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DESIGN CONCEPT AND COMPUTER SIMULATION OF NUCLOTRON BEAM EXTRACTION SYSTEM WITH A BENT CRYSTAL

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The scheme of nuclei beam extraction from Nuclotron by means of a bent crystal has been considered. Different methods for the beam guidance onto the crystal were discussed. It is more reasonable to simultaneously use an orbit bump and a transverse diffusion of the beam particles. Deflection efficiency of the nuclei beam with energy of 6 GeV/u by a bent silicon crystal and their multiturn extraction from Nuclotron has been studied by computer simulation. It was shown that with an optimal crystal length the extraction efficiency may be increased considerably due to multiple passages of particles through the crystal deflector.

The investigation has been performed at the Laboratory of High Energies, JINR.

Концепция и компьютерное моделирование системы вывода пучка из Нуклотрона изогнутым кристаллом

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Рассмотрена схема использования изогнутого кристалла для вывода пучка релятивистских ядер из Нуклотрона. Дан анализ различных методов наведения частиц на дефлектор. Показана целесообразность использования одновременно локального искажения орбиты и поперечной диффузии частиц. Компьютерным моделированием исследована эффективность отклонения ядер с энергией 6 ГэВ/нуклон изогнутым монокристаллом кремния и многооборотный вывод их из Нуклотрона. Показано, что при оптимальной длине кристалла эффективность вывода пучка может быть значительно увеличена за счет кратных прохождений частиц через кристаллический дефлектор.

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1. Introduction

The first beam extraction from a cyclic accelerator by means of a bent crystal was performed at the Dubna synchrophasotron [1] and then at the IHEP synchrotron [2]. In both the cases the extraction efficiency was small enough, about 10^{-4}, because the systems used for the beam guidance were not optimal. So, a fast decreasing of the closed orbit radius was used at the synchrophasotron and the orbit bump at the IHEP synchrotron.

The crystal deflectors have good perspectives of usage for particle extraction from a beam halo at the largest proton and ion colliders SSC, LHC, RHIC and UNC. The most attractive feature of such an extraction is that the colliding mode of machine operation is not disturbed, and some fixed target experiments may be carried out simultaneously. The experimental study of appropriate extraction systems for SSC and LHC are under investigation now at the Tevatron and the SPS [3,4]. So, a successful extraction of 120 GeV proton beam from the SPS with a record efficiency of about 10% was fulfilled recently at CERN [5]. The injection of a white noise at the deflector plates of the feedback system was used to initiate the transverse diffusion of particles onto the bent crystal. On the other hand, a longitudinal diffusion of beam halo particles onto the crystal was proposed for the SSC beam extraction [6]. Moreover, a resonance method for increasing the longitudinal oscillations of beam halo particles without perturbation of the beam was offered by the authors [7].

The extraction efficiency of the beam from a cyclic accelerator P_{ex} may be higher than a beam deflection efficiency by a bent crystal due to multiple passages of the beam particles through the crystal [8,9]. It occurs when the crystal length is not large, so $S_{cr} < S_{ms}$ and $S_{cr} < S_n$, where S_{ms} is the length through which the rms angle of multiple scattering becomes equal to the channeling critical angle θ_c, and S_n is the nuclear interaction length of the crystal. The first condition determines the growth rate of the beam divergence due to multiple scattering in the crystal; the second one, decreasing of the circulating beam intensity.

In this work the analytical estimations and computer simulation of the nuclei deflection efficiency were fulfilled for JINR Nuclotron, at which the first results with the beam accelerating have been received recently [10,11]. It is necessary to locate the crystal deflector at the azimuth, where the beam divergence is maximum, and the beam envelope is far from the closed orbit. That is, near a focusing quadrupole. A necessary angle of deflection by the crystal is about 50 mrad for Nuclotron to go out a next defocusing quadrupole. The cryogenic equipments are the obstacles for the extraction in a horizontal direction. Therefore, the extraction in a vertical direction is considered here. Figure 1 shows the scheme for the beam extraction from Nuclotron. The possibilities for the Nuclotron beam guidance onto the crytal deflector either by means of the closed orbit bump, which may be created by the existing system of correcting magnets, or as the result of a transverse diffusion initiated due to a noise injection into the inflector plates, have been studied by computer simulation. It was shown, that for

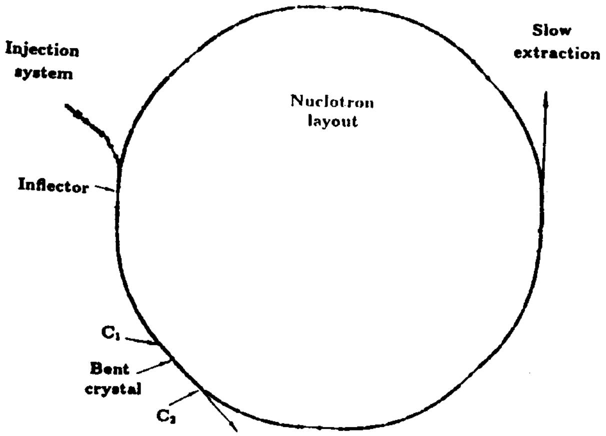

Fig.1. Nuclotron layout with the elements for the beam extraction by means of a bent crystal: inflector, C_1, C_2 — correcting coils, bent crystal

Nuclotron in the case of the maximum particle energy the extraction efficiency may be increased considerably due to multiple passages of the circulating beam particles through the deflector.

2. Beam Deflection Efficiency by a Bent Crystal

1. *Dependence on $\omega = A/Z$.* Let us consider according to [12] the change of the main characteristics of particle channeling in a bent crystal in going from protons to nuclei (Z,A) with the same energy per nucleon E_1, and estimate for Nuclotron the crystal deflector efficiency with a maximum particle energy. The critical bend radius of the crystal R_c, at which the particle channeling is possible yet, is proportional with ω

$$R_c^{\omega}(E_1) = \omega R_c^{1}(E_1). \qquad (1)$$

If the bend is measured in the relative units, $r = R/R_c$, then a critical angle of the particle direction with the atomic planes of the crystal for channeling decreases with ω

$$\vartheta_c^{\omega}(r;\, E_1) = \omega^{-1/2}\vartheta_c^{1}(r;\, E_1). \qquad (2)$$

Suppose also that the rms beam divergence is measured in the relative units, $k = \theta_x/\theta_c$, then at the same crystal bend r, the particle capture into the channeling states does not depend upon ω

$$P_c^{\omega}(r, k; E_1) = P_c^1(r, k; E_1), \qquad (3)$$

and the dechanneling length increases proportionally with ω

$$S_d^{\omega}(r, k; E_1) \cong \omega S_d^1(r, k; E_1). \qquad (4)$$

So, the beam deflection efficiency by a bent crystal at a required angle α does not depend on ω also at the same r and k

$$P_d^{\omega}(\alpha; r, k; E_1) = P_d^1(\alpha; r, k; E_1), \qquad (5)$$

$$P_d^1(\alpha; r, k; E_1) = P_c^1(r,k; E_1) \exp[-\alpha\, rR_c^1/S_{1/e}^1(r, k; E_1)]. \qquad (6)$$

By the other words in going from protons to nuclei with the same energy per nucleon, E_1, the crystal efficiency for the beam deflection remains without changing for the nuclei beam with divergence which is smaller $\omega^{1/2}$ times than for the protons, and when a curvature of the crystal used is smaller ω times.

2. *Optimal dimensions and bend of the crystal deflector.* The efficiency of deflection by a bent crystal is maximum for a parallel particle beam. For this case Fig.2 shows the dependence of the deflection efficiency at the angle $\alpha = 50$ mrad for protons, and nuclei of ${}^6C^{12}$ and ${}^{79}Au^{197}$ with energy 6 GeV/u upon the bend radius of the silicon crystal bent along (110) planes. It reaches about 20% in a maximum. The corresponding dependences of the dechanneling lengths are shown in Fig.3. These results were recieved by computer simulation of the beam passage through the crystal in the frame of the model with the averaged potential of the bent crystal planes, and with taking into account the change of the particle transverse energy due to multiple scattering by the crystal electrons and nuclei [13]. The dependences shown for the deflection efficiency differ by the scale of R. They are close to each other when the crystal bend is measured in the relative units r, that confirms our theoretical conclusions. The crirical radii of the crystal bend R_c^{ω} equals 1.16, 2.32 and 2.88 cm for the protons, nuclei C and Au, respectively. The optimal bend radius of the silicon crystal at which the beam deflection efficiency is maximum for the nuclei beam extraction from Nuclotron is about 20 cm. The corresponding length of the crystal is 1 cm.

The considered deflection efficiencies of nuclei beams are maximum which may be recived. In reality, the particle beams have some divergence. The probability of the particle capture into the channeling regime at the entrance into the crystal and their dechanneling lengths decrease when the beam divergence increases. So, when the beam divergence equals the

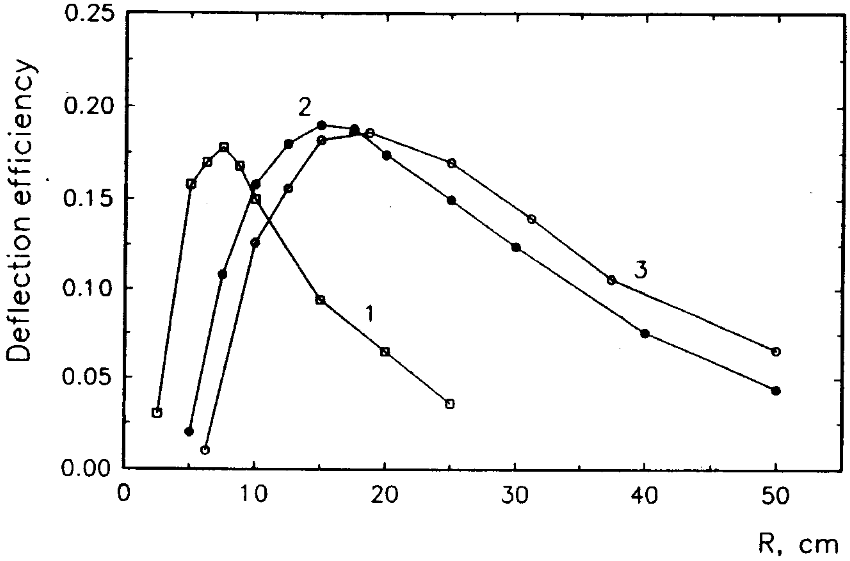

Fig.2. The deflection efficiency of the parallel nuclei beam with energy 6 GeV/u by a silicon crystal bent along (110) planes as a function of the crystal bend radius *R*. The crystal bending angle 50 mrad. Curves: 1 — protons, 2 — $^{6}C^{12}$, 3 — $^{79}Au^{197}$

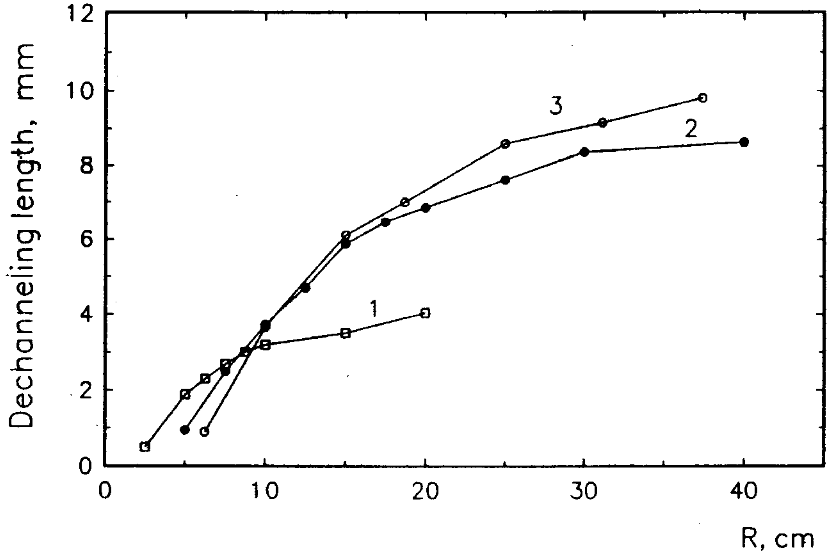

Fig.3. The nuclei dechanneling length as a function of the crystal bend radius. The conditions are the same as for Fig.2

critical channeling angle θ_c, that is close to the value expected for Nuclotron at the beam guidance onto the crystal by a combination method (see below), the capture probability P_c and the dechanneling length S_d decrease two times. As a result the beam deflection efficiency at the considered angle of 50 mrad decreases approximately by an order of value.

The space acceptance of the crystal deflector, which is determined by its transverse dimensions, depends on its bend radius R. The point is that the perfect silicon and germanium crystals usually used in the channeling experiments may be elastically bent up to the definite limit after which they will be broken. This radius is proportional to the thickness of the crystal plate t. In the first experiment there was studied the beam deflection by a bent crystal, which was fulfiled in Dubna [14], it was shown that for a silicon crystal bent along (111) planes R_{br} (cm) $\approx 76 \times t$ (mm). So, in our case for the realization of the optimal bend with $R = 20$ cm the crystal thickness has not to be more than 0.3 mm. The deflector width may be varied. When the width is 10 mm it is enough to overlap the beam. However, it may be profitable to have a more narrow deflector to increase the distribution width of particles in the vertical coordinate at the entrance into the deflector due to initial misses at the beam broadening.

So, the optimal dimensions of the silicon deflector for the beam extraction from Nuclotron are 10x10x0.3 mm. The usage of the crystals with the length about 2—6 cm is more usual. However, in our case increasing of the crystal length up to 2 cm will decrease the deflection efficiency about three times. Moreover, for nuclei it will decrease considerably the extraction possibility due to multiple passages through the deflector.

As it was marked, due to multiple passages through the deflector the extraction efficiency P_{ex} is higher than the deflection efficiency P_d for the beam with the same divergence. The maximum of P_{ex} shifts to a smaller bend radius to compare with P_d [8]. It means that the usage of a shorter crystal is more profitable. However, in our case the crystal length selected according to the condition that P_d is maximum is small enough to decrease it more.

3. Beam Guidance onto the Crystal

1. *Orbit bump.* A slow uniform shift of the beam onto the crystal by means of the closed orbit bump gives possibility for the beam particles to enter the planar crystal channels with very small angles. However, in this case «inpact parameters» are very small too. It means that these particles will move through the crystal in a narrow surface region. Therefore, they

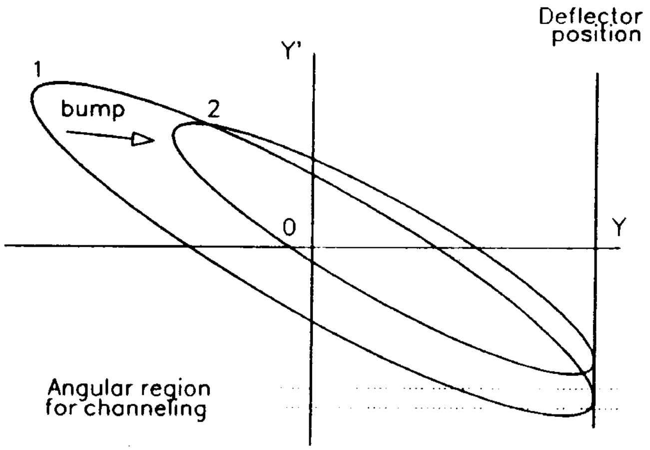

Fig.4. Schematic picture of growing orbit bump which takes away the beam from the angular region of the capture into the channeling states in the bent crystal

will not deflect at the first hits with the deflector when there is an imperfection of the surface layer or the crystal surface is not parallel with the considered atomic planes.

Besides, there is another circumstance which appears at the bump usage. The deflector location near the center of the focusing quadrupole leads to large troubles with the crystal alignment while it is possible. On the outher side when it is located outside the quadrupole the growing orbit bump takes away the beam fast from the angular region of the capture into the channeling states, that is shown in Fig.4.

Increasing of the betatron oscillations of the beam particles may be used for their guidance onto the deflector. It may be made by means of either the transverse diffusion initiated due to the noise injection on the inflector plates or the resonance excitation of these particles at the frequencies to which a rotation frequency f_0 and the betatron oscillation one qf_0 are multiple.

2. *Transverse diffusion.* Resonance excitation. The crystal deflector has to be located at the distance about 3 cm from the closed orbit to be not the obstacle for the beam particles at the injection stage. The rms particle distance from the closed orbit at the crystal azimuth is $\sigma_{y0} = 0.5\sqrt{\varepsilon_{y0} \cdot \beta_y} \cong 2.5$ mm, when the vertical emittance of the nuclei accelerated up to 6 GeV/u is $\varepsilon_y = 2\times10^{-6}$. Assuming that the beam begins to touch with the deflector at $3\sigma_y$, it means that the beam emittance has to be

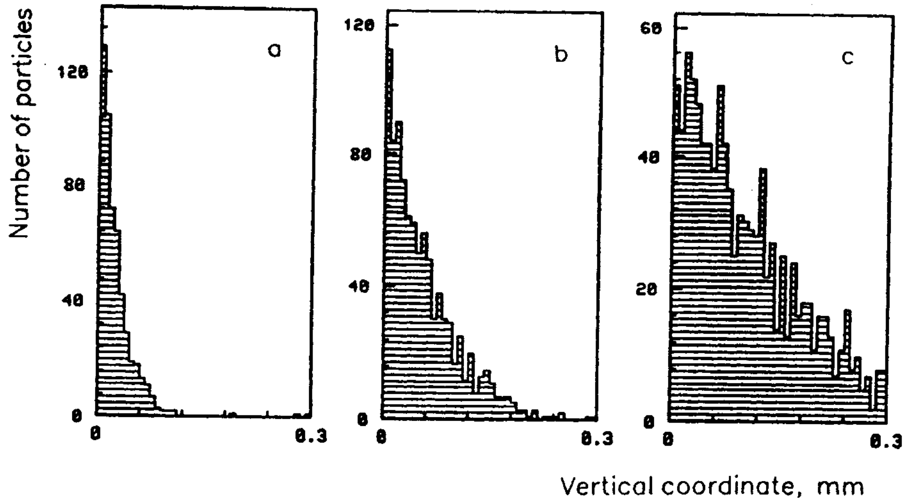

Fig.5. Transverse diffusion. The particle distributions in a vertical coordinate at the entrance into the crystal for the different values of the rms angular deviations received at their passage through the inflector σ_{noi}, μrad: .1 (a), 2.5 (b), 5 (c). The full crystal thickness is 0.3 mm

increased sixteen times to beging the extraction process. This beam broadening leads to the unprofitable increase of the angular divergence of the particles entering the crystal. The rms deflection angle of the beam particles at the passage through the inflector plates to have the required extraction duration τ may be estimated as

$$\sigma_{noi} = \sqrt{\frac{\Delta \varepsilon_y T_0}{\beta_y \tau}}. \qquad (7)$$

So for $\tau = 1$ s it will be necessary to have $\sigma_{noi} = 1.5$ μrad. The rms voltage at the inflector plates equals respectively $\langle U \rangle = 0.6$ kV for the nuclei with energy 6 GeV/u and $\omega = 2$.

For the simulation of the beam extraction from the Nuclotron two points in the accelerator lattice were considered. The inflector is located in the first point, and the bent crystal in the second one near the defocusing quadrupole through the superperiod from the inflector. The initial beam distribution is given at the bent crystal position. It is generated according to Gaussian with the rms deviations the values of which are determined by the beam emittance. Two transfer matrices are used to transport the particles from the bent crystal to the inflector and back. When the particles pass through the inflector plates they acquire the chance angular deflections in a vertical

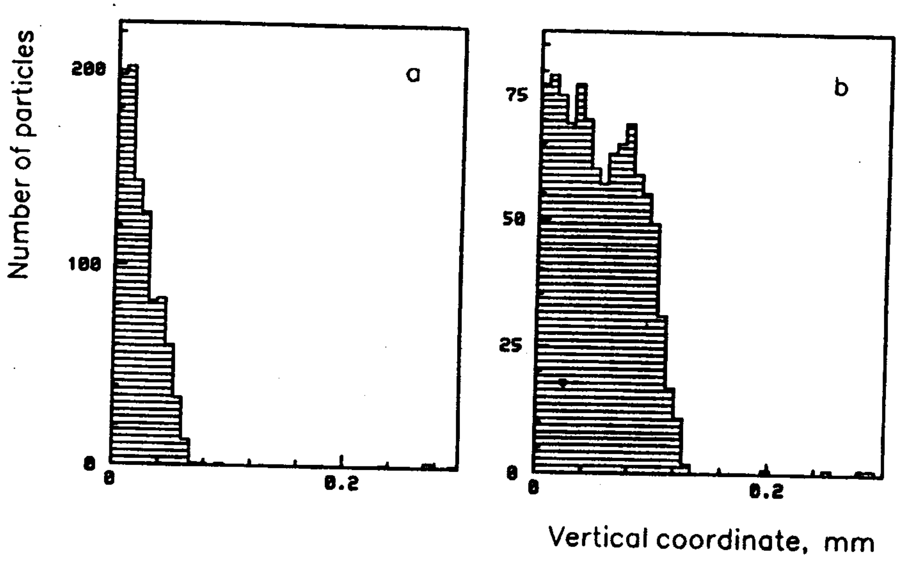

Fig.6. Resonance excitation. The particle distributions in a vertical coordinate at the entrance into the crystal. For the different angular deflections of the particles in the inflector θ_v, μrad: 5 (a), 10 (b). The period of the perturbations is $T_v = 20\ T_0$

direction. It causes their diffusion, and they begin to hit the crystal deflector.

Figure 5 shows the particle distributions in the vertical coordinate at the entrance into the crystal. They were calculated for the different values of the rms angular deviations received at the particle passages through the inflector. When $\sigma_{noi} = 5$ μrad the distribution width approximately equals the deflector thickness. With decreasing the noise value the width decreases.

The corresponding distributions when the resonance excitation of the beam particles was used are shown in Fig.6. The particle deflections in a vertical direction with the values of 5 μrad (a) 10 μrad (b) were realized at their passage of the inflector with the period $T_v = 20\ T_0$. It was considered here with a vertical betatron tune $q_v = 6.85$. The distributions have a bell-shape and are more narrow than in the case of the transverse diffusion with the same value of the rms angular deflections. Besides, the required time for the beam ejection onto the crystal is considerably smaller.

3. *The combination method for the beam guidance. The multiturn beam extraction.* So, the orbit bump takes away the beam from the angular region of the capture into the channeling states; on the other band, the beam broadening during the transverse diffusion decreases the deflection efficiency. Therefore, it will be more optimal to decrease the distance be-

tween the beam and the deflector by means of the bump up to the touching at $3\sigma_{y0}$, that is about 7 mm, and only then to throw the beam particles onto the deflector due to the transverse diffusion or the resonance excitation.

Assuming the usage of this method for the beam guidance onto the crystal the computer simulation of the Nuclotron beam extraction was fulfiled. The silicon crystal bent along (110) planes with the bending angle of 50 mrad has the optimal dimensions. The noise generator of the inflector begins to work when the beam approaches the crystal at the distance of 7 mm by means of the orbit bump. Some particles which enter the crystal may be lost due to the inelastic nuclear interactions. The mean path before the interactions for nuclei in the crystal S_n is proportional to $A^{-0.71}$. In the silicon it equals 45.5, 7.8 and 1.07 cm for protons, nuclei C and Au accordingly. The density of the other particle depends on the angle Y', which they have after the crystal passage. When $Y' > \alpha - \theta_{col}$, where α is the bending angle, $\theta_{col} = 100\,\mu$rad is a collimation angle, the particle will be extracted from the accelerator. The particles are lost downstream at the wall of the beam pipe when $\theta_{ac} < Y' < \alpha - \theta_{col}$, where $\theta_{ac} = 10$ mrad is the angular acceptance of Nuclotron. Otherwise the particles remain in the circulating beam.

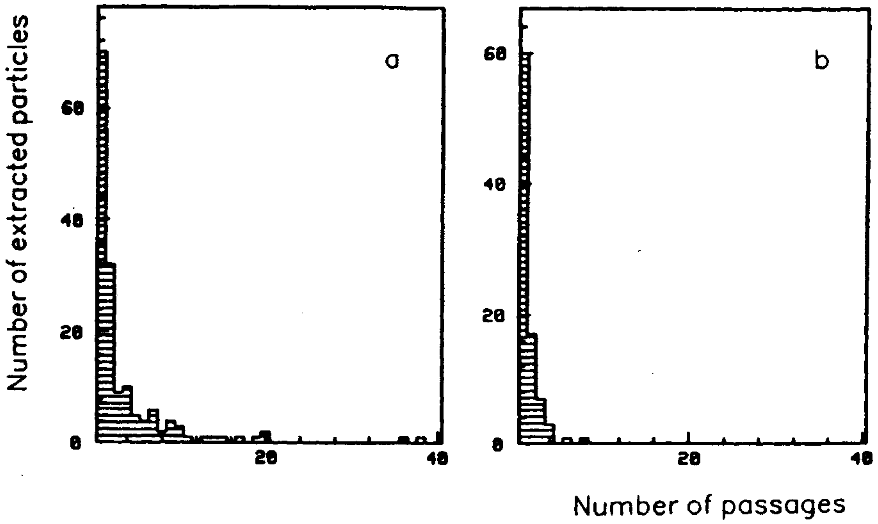

Fig.7. The distributions of the extracted particles in the number of passage through the crystal before the extraction for the nuclei with energy 6 GeV/u: (a) — ${}^{6}C^{12}$, (b) — ${}^{79}Au^{197}$

The calculated extraction efficiency is more than 7% for nuclei of ${}^{6}C^{12}$ and 4% for ${}^{79}Au^{197}$. The distributions of the extracted particles in the number of passages through the crystal before the extraction are shown in Fig.7 for nuclei C (a) and Au (b). The contribution of multiple passages increases significantly the extraction efficiency, which for the first hits with the crystal is only about 3% for both cases. The passage multiplicity is higher for nuclei of C, where it achieves 20, because the particle loss due to the nuclear interactions in the crystal is smaller for C than for Au. It is necessary to mark here that the extraction possibility due to multiple passages through the deflector may be considerably smaller for ions comparison with nuclei because their charge states may change at the first passage, and they may be lost from the circulating beam.

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