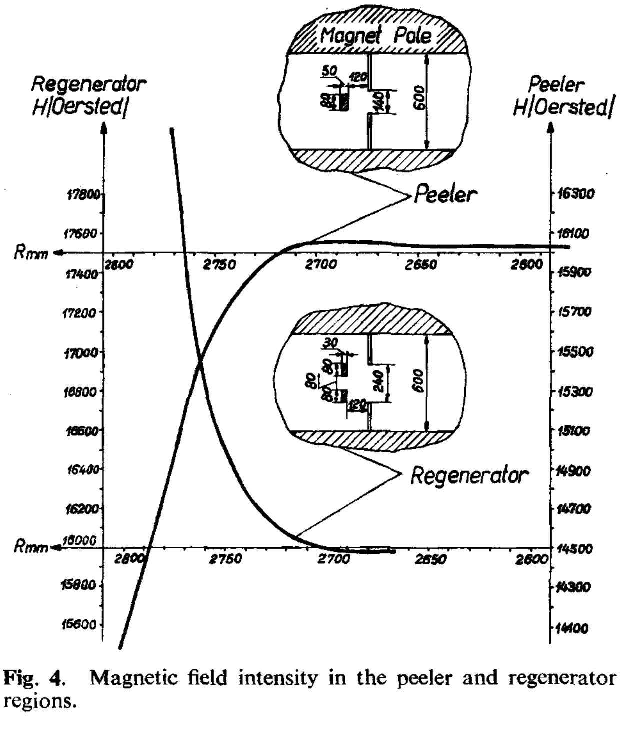

Fig. 4. Magnetic field intensity in the peeler and regenerator regions.

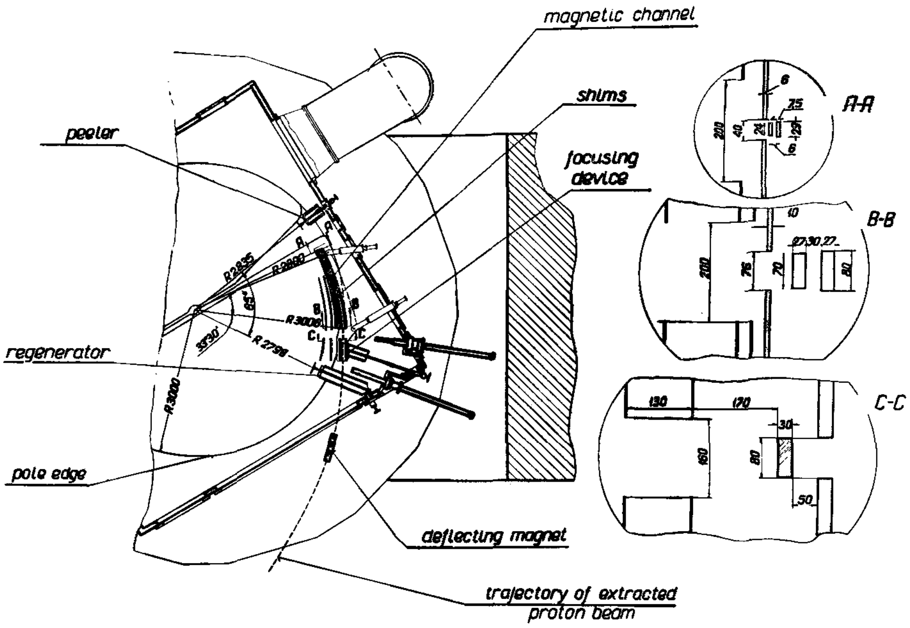

Fig. 5. Proton beam extraction.

the Institute of Nuclear Problems of the USSR Academy of Sciences [3] and at the Nuclear Physics Research Laboratory of the University of Liverpool [4] and is based on the excitation of radial oscillations of the particles by local perturbations of the magnetic field.

Local perturbations of the magnetic field strength were obtained by placing iron masses in the zone of the final orbits in the accelerator. Radial oscillations are excited by a generator. In the vicinity of the exciter the magnetic field decreases with radius (fig. 4); the azimuthal extent of this region amounts to 0.072 radians. Precession of the centre of curvature of the particles is compensated by means of a second perturbation region (regenerator) of azimuthal extent of 0.09 radians in which the magnetic field increases rapidly with radius (fig. 4).

The configuration of the magnetic field in the perturbation zone and the radial extent of that zone satisfy conditions which provide a sufficiently large radial step on the last revolution (about 40 mm. [5]) without affecting the stability of the particles in the vertical plane.

Computation of the magnetic field in the perturbation zone has been carried out on the assumption that the iron masses are magnetized axially to saturation[6]. The configuration of the magnetic field outside the perturbation zone was corrected with the aid of thin shims set up on the pole pieces of the electromagnet.

The problems connected with the utilization of local perturbations in the different zones of variation of the magnetic field with radius ($n = 0.1$, $n = 0.2$) were checked experimentally on the 5 m. variant of the Institute of Nuclear Problems synchrocyclotron[7].

The particles emerge from the accelerator chamber by means of a magnetic channel consisting of two iron plates of varying cross-section. The difference in the cross-sections of the front and back plates must satisfy the requirement that the magnetic field be uniform inside the channel[8].

The spatial configuration of the magnetic field near the channel was corrected with the help of several thin shims of varying cross-section. The uncorrected perturbation zone of the magnetic field due to the iron masses forming the channel does not extend for more than 30-35 mm. (from the axial line of the channel).

To compensate the angular divergence of the ejected proton beam, a focusing arrangement is set up beyond the magnetic channel which decreases the divergence of the beam in the horizontal plane[9]. The magnetic field in the vicinity of the focusing device is due to iron masses set up along both sides of the beam trajectory. The maximum gradient of the magnetic field of the focusing device, $\partial H/\partial m$ is about 1,000 Oersteds per cm., m being the normal to the beam trajectory.

The scheme of the ejection arrangement is shown in fig. 5. To obtain optimum ejection conditions all the iron constructions have devices which enable them to be set up at given radii without destroying the vacuum in the accelerator chamber.

The total intensity of the ejected beam, as well as its density at various distances from the chamber along the beam trajectory, were determined from the induced β-activity due to the reaction C^{12} (p, pn) C^{11}.

It was found by measurement that the total flux of protons at the exit from the magnetic channel equals

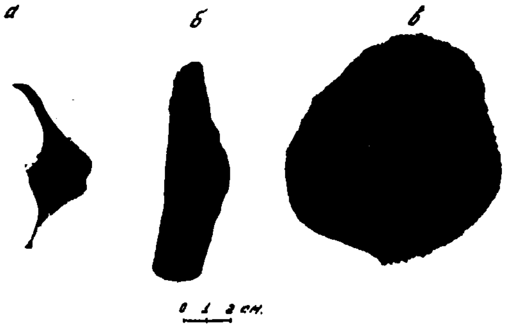

Fig. 6. Cross section of the extracted proton beam at different points along the trajectory.

7 × 10^{10} sec^{-1}, or 5-6 % of the mean flux of particles in the zone of final orbits.

Fig. 6 shows the photographs of the ejected proton beam;

(*a*) at the exit from the magnetic channel;

(*b*) 180 cm. from the channel exit;

(c) 700 cm. from the channel exit.

The angular divergence of the ejected beam does not exceed ± 0.5°.

With the aid of a deflecting magnetic field the extracted beam can be directed into one of three collimators (6, 7 or 8) fitted in the concrete wall (fig. 2). In this way we can considerably extend the space available for the experimental apparatus needed in investigations with protons on the one hand and create the most favourable working conditions on the other hand, for the greater part of the apparatus.

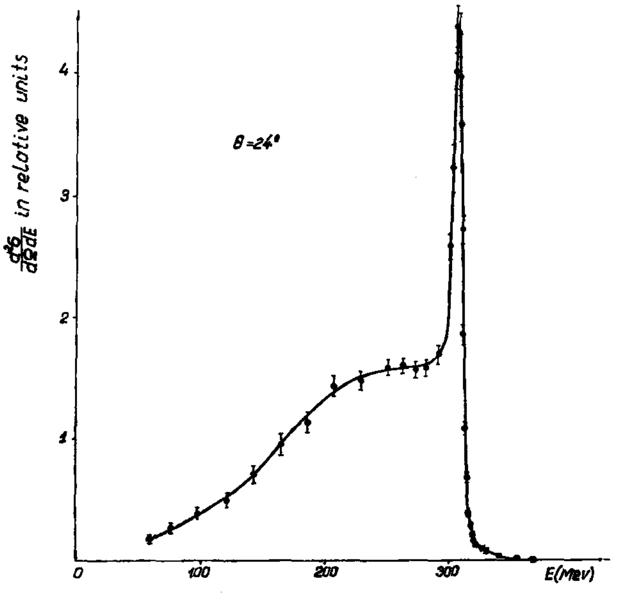

Fig. 7. Energy spectrum of π mesons produced in pp collisions.

The density of the proton beam in the experimental room at a distance of 15 meters from the exit window of the chamber is (1–2) × 10^8 protons/cm^{2}sec. The energy distribution of the protons in the beam is very homogeneous. Deviations of particle energies from E_{av} = 657 Mev as measured from the range distribution of the protons in copper do not exceed ± 5 Mev[10]).

The great intensity of the ejected proton beam made it possible to obtain beams of π^+ mesons outside the accelerator chamber of energy up to 400 Mev at a density up to 60 mesons/cm^{2}sec (for an energy of about 240-270 Mev). In these experiments, a liquid hydrogen or polyethylene target was placed in the way of the proton beam in front of the deflecting electromagnet (see fig. 2). The beam intensity at that point is about 10^9 protons/cm^{2}sec; the π mesons were analyzed by their momenta and entered the experimental room through collimators 8 and 9. The energy-spread of the π mesons in these beams amounted to ± 5 Mev for an energy of 300 Mev[11]). Fig. 7 shows a typical energy spectrum of π^+ mesons generated in collisions of protons with protons at an energy of 657 Mev[11]).

Beams of neutrons, γ-quanta aud polarized nucleon beams

Neutrons are obtained in the 6 m. synchrocyclotron just as in all other high-energy particle accelerators by proton bombardment of an internal target (usually beryllium) set up on a probe-holder (probe-holder III, fig. 2) in the zone of final orbits. Collimators 10, 11, 12 and 15 cut four narrow beams out of the wide beam of neutrons emerging from the target. The first three neutron beams are unpolarized. At the energy of 680 Mev of the primary protons the density of the neutron flux with energies over 400 Mev in the region of the experimental room is about 2 × 10^4/cm^2 sec. The fourth neutron beam (collimator 15) (emitting angle 18°) is partially polarized. As the experiment shows, its polarization is approximately 15%[12]). The energy spectrum of the neutrons emerging from the central collimator (11) is shown in fig. 8. The spectra of the neutrons emerging from the other collimators are

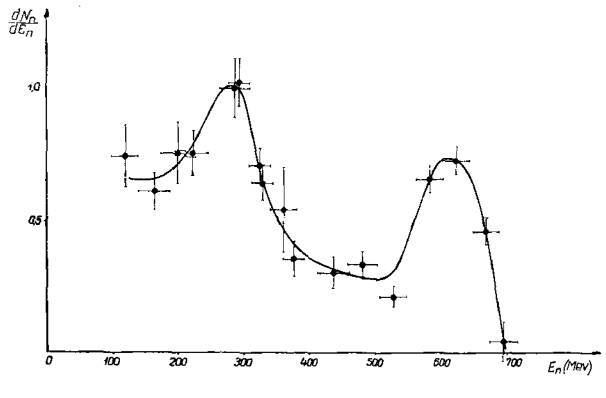

Fig. 8. Neutron energy distribution.

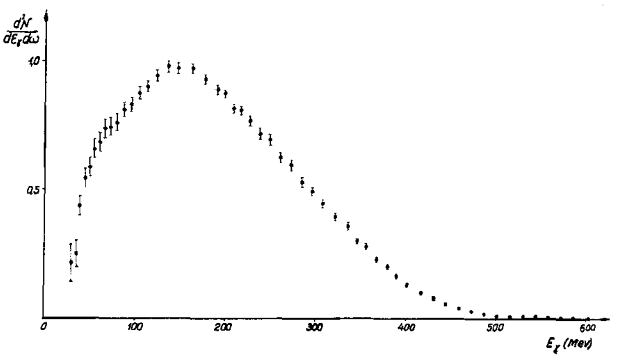

Fig. 9. Energy distribution of γ-rays from the decay of π^0 mesons produced in the collisions of 680 Mev protons with carbon nuclei.

similar except that their maxima are slightly displaced in the direction of lower energies. This displacement of the main maximum is the greatest for beam No. 15 and amounts to about 80 Mev[13]).

In addition to the four neutron beams, the same target emits four beams of high-energy γ-quanta from the disintergration of the neutral π mesons generated in the target. The intensity of the beam of γ-quanta of energy greater than 10 Mev in the experimental room is about 2×10^3 quanta/cm²sec (collimator 11). The energy distribution of the γ-quanta is shown in fig. 9[14]). The investigation of this γ-radiation is the main source of information about the properties and nature of interaction of π^0 mesons with matter.

In view of the great interest attached to experiments with polarized beams of nucleons in the 6 m. synchrocyclotron, the ejection of two polarized proton beams was also effected. One of these beams, which passes through collimator 4, consists of protons elestically scattered on beryllium nuclei inside the vacuum chamber. The degree of polarization of the beam reaches about 60%[15]). The proton energy is about 635 ± 15 Mev. Another beam, which passes through collimator 5, consists of protons quasi-elastically scattered on the nucleons of beryllium nuclei. The polarization of this beam equals about 30%[15]). The intensity of the two beams is approximately the same and equals about 4×10^4 protons/cm²sec.

Beams of π mesons

In order to create the most favourable conditions for work with negative π mesons, a "meson" laboratory was set up immediately beyond one of the vertical parts of the electromagnet yoke. The yoke has a thickness of about three meters of iron and affords safe protection against the direct radiation coming from the accelerator chamber. The concrete walls and ceiling of the laboratory are 1 m. thick and serve as protection against scattered neutrons and γ-radiation. The mesons enter the laboratory by way of three collimators (1, 2, 3) set in the yoke of the magnet; multiple-layer screens reduce the magnetic field in these collimators from 1,600 to 1-2 Oersteds.

π mesons generated in the beryllium target (10 mm. thick) set up inside the accelerating electrode (dee) are directed into these collimators by the magnetic field of the accelerator. The target is equipped for remote control. By changing its azimuthal or radial position with a direct or reversed field in the gap of the electromagnet, π mesons of different energies and of both signs enter the " meson" laboratory. In this way, beams of π^- mesons of energies of 140 to 410 Mev and π^+ mesons of energies of 140 to 245 Mev are obtained. The intensity of the π^- meson beams in the "meson" laboratory varies, depending on the energy, from 200 to 2-3 particles/cm²sec [16]). The background of accompanying radiations in this laboratory is nevertheless relatively high : total radiation background is 1-2 μr/sec, γ-radiation 10^1/cm²sec, thermal neutron intensity 500/cm²sec and neutron intensity with $E_n > 50$ Mev is 3n/cm²sec[16]). To reduce this background the thickness of the concrete shielding walls should be increased to 1.5-2 m.

In experiments with cloud chambers and diffusion chambers, the intensity of the beams of charged particles should not exceed 20-30 per cm²sec while the background of secondary radiations should be very small. In such experiments, negative π mesons of energies of 150 to 400 Mev are used which enter the experimental room through collimators 13, 14 and 16. The intensity of these beams varies from 40 per cm²sec ($E_{\pi^-} = 230$ Mev) to 1-2 per cm²sec ($E_{\pi^-} = 400$ Mev). The energy-spread is ± 6 Mev for $E_{\pi^-} = 230$ Mev[17]). As a meson source, a movable target is used the driving mechanism of which is installed on the front wall of the accelerator vacuum chamber.

In concluding the description of the particle beams, it should be noted that the laborious work involved in tracing the beams of charged π mesons was considerably facilitated by extensively applying the method of a fine taut current-carrying wire[18]).

Irradiation of samples inside the synchrocyclotron chamber

In addition to movable targets in the chamber, the accelerator is provided with four probe-holders whereby samples of different materials can be quickly introduced into (and removed from) the vacum chamber where they are to be irradiated by proton beams of the desired energy. This method of irradiating samples is widely applied in radio-chemical investigations.

Simultaneous work on several beams of particles

Various techniques were used in experiments with high-energy particles : electronic methods of recording the particles (scintillation counters and Čerenkov radiation counters in conjunction with photo multipliers), thick-layer photo-emulsions, magnetic spectrometers, Wilson cloud chambers, diffusion chambers, bubble chambers, etc.

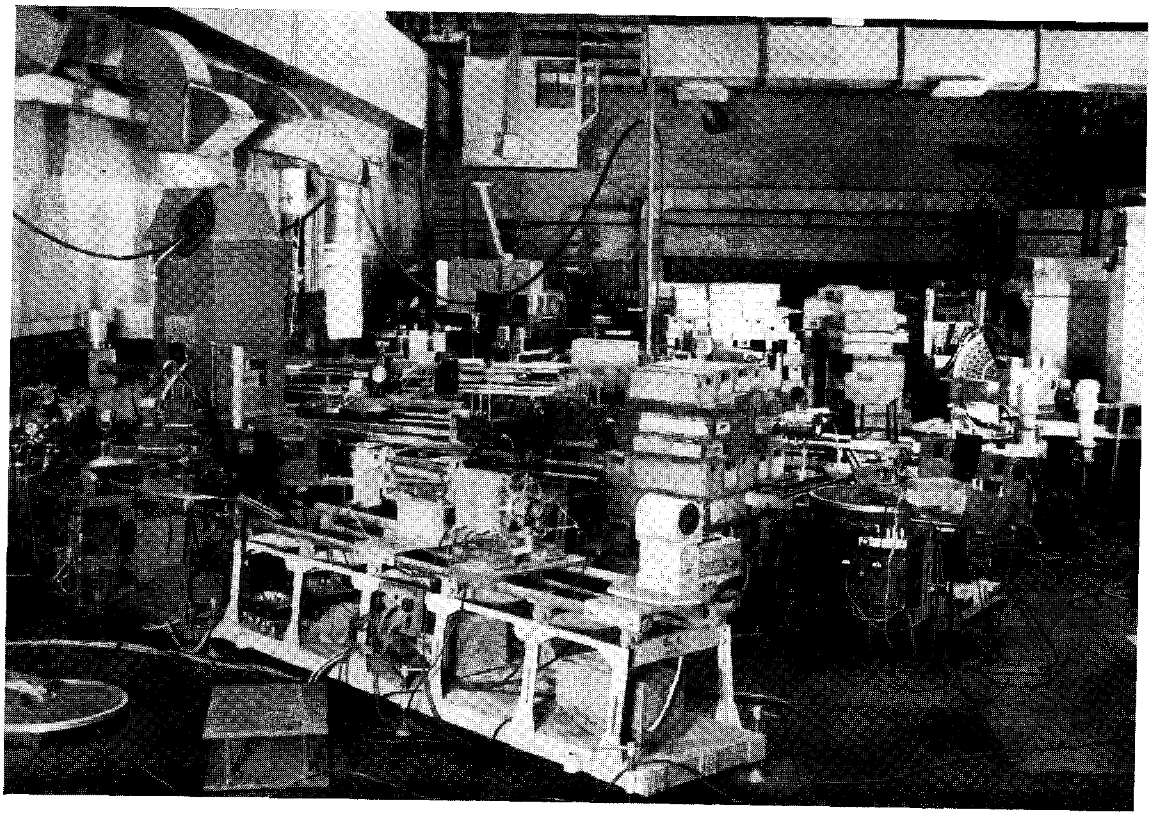

Fig. 10.

10 electromagnets with pole diameters from 30 to 100 cm. equipped with power systems allowing a simultaneous work with five magnets are at the disposal of research workers. There are also several thousand concrete slabs each 50 kg. in weight and used as bricks for local shielding.

A photograph of the layout of the experimental apparatus in the experimental rooms is given in fig. 10. All the terminal recording devices (scaling circuits, self-recorders, electromechanical counters etc.), as well as the remote control panels of the units in the experimental room and in the "meson" laboratory, are located in a special recording appliance room separated from the experimental room by a 2 m. thick concrete wall (see fig. 3). The equipment in these rooms is connected up by a special wiring. The system of cable panels permits the use of the recording equipment together with any of the experimental devices installed in any part of the measuring appliance room. Entry into the experimental rooms is strictly forbidden when the synchrocyclotron is in operation : the doors are fitted with automatic block systems. During this time the scientific personel engaged in carrying out nuclear investigations on the accelerator is in the recording appliance room. As pointed out above, the background level due to accompanying radiations is extremely low in this room, thus making it possible to stay here for any length of time.

The collimator system and the shielding are to be constructed as to permit wide application of the principle of parallel (simultaneous) work of experimental arrangement groups with several beams of the same or different particles. Thus experiments have been proceeding for some time on 10-12 installations with four neutron beams and two polarized proton beams. It is also possible to carry on simultaneous experiments on two chambers (cloud and diffusion) with beams of negative π mesons emerging into the recording room.

In connection with the latter it should be noted that the accelerating voltage on the 6 m. synchrocyclotron can be "manipulated" [19] in such way that the generation of high-frequency oscillations can be cut off at the right moment and the particles are thus ejected from the accelerator only at limited time intervals when the chambers are prepared to record them.

Finally, "the accumulation régime" was used in the operation of the accelerator to increase the intensity of π mesons in the pulse in the cloud chamber and diffusion chamber experiments—a very important matter in experiments with π mesons of maximum energy (the number of which is small [20]). This consists in the fact that during 3 or 4 accelerating cycles particles are accelerated only to the radius of 160-180 cm. (with the frequency changing from 25 to 19.5-18 Mc/s and the energy of the particles 240-300 Mev), and then in the fourth cycle the accelerating voltage is applied to the dee (at all frequencies from 25 to 14 Mc/s) and the particles accelerated to the maximum radius of 278-279 cm.

In this way, the intensity of the π meson beam in the pulse can be increased about 3 times and the efficiency of the operation of the chamber will be greater.

Conclusion

The ejection from the synchrocyclotron chamber of a large number of high-energy particle beams has enabled investigations to be conducted on a large scale.

Simultaneous experiments on several installations, the utilization of multiple channel systems and remote control of the apparatus located in the zone of enhanced biological danger (the experimental room and the "meson" laboratory) have made it possible to raise the accelerator utilization coefficient considerably and reduce unproductive losses in operation time. The latter amount to no more than 7-8 % and are mainly determined by the time required for servicing the experimental installation equipment and the synchrocyclotron.

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