PLANS FOR PHYSICS WITH THE INTERSECTING STORAGE RINGS

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1. *Introduction*¹

In 1971 the Intersecting Storage Rings (ISR) at CERN will start operating. The ISR will allow us to study proton-proton collisions in an energy region, which is until now only accessible to cosmic ray experiments.

The total energy in the centre-of-momentum system of two particles with energies $E_1$ and $E_2$, and momenta $\vec{p}_1$ and $\vec{p}_2$, is

$$E_{CM}^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$$  \hfill (1a)

For individual energies $E_1 = E_2 = E$, and for $E \approx |\vec{p}| = |\vec{p}|$, and for a collision angle $\approx \pi$ we obtain ($\Theta = \pi$ - collision angle):

$$E_{CM} \approx 2E(1 - \frac{1}{8} \Theta^2)$$  \hfill (1b)

With $E = 25$ GeV we can consequently reach a CM energy of 50 GeV. This has to be compared to the CM energy of a 25 GeV proton incident on a proton at rest: $E_2 = M$

$$E_{CM} \approx \sqrt{2ME_1}$$  \hfill (1c)

which is about $E_{CM} \approx 7$ GeV for $E_1 = 25$ GeV. In order to obtain $E_{CM} = 50$ GeV under these conditions one has to apply an energy of the incident proton of $E_1 = 1340$ GeV.

As we will see later, the ISR are not equivalent.
to a 1 TeV accelerator. Whereas the ISR can reach an interaction
rate of roughly $10^6$ sec, at all intersects together, an
accelerator can dump its full accelerated current, which may
be as much as $10^{12}$/sec.

2. The Intersecting Storage Rings

2.1 ISR Parameters

The intersecting storage rings are essentially two
alternating gradient synchrotrons, each being roughly a rounded
square, one turned by $45^\circ$ with respect to the other, and thereby
intersecting at 8 points. Both rings are contained in the same
tunnel. The beam circulates in a stainless steel vacuum tube of
elliptic shape pumped by sublimation pumps to a vacuum of $10^{-9}$ Torr
all around and $10^{-11}$ Torr at the intersects. Some parameters
are listed in the table below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>total circumference</td>
<td>942.6 meters</td>
</tr>
<tr>
<td>intersection angle</td>
<td>14.8 degrees</td>
</tr>
<tr>
<td>vertical betatron amplitude</td>
<td>$\pm 0.5$ cm</td>
</tr>
<tr>
<td>horizontal betatron amplitude</td>
<td>$\pm 1.0$ cm</td>
</tr>
<tr>
<td>vertical betatron angle</td>
<td>$\pm 0.4$ mrad</td>
</tr>
<tr>
<td>horizontal betatron angle</td>
<td>$\pm 0.5$ mrad</td>
</tr>
<tr>
<td>momentum dispersion</td>
<td>$2.3$ cm/°/o</td>
</tr>
<tr>
<td>total momentum bite</td>
<td>$2^\circ$/o</td>
</tr>
<tr>
<td>maximum momentum</td>
<td>28 GeV/c</td>
</tr>
<tr>
<td>max. number of stacked particles</td>
<td>$4.10^{14}$/ring</td>
</tr>
<tr>
<td>max. current</td>
<td>20 Amp</td>
</tr>
<tr>
<td>luminosity</td>
<td>$4.10^{30}$ cm$^{-2}$ sec$^{-1}$</td>
</tr>
<tr>
<td>half life of luminosity</td>
<td>20 hours</td>
</tr>
</tbody>
</table>
Fig. 1

Fig. 2
2.2 The Stacking Process

Protons are injected from the inside of the rings on a stable orbit by means of a kicker magnet. Before injecting the next PS burst these protons have to be removed from this injection orbit, since the next pulse of the kicker would dump them on the wall. The shifting of the injected beam away from the injection orbit is achieved by a programmed R.F. acceleration. It is known that the equilibrium orbit in a synchrotron is given by the frequency of the acceleration voltage. To shift the beam the R.F. is switched on with a frequency corresponding to the injection orbit. Then a slow decrease in frequency will move the beam to a larger circumference and, correspondingly, to a higher energy. Having reached the final orbit, the R.F. is switched off. In order to keep the momentum spread of the beam as small as possible, two conditions have to be fulfilled:

(i) not to induce synchrotron oscillations with big amplitude, the R.F. amplitude has to be small;

(ii) to capture all the beam by the R.F., the stable phase has to include almost $2\pi$, i.e. the equilibrium phase is almost $\pi$; the acceleration has to be slow.
This process is trivial if there is only one PS pulse to be stacked. The aim is, however, to stack as many pulses as possible side by side. To do that a new pulse must be brought close to the previous one without affecting its position. To accelerate a particle with an energy and an orbit which is slightly different, it has not only to be in a stable phase region, but also the R.F. voltage has to be sufficiently high. Otherwise the particle slips in phase and obtains on the average no acceleration. From that we conclude the condition for not affecting the previously stacked pulse:

(iii) the R.F. amplitude has to be sufficiently low just to accelerate the new pulse, but not the previous one.

By this operation, described here in a simplified way, one obtains a number of stacked pulses side by side with slightly different energies.
The number of stacked particles is:

\[ N_{ST} = N_{PS} \frac{\Delta p}{\Delta p_{\phi}} \text{ ISR} \approx 10^{12}\cdot 400 \quad (2a) \]

It proportional to the phase space occupied

\[ N_{ST} = 2.10^{16} \frac{\Delta p}{p} \quad (2b) \]

The circulating electric current is \( (e = 1.6 \cdot 10^{-19}\text{Coulomb}) \)

\[ I = \frac{N_{ST} \cdot e \cdot c}{2\pi R} \approx 20 \text{ Ampere} \]

2.3 Interaction Rate and Luminosity

The number of beam beam interactions can be easily calculated from the known relation

\[ N_{int} \text{[sec}^{-1}] = \sigma \text{[cm}^2] n_1 \text{[sec}^{-1}] \rho_2 \text{[cm}^{-3}] \ell_2 \text{[cm]} \quad (3a) \]

\[ = \sigma \cdot \frac{N_1 c}{2\pi R} \frac{N_2}{2\pi R h w} \frac{w}{\tan \frac{\theta}{2}} \quad (3b) \]
where \( N_{1,2} \) are the number of particles in each beam, \( 2\pi R \) the total circumference of one ring, \( w \) the beam width, \( \Theta \) the angle of intersect, \( \ell \) the effective length

\[
\ell = \frac{w}{\tan \frac{\Theta}{2}}
\]  

(4)

and \( h \) the effective height, defined by

\[
\rho = \frac{N}{2\pi R w h_{\text{eff}}} = \frac{N}{2\pi R w} \cdot \frac{\int \rho_2(y) \rho_1(y) \, dy}{\int \rho_1(y) \, dy \int \rho_2(y) \, dy}
\]  

(5)

Here \( \rho_{1,2}(y) \) is a one-dimensional vertical particle density on one beam. For equal numbers in either beam

\[
N_{\text{int}} = \frac{\sigma c}{h \tan \frac{\Theta}{2}} \left( \frac{N}{2\pi R} \right)^2
\]  

(3c)

\[
= \sigma L
\]  

(6)

where \( L \) [cm\(^{-2}\) sec\(^{-1}\)] is the luminosity, i.e. the rate per second for a cross section of 1 cm\(^2\). Inserting numbers, and using \( \sigma = \sigma_{\text{tot}} = 40 \text{ mb} \), we obtain

\[
L = 10^{34} \left( \frac{\Delta p}{p} \right)^2 \\
N_{\text{int}} = 4 \cdot 10^8 \left( \frac{\Delta p}{p} \right)^2 \\
L_{\text{max}} = 4 \cdot 10^{30} \\
N_{\text{int}}^{\text{max}} = 1.6 \cdot 10^5
\]

In order to see this result in the right proportion we calculate a "luminosity" \( L \) for a hydrogen target of 1 foot \( \approx 30 \text{ cm} \) at a PS beam of \( 10^{12} \) protons/second: (one foot of liquid \( \text{H}_2 \) \( \rightarrow 1 \) event/sec. barn)

\[
L_T = 10^{36}
\]

This is more than five orders of magnitude higher than the ISR luminosity.
2.4 Background

Besides the beam-beam interactions there are of course collisions of the circulating protons with the rest gas in the vacuum chamber, predominately hydrogen desorbed from the stainless steel walls. The vacuum is supposed to be $10^{-9}$ Torr all around the ring and $10^{-11}$ Torr at the intersects. The resulting effects are the following:

(i) beam loss by nuclear interactions;

(ii) beam blow-up and subsequent beam loss by multiple Coulomb scattering. Although the beam loss by this effect is not considerable, the increase of beam height and the corresponding decrease in luminosity is expected to determine the beam (luminosity) life time to 20 hours;

(iii) beam gas background reactions. The rate of these reactions is at $10^{-11}$ Torr ($N_{\text{Avogadro}} = 2.7 \cdot 10^{19} \text{ cm}^{-3}$)

\[
N_{BG} = \sigma n_B \rho_g \tau_g
\]

\[
= \sigma N \frac{C}{2\pi R} 2 \cdot N_{\text{Avogadro}} \rho_g \left[ \frac{\text{kg}}{\text{cm}^2} \right] \tau_g
\]

\[
\approx 300 \text{ [sec}^{-1} \text{ m}^{-1}]
\]

This tells us that the serious background is not produced at the intersect, but comes from particles produced with small angles upstream in $10^{-9}$ vacuum region.

3. Present Knowledge about Physics at Ultra High Energies \(^3\)

Cosmic ray experiments have been performed for many years and yielded information about high energy reactions. What is known at 1000 GeV proton energy?
(i) the total \( pp \) cross section is unequal zero and probably between 30 and 50 mbarn;

(ii) the multiplicity of charged particles, mostly pions, produced in an interaction is \( \langle n^\pm \rangle \approx 14 \). Its dependence from energy may be

\[
\langle n^\pm \rangle = 2 \sqrt{E_{\text{CM}}}
\]

One expects a corresponding number of neutral \( \langle n^0 \rangle \approx \sqrt{E_{\text{CM}}} \).

The distribution of multiplicity is rather uniform.

(iii) The angular distribution is usually parametrized by that of transverse and total momentum. One finds an exponential distribution function for \( p_T \):

\[
\frac{dN}{dp_T} \propto p_T \exp\left(-\frac{p_T}{p_{T0}}\right)
\]

with \( p_{T0} = 0.15 \text{ GeV/c} \)

and \( \langle p_T \rangle = 2 p_{T0} = 0.3 \text{ GeV/c} \)

(iv) the distribution of total momentum is different for nucleons and pions. For nucleons it is found to be flat, which is equivalent to a uniform distribution of inelasticity. With an average inelasticity of 0.5 we expect a mean pion momentum of

\[
\langle p^\pi_T \rangle \approx \frac{0.5 E_{\text{CM}}}{\langle n^\pm \rangle + \langle n^0 \rangle} = \frac{1}{6} \sqrt{E_{\text{CM}}}
\]

which yields about 1 GeV at the ISR. The distribution function of pion momenta seems to be gaussian or exponential.

The correlation between \( p_T \) and \( p \) is represented in the "Peyrou plot":
The present knowledge of high energy collisions is expressed by the "fire ball" model. This model claims that

nucleons continue as "leading particles" with little change in energy and direction, possibly exited to an \( N^+ \);

pions evaporate from the fire ball which is an energy cloud at rest in the C.M., deposited by the peripheral collision of the initial nuclei.
4. Plans for Experiments at the ISR

4.1 The Total Cross Section

The experiment to measure the total pp cross section is probably the conceptually easiest. Since the total path length in the gas is about $10^2$ times more than that in the crossing beam, a transmission experiment is not possible. Therefore the total number of interactions is counted in an almost 4π-counter-geometry. The cross section is then obtained from (6).

$$\sigma_{\text{tot}} = \frac{N_{\text{tot}}}{L}$$

A 1% statistical error can, in principle, be obtained in 0.1 sec.

In practice there are however several difficult problems:

(i) the counters see always the sum of beam-beam and beam gas interactions. To exclude the beam-gas background the coincidence of both sides is required, since a target at rest will emit particles preferentially into one cone only. The validity of this hypothesis can be checked by one-beam operation.

(ii) some fraction of events all charged particles will remain inside the beam tube. This is for example the case with small angle elastic scattering. One estimates this fraction to be of the order of 10%o. This is corrected for by an extrapolation of detected particles to 0°.
the quality of the measurement of the total cross section is dependent on the normalization, i.e. the determination of luminosity (eqs. 5 and 6)

\[ L = \frac{c}{h_{\text{eff}} \tan \theta} \left( \frac{N}{2\pi R} \right)^2 \]

where \( \frac{1}{h_{\text{eff}}} = \frac{\int \rho_2(y) \rho_2(y) \, dy}{\int \rho_1(y) \, dy \int \rho_1(y) \, dy} \)

The experimenters intend to determine \( h_{\text{eff}} \) numerically after having measured \( \rho_1(y) \) and \( \rho_2(y) \) independently. For this purpose they measure the \( y \)-distribution of beam gas interaction vertices along the upstream beam pipe by a spark chamber arrangement. They estimate that a 1 °/o accuracy can be obtained by this method.
4.2 Elastic Scattering

Four definitions to start with:

(i) **diffraction scattering**:

\[
\left( \frac{d\sigma}{dt} \right)_N = A e^{bt} \tag{11}
\]

\[ b = \frac{R^2}{4} \] \text{ with } R \text{ the "radius" of the scattering body}

\[-t = 4 k^2 \sin^2 \left( \frac{\theta}{2} \right) \approx k^2 \theta^2 \tag{12}\]

\[ \text{with } k = p_{\text{CM}} \text{ and } \theta \text{ the scattering angle} \]

Note: \[
\frac{d\sigma}{d\Omega} = \frac{k^2}{\pi} \frac{d\sigma}{dt} \tag{13}
\]

(ii) **optical theorem**:

\[ \text{Im } F(\omega) = \frac{k}{4\pi} \sigma_{\text{tot}} \tag{14a}\]

\[ \text{with } F(\omega) \text{ the scattering amplitude} \]

For a scattering on a black disk \( F(\omega) \) is imaginary and

\[ \frac{d\sigma}{d\Omega} \left( 0^0 \right) = \frac{k^2}{16\pi^2} \sigma_{\text{tot}}^2 \tag{14b}\]

(iii) **real part of forward scattering**:

\[ F_R = \alpha F_I \quad (|\alpha| \approx 0.1 \text{ at } 25 \text{ GeV}) \]

\[ F = F_R + i F_I \]

\[ \frac{d\sigma}{d\Omega} \left( 0^0 \right) = \frac{k^2}{16\pi^2} \sigma_{\text{tot}}^2 \left( 1 + \alpha^2 \right) \tag{14c}\]

where the real part adds of the order \( \alpha^2 \approx 0.01 \) to eq.(14b).
iv) Coulomb scattering:

\[
\frac{d\sigma}{dt} = \frac{4\pi e^4}{\beta^2 t^2} G_E^4(t)
\]  

(15)

where \(G_E(t)\) is the proton electric form factor, which is equal unity at the values of \(t\) under consideration.

From here we can elaborate the following experimental objectives:

(a) determination of the slope of the diffraction peak. At PS energies \(b\) is found to be of the order of 10. At 50 GeV (Serpukhov) a recent experiment established \(b = 11\). A logarithmic extrapolation to ISR energies yields \(b = 15^6\). This shrinkage of the diffraction peak may indicate an increase in the proton size\(^7\). The value of \(b = 15\) limits experiments to \(t \leq 1.5\) i.e. to \(\theta \leq 50\) mrad.

<table>
<thead>
<tr>
<th>(\theta) mrad</th>
<th>(-t [\text{GeV}^2/c^2])</th>
<th>(d\sigma/d\Omega [\text{mb/sterad}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1.6 (\cdot 10^4)</td>
</tr>
<tr>
<td>1</td>
<td>6 (\cdot 10^{-3})</td>
<td>1.58 (\cdot 10^4)</td>
</tr>
<tr>
<td>2</td>
<td>2.3 (\cdot 10^{-3})</td>
<td>1.54 (\cdot 10^4)</td>
</tr>
<tr>
<td>5</td>
<td>15 (\cdot 10^{-3})</td>
<td>1.26 (\cdot 10^4)</td>
</tr>
<tr>
<td>10</td>
<td>0.06</td>
<td>6.3 (\cdot 10^3)</td>
</tr>
<tr>
<td>20</td>
<td>0.25</td>
<td>3.75 (\cdot 10^2)</td>
</tr>
<tr>
<td>50</td>
<td>1.56</td>
<td>1.07 (\cdot 10^{-6})</td>
</tr>
</tbody>
</table>

(b) measurement of the Coulomb scattering, which dominates for angles of less than 2 mrad at 25 GeV. This experiment yields an absolute and calculable cross section and is therefore a measurement of the luminosity.
(c) extrapolation of the nuclear cross section to $0^\circ$ which yields independent determination of the total cross section by the optical theorem.

**pp scatt.** $E^* = 50$ GeV

- --- Coulomb scattering
- --- Nuclear scattering
- ___ Sum ($\alpha = 0$)

\[ \sigma_{tot} = 40 \text{ mb} \]

\[ b = 15 \text{ (GeV/c)}^{-2} \]

**Scattering angle [m rad]**

Fig. 3
The pp scattering experiment, is in principle, straightforward by measuring the coincidence of two collinear (in the CM!) particles from the intersect. Practical difficulties arise for small angles from the fact that in order to measure at 2 mrad the counters have to be at a distance of 2 cm from the central axis of the beam if 10 meters downstream. So the beam shape has to be carefully determined, and the absolute measurement of the scattering angle requires a calibration.

At larger angles the cross section drops so steeply that above 20 mrad events giving accidentally a collinear configuration such as

$$\text{pp} \rightarrow N^X N^X$$

where the $N^X$ decay produces protons with larger transverse momentum, will dominate in the detection. Two ways are foreseen to improve the discrimination:

- anticounters against other particles emerging from the vertex;
- magnetic analysis of the protons.
4.3 Inelastic Scattering, Diffraction and Exchange Reactions

One starting remark:

Two-body and quasi two-body processes can be split into the classes of diffraction and exchange reactions:

(i) Diffraction reactions are interpreted to occur at the boundary of the scattering body (black or opaque disk) and the cross section should be independent from energy, if the size of the scattering body does not change with energy. The differential cross section follows the exponential law

\[
\frac{d\sigma}{d\Omega} \propto e^{bt}
\]

Besides momentum there is only orbital angular momentum and the corresponding parity \( P = (-1)^{\Delta L} \) which can be transferred in a diffraction reaction (diffraction dissociation, or Pomeranchon exchange).

(ii) Exchange processes are invoked if there are other quantum numbers such as charge, isospin and intrinsic parity are to be transferred. These processes are known to have a cross section dropping with energy.

Turning now to pp interactions we see that the prominent quasi two-body process is the production of isobars:

\[
\begin{align*}
\text{pp} & \rightarrow \text{p} N^{X+} \\
\text{pp} & \rightarrow N^{X} N^{X}
\end{align*}
\]

Considering the conservation of quantum numbers we can separate the two mechanisms:
The diffraction process should be detectable at the ISR with a cross section of \( \sim 1 \) mbarn; the exchange process should be suppressed.

To discuss the detection of the isobar production we consider the reaction

\[
pp \rightarrow p N^X(1480) \\
\downarrow n \pi^+ \\
\pi^+ \theta \pi^{-} \\
\hbar
\]

Momentum and direction of the incident protons are known. If one measures the directions of the final proton, pion and neutron, one constraint is left after the application of 4-momentum conservation laws and the event can be reconstructed. The
distribution of the effective \((n \pi^+)\) mass indicates if a \(N^x\) was produced. We now discuss the problems of resolution, rate and background:

(i) the resolution is mainly determined by the momentum spread of the incident protons \(p/p = \pm 1\) \(^0/\circ\). This error is reflected after the fit in the fitted values of the particle momenta. The effective \((n \pi^+)\) mass \(M\) is:

\[
M^2 = m_n^2 + m_{\pi}^2 + 2E_{\pi}E_{n} - 2p_n p_{\pi} \cos \phi
\]

\[
\approx m_n^2 + p_n p_{\pi} \delta \phi^2
\]

\[
M \approx \frac{\phi}{2M} \left( p_n^2 \delta p_n^2 + p_n^2 \delta \phi^2 + 3p_n^2 \delta \phi^2 + 4p_n^2 \right) \left( p_n^2 \delta \phi^2 \right) \right)^{1/2} + \text{correlations}
\]

with assumed values we obtain for example

\[
\phi \approx 0.05 \quad \delta \phi \approx 0.002
\]

\[
p_n \approx 7 \quad \delta p_n \approx 0.07
\]

\[
p_n \approx 18 \quad \delta p_n \approx 0.18
\]

\[
\delta M \approx 0.03 \text{ GeV}
\]

(ii) the cross section of \(N^x\) production at PS energies is about 1 mb, and the diffraction mechanism invoked predicts the same cross section, which is about one order of magnitude down from the elastic, at ISR energies. The differential cross section should follow the same exponential law (see table 2)

\[
\frac{d\sigma}{dt} = Ae^{bt} \quad \text{with} \quad b \approx 15 \text{ GeV}^{-2}
\]

(iii) similar to the elastic scattering the limit in the four momentum transfer \(t\) is given by events which accidentally fulfil the kinematical conditions for this reaction. Similar are also the methods to suppress these events: the anti-coincidence counters against additional particles, and,
especially, momentum analysis of the charged secondaries. This makes the fit to have 3 constraints with only the neutron energy unmeasured. A large magnetic analysis system is being constructed to serve for this and other experiments.

4.3.1 The Split-Field-Magnet (SPM)

A big magnetic analysis system is foreseen at one of the intersects. It consists of one 5 m magnet on each of the outgoing beams. The magnets are magnetically coupled such that the same flux passes the two gaps, but in opposite direction (fig. 4). Two compensator magnets in each line keep the outgoing proton beam in its original position and direction. The magnet will be equipped with proportional wire chambers, which are self triggering and do not require scintillation counters. Additional particle identification detectors, such as Čerenkov and neutron counters, can be easily added. The detector is connected to a computer and should serve as a general facility.
4.4 Particle Production\textsuperscript{9)}

Particle production has been parametrized by empirical formulae and is theoretically described by the thermodynamical model. The experimental aim is to measure absolute yields of stable particles, such as $\pi^\pm$, $K^\pm$, $p$, $\bar{p}$ and $\gamma$ rays, and to determine their production cross section as function to their energy and angle. Experiments to provide these data are planned\textsuperscript{10)}, and they will cover a range from 15 mrad up to 90°. Magnetic spectrometers equipped with wire spark chambers will measure the particle production angle and momentum, Cerenkov counters will determine its nature.
Another aspect of particle production is concerned with the production of massive new particles with $M > M_{\text{proton}}$, such as

(i) quarks

\[ pp \rightarrow NN \bar{q}q \]

\[ pp \rightarrow N \bar{q}^{1/3} q^{2/3} \]

(ii) heavy bosons:

\[ pp \rightarrow NN W \rightarrow \mu^+ \mu^- \]

(iii) vector mesons:

\[ pp \rightarrow NN V^0 \rightarrow e^+ e^- \]

It is obvious that the high obtainable CM energy of the ISR shifts the threshold of produced masses to higher energies. It does not, however, in the frame of a statistical model, change the mass dependence of the production cross section

\[ \sigma \propto \exp \left( - \frac{M}{0.15} \right) \]

where $0.15 \rightarrow kT$ is the "temperature" of the system. The formula predicts a $\pi/p$ ratio of 250, but a $\pi/M$ ratio for $M = 5$ GeV of $10^{-13}$!

There is no quark experiment proposed at the ISR at the moment (see ref. 11). There are proposals for the search of heavy bosons and vector mesons\(^{12}\). These experiments do not necessarily try to reconstruct a particle from its decay products but try to find evidence for the decay of a heavy mass. The particle emitted in a two body decay energetic leptons, and these leptons do not have the limitation in transverse momentum, as have particles produced in strong interaction; secondary pions are bound to have small $p_T$, and so are their decay muons because of the small decay energy. The heavy boson W may be produced with small $p_T$, but not its decay muon because of the high decay energy.
So the experiments search for leptons with high $p_T$ there, where the tail of the exponential production distribution from strong interaction has become very small. The experiments aim at a limit $\sigma \cdot BR \approx 10^{-34} \text{ cm}^2$. 
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