STRUCTURE OF LIGHT.

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Abstract. In this talk I briefly explain the concept of the structure function of a photon (the best known boson). Then I review some of the current experimental evidence which confirms the existence of ‘strong’ interactions of photon suggested by this idea. I end by pointing out how the photon ‘structure’ has important implications for the interactions of high energy photons and hence for the design of the next generation of the high energy \( e^+e^- \) (linear) colliders which are absolutely essential for locating the missing links in our knowledge of fundamental particles and interactions among them.

1. Introduction

This symposium is being held to celebrate the birth centenary of S.N. Bose after whom half of the elementary particles are named, i.e., the particle with integral spin: bosons. In this talk I want to discuss an interesting feature of interactions of the one boson best known to the particle physics community viz. the photon. In spite of the fact that the theory of interaction of photons with electrons is the best formulated, most studied and best tested theory, interactions of photons with matter continue to exhibit interesting features which give further insight into the question of fundamental constituents of matter and interactions among them. At high energies, the measured cross-sections in processes involving photons seem to imply that the elementary, point-like photons behave at high energies like strongly interacting particles (hadrons) which are bound states of more fundamental quarks and antiquarks. In this talk I discuss the issue of this ‘structure’ of photons and the implications of this for the design and planning of the next generation high energy \( e^+e^- \) colliders.
2. Standard Model and Supercolliders

To understand the concept of photon structure and its implications for the high energy photon interactions clearly, let us first summarize briefly our current understanding of the fundamental constituents of matter and interactions among them: the standard model (SM). The fundamental (elementary) constituents of matter are the spin 1/2 fermions (along with their antiparticles) summarised in Table 1. There exist four fundamental interactions among these matter particles, out of which only the strong, electromagnetic and weak interactions are relevant for this discussion. The corresponding coupling constants satisfy the hierarchy \( g_s > g_e = e > G_W \).

All the interactions among these fundamental constituents can be understood in terms of exchange of spin 1 (vector) bosons. The theoretical framework for their description is that of the gauge field theory and the interaction mediating bosons are called gauge bosons. The mediators of the electromagnetic and strong interactions (the photon \( \gamma \) and the gluon \( g \)) are massless whereas those corresponding to weak–interactions viz. \( W^\pm /Z \) are massive. The massive nature of the \( W^\pm /Z \) would normally spoil the gauge symmetry and hence would come in the way of a gauge field theoretical description of the weak–interactions. However, the ingenious mechanism of spontaneous breakdown of the gauge symmetry (SSB), where the symmetry of the vacuum and the lagrangian are different, makes it possible to have such a description. However, this description requires existence of one more elementary spin 0 boson, the Higgs scalar, in addition to the twelve gauge bosons and the fermions listed in Table 1. This mechanism provides a rather neat way of giving masses to the fermions as well. At present all the features of this picture (SM) have been verified to a great accuracy except the existence of the Higgs boson. It is the quest for this, still missing, member of the SM that mainly prompts the planning of the next generation of high energy colliders. It can be argued on very general grounds that experiments around an energy scale 1 TeV, aught to either find this Higgs scalar or confirm that the solution to the basic problem of mass generation

| Quarks | Leptons |
|--------|---------|
| (u) (c) (t) \times 3 colours | (\nu_e) (\nu_\mu) (\nu_\tau) |

| Quarks | Leptons |
|--------|---------|
| (d) (s) (b) \times 3 colours | (e^-) (\mu^-) (\tau^-) |
for the $W^\pm/Z$ and the fermions lies somewhere else other than in the SSB mechanism and give us hints about the possible mechanism which achieves this. It should also be mentioned here that as far as the particle physicists are concerned the SSB mechanism is theoretically the most attractive and only truly viable mechanism that exists at present. The supercolliders, which are required to have super–high energies and luminosities, that are currently under discussion are the $p\bar{p}$ collider (LHC) with a total centre of mass (c.m.) energy ($\sqrt{s}$) of $\sim 15$ TeV ($1\text{TeV} = 1000\text{GeV}$) with a luminosity of $\sim 10^{34}/\text{cm}^2/\text{sec}$ and an $e^+e^-$ collider with a c.m. energy $\sqrt{s} \geq 500$ GeV and $\mathcal{L} = 10^{33}/\text{cm}^2/\text{sec}$. A point to note also is that these colliders are expected to operate at much higher energies and higher luminosities than at the current colliders: $\sqrt{s} = 2$ TeV for a $\bar{p}p$ collider with $\mathcal{L} \simeq 10^{31}$ at the Tevatron at FNAL and $\sqrt{s} \simeq 100$ GeV for an $e^+e^-$ collider with $\mathcal{L} = 5 \times 10^{30}/\text{cm}^2/\text{sec}$ at LEP at CERN. Hence potentially new phenomena might occur at these supercolliders.

3. Structure of matter

The terminology of the ‘structure’ of a photon is essentially a short hand way of describing how a high energy photon interacts with other particles: hadrons and photons. It does not of course imply that the $\gamma$ is not an elementary particle. As an introduction to photon structure let us briefly understand how one describes structure of matter in general. According to the currently accepted picture all the strongly interacting particles observed in nature (called hadrons) are bound states of quarks, antiquarks and gluons. The interactions among these hadrons, at high energies, are described in terms of those between the constituents, $q, \bar{q}$ and $g$, collectively called partons. This is the so called parton–model picture shown in fig. 1. This picture is rigorously proved in the perturbative Quantum–

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Parton_Model.png}
\caption{Parton Model}
\end{figure}
Chromo–Dynamics (pQCD) which is the field theoretical description of the strong interactions in terms of an $SU(3)$ gauge theory. Such a description of high energy processes requires, in addition to the knowledge of QCD, also the information on the parton content of the hadrons viz: the parton density functions $f_{p_1/H_1}(x_1)$; the probability of finding a parton $p_1$ in hadron $H_1$ carrying the momentum fraction $x_1$ of the hadron $H_1$. The functions $f_{p_1/H_1}(x_1)$ can not, as yet, be computed from first principles in QCD and have to be measured experimentally. This information is obtained by studying the deep inelastic scattering (DIS) of high energy leptons of energy $E$ off hadron targets,

$$e^- + H \rightarrow e^- + X$$

(1)

The double differential cross–section for the process is a function of two independent variables $y = \nu/E$ where $\nu$ is the energy carried by the probing photon in the laboratory frame, and $x = Q^2/(2M\nu)$ where $M$ is the proton mass and $-Q^2$ is the invariant mass of the virtual photon in fig. 2 (a) which shows the DIS process for a proton. In the quark-parton-model (QPM) this double differential cross–section is given by,

$$\frac{d^2\sigma^{ep\rightarrow X}}{dx dy} = \frac{2\pi}{Q^4} \frac{\alpha^2}{s} \times \left( 1 + (1 - y)^2 \right) F^p_2(x) - y^2 F^p_L(x),$$

(2)

where

$$F^p_2(x) = \sum_q e_q^2 x f_{q/p}(x);$$

$$F^p_L(x) = F^p_2(x) - 2xF^p_1(x)$$

are the two electromagnetic structure functions of the proton and $f_{q/p}(x)$ the probability for quark $q$ to carry a momentum fraction $x$ of the proton and $e_q$ denotes the electromagnetic charge of quark $q$ in units of the proton charge. QCD implies some corrections to the QPM and these give
the structure function $F_2^p$ a $Q^2$ dependence which is given by the evolution equations [1] predicted in pQCD. The corrections also change $F_2^p(x, Q^2)$ from its QPM value of zero. But we will not concern ourselves with these here.

To measure the structure function of a photon such an experimental situation is provided at $e^+e^-$ colliders in $\gamma^*\gamma$ reactions as shown in fig. 2 (b). Here the virtual photon with invariant mass square $-Q^2$ probes the structure of the real photon. The idea that photons behave like hadrons when interacting with other hadrons dates back to the early days of strong interaction physics and is known to us under the name of the Vector Meson Dominance (VMD) picture. This essentially means that at low 4–momentum transfer, the interaction of a photon with hadrons is dominated by the exchange of vector mesons which have the same quantum numbers as the photon. If the VMD picture were the whole story then one would expect that such an experiment will find

$$F_2^\gamma \simeq F_2^{\gamma, VMD} \propto F_2^{\rho^0} \simeq F_2^{\pi^0}.$$  \hspace{2cm} (3)

Then with increasing $Q^2$, the structure function $F_2^\gamma$ will behave just like a hadronic proton structure function. However, there is a very important difference in case of photons, i.e., photons possess pointlike couplings to quarks. This has interesting implications for $\gamma^*\gamma$ interactions as first noted in the framework of the QPM by Walsh [2]. It essentially means that $\gamma^*\gamma$ scattering in fig. 2 contains two contributions as shown in fig. 3. The contribution of fig. 3 (a) can be estimated by eq.(3), whereas that of fig. 3 (b) was calculated in the QPM [2]. The dominant contribution comes from the kinematical region when the quark in the $t$ and $u$ channel is on mass-shell and hence can be calculated only when one considers quarks with finite

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure3.png}
\caption{Two contributions to $F_2^\gamma$.}
\end{figure}
masses. The result can be recast in a form equivalent to eq. (2):

$$\frac{d^2 \sigma_{e\gamma \rightarrow X}}{dx dy} = \frac{2 \pi \alpha^2 s_{e\gamma}}{Q^4} \times \left[ \frac{3\alpha}{\pi} \sum_q e_q^4 \left\{ (1 + (1 - y)^2) \times [x(x^2 + (1 - x)^2) \times \ln \frac{W^2}{m_q^2} \right. \right.$$

$$+ 8x^2(1 - x) - x] - y^2[4x^2(1 - x)] \left\} \right].$$

(4)

where $$W^2 = Q^2(1 - x)/x$$. On comparing eqs. (2) and (4) we see that the factors in square brackets in the above equation have the natural interpretation as photon structure functions $$F^\gamma_2, F^\gamma_L$$ and one has

$$F^\gamma_{2,\text{pointlike}}(x, Q^2) = \frac{3\alpha}{\pi} \sum_q e_q^4 \left[ x(x^2 + (1 - x)^2) \times \ln \frac{W^2}{m_q^2} + 8x^2(1 - x) - x \right]$$

$$= \sum_q e_q^2 x \ f_{q/\gamma}^{\text{pointlike}}(x, Q^2).$$

(5)

Two points are worth noting: the function $$F^\gamma_{2,\text{pointlike}}(x, Q^2)$$ can be completely calculated in QED and secondly this contribution to $$F^\gamma_2$$ increases logarithmically with $$Q^2$$. So in this simple ‘VMD + QPM’ picture, $$F^\gamma_2$$ consists of two parts, $$F^\gamma_{2,\text{pointlike}}$$ and $$F^\gamma_{2,\text{VMD}}$$, with distinctly different $$Q^2$$ behaviour and with the distinction that for one part both the $$x$$ and the $$Q^2$$ dependence can be calculated completely from first principles.

This QPM prediction received further support when it was shown by Witten [3] that at large $$Q^2$$ and at large $$x$$, both the $$x$$ and $$Q^2$$ dependence of the quark and gluon densities in the photon can be predicted completely even after QCD radiation is included. An alternative way of understanding this result is to consider the evolution equations [4] for the quark and gluon densities inside the photon. In the ‘asymptotic’ limit of large $$Q^2$$ and large $$x$$, the $$f_{q_i/\gamma}(x, Q^2)$$ have the form

$$f_{q_i/\gamma}^{\text{asymp}}(x, Q^2) \propto \alpha \times \ln \left( \frac{Q^2}{\Lambda_{\text{QCD}}^2} \right) F_i(x)$$

$$\approx \frac{\alpha}{\alpha_s} F_i(x),$$

(6)

where $$\Lambda_{\text{QCD}}$$ is the QCD scale parameter, $$\alpha_s(Q^2)$$ is given in terms of the running strong coupling constant by $$g_s^2(Q^2)/4\pi$$ and the $$x$$ dependence of the $$F_i(x)$$ is completely calculable. Note here the factor $$\ln \left( \frac{Q^2}{\Lambda_{\text{QCD}}^2} \right)$$ on the
r.h.s. Measurements [5] of the photon structure function $F_2^\gamma$ in $\gamma^*\gamma$ processes did indeed confirm the basic QCD predictions of the linear rise of $F_2^\gamma$ with $\ln(Q^2)$ at large $x$. This discussion thus means that just like one can ‘pull’ quarks and gluons out of a proton one can look upon the photon as a source of partons and that the parton content of the photon rises with its energy. Physically this means that the photon splits in a $q\bar{q}$ pair and these radiate further gluons and thus fill up a volume around photon with partons.

The asymptotic solutions discussed above, though very useful to understand the rise of the photon structure function with $Q^2$, are valid only at large $x$ and large $Q^2$. At small values of $x$ these solutions diverge, indicating thereby that ‘hadronic’ part of $F_2^\gamma$ can not be neglected at small $x$. Hence it is now generally accepted that for practical purposes, specially if one wants to use the parton model language for the interactions of high energy photons, it is better to forego the absolute predictions of $F_2^\gamma$ of the asymptotic part, that are possible in pQCD and use only the prediction of the $Q^2$ evolution of the photon structure function in analogy to the case of the proton structure function. At present there exist fourteen different parametrisations of the photon structure function [6]. The DIS measurements described above measure only the quark-parton densities $f_{q/\gamma}(x, Q^2)$ (for $x > 0.05$ and $Q^2 < 100 - 200$ GeV$^2$) directly and $f_{G/\gamma}(x, Q^2)$ is only inferred indirectly. As a result there is considerable uncertainty in the knowledge of $f_{G/\gamma}(x, Q^2)$. The different parametrisations differ quite a lot from each other in the gluon content. It should also be mentioned here, that these differences reflect the differences in different physical assumptions in getting $f_{G/\gamma}(x, Q^2)$ from the data on $F_2^\gamma$. So independent information on $f_{G/\gamma}(x, Q^2)$ is welcome.

4. Calculation of jet production in $\gamma\gamma$, $\gamma p$ collisions

One such possibility is the study of jet production in $\gamma\gamma$, $\gamma p$ collisions. Jet production in $\gamma\gamma$ collisions can receive contributions from three different types of diagram [7] as shown in fig. 4. The ‘direct process’ of fig. 4a is due to $\gamma\gamma \rightarrow q\bar{q}$ production, present already in the naive quark-parton model. Fig. 4b depicts the case where only one photon is resolved into its partonic components, which then interact with the other photon; we call these the ‘once-resolved’ processes (‘1-res’ for short). Finally, fig. 4c shows the situation where both photons are resolved, so that the hard scattering is a pure QCD $2 \rightarrow 2$ process; we call these the ‘twice-resolved’ contributions (‘2-res’ for short). It is very important to note here that every resolved photon will produce a spectator jet of hadrons with small transverse momentum relative to the initial photon direction, which for (quasi-) real photons co-
incides with the beam direction. The resolved contributions of fig. 4b and c can therefore be separated if one can tag on these spectator jets.

The cross-section for jet production in $\gamma\gamma$ collisions (the $\gamma^{-}/\gamma^{+}$ acts as the source of ‘almost’ real photons when the $\gamma^{-}/\gamma^{+}$ is scattered at very small angles, and thus $\gamma^{+}\gamma^{-}$ collisions can be used to study $\gamma\gamma$ collisions) for the ‘2-res’ processes can be written as [8, 9]

$$\frac{d\sigma}{dp_T} = \sum_{p_1, p_2, p_3, p_4} \int_{z_1\text{min}} dz_1 f_{\gamma^1/e}(z_1) \int_{z_2\text{min}/z_1} dz_2 f_{\gamma^2/e}(z_2) \int_{z_{2\text{min}}/z_2} dx_1 f_{p_1/\gamma^1}(x_1) \int_{x_{1\text{min}}/x_1} dx_2 f_{p_2/\gamma^2}(x_2) \times \frac{d\hat{\sigma}(p_1 + p_2 \rightarrow p_3 + p_4)}{dp_T},$$

(7)

where the $d\hat{\sigma}/dp_T$ are the cross sections for the hard 2 $\rightarrow$ 2 subprocesses, $f_{p_j/\gamma_i}(x_j, Q^2)$, $f_{\gamma_i/e}(z_i)$ denote parton densities inside the photon and photon fluxes inside the electron respectively and $z_{1\text{min}} = 4p_T^2/s$. For the ‘1-res’
(direct) processes, one (both) of the parton density functions $f_{p_i/\gamma}(x_i)$ have to be replaced by $\delta(1-x_i)$, and the proper hard sub-process cross-sections have to be inserted. Recall eq.(6) for $f_{q_i/\gamma}(x_i,Q^2)$. This relation makes it clear that all three classes of diagrams are of the same order in $\alpha$ and $\alpha_s$. The ‘resolved’ events will also have additional ‘spectator’ jets in the direction of the $\gamma$, i.e, in the direction of the $e^-/e^+$. Fig. 5 shows the energy dependence of the cross-section for the production of two jets with $p_T = 3$ GeV, as predicted [9] for one of the parametrizations of $F_2^\gamma$, in the range covered by the $e^+e^-$ colliders PETRA and TRISTAN. The cross-section is also well above the background from annihilation events with hard initial state radiation (dotted curve). More importantly twice–resolved contribution grows faster than $\sqrt{s}$ with increasing machine energy and, for this choice of $p_T$, begins to dominate the cross–sections in the energy range of TRISTAN. The $\gamma$ energies increase with the $\sqrt{s}$ of the $e^+e^-$ machine. With increasing $\gamma$ energies increasingly more energy becomes available to the partons participating in the subprocess, for a fixed $p_T$ or inv. mass of the final state. Hence the importance of the ‘resolved’ processes increases with increasing energy. Experimental studies of the jet–production in $\gamma\gamma$ collisions [10] at the $e^+e^-$ colliders TRISTAN and LEP, have confirmed the existence of the ‘resolved’ contributions [9]. These studies have even ruled out some of the very hard parametrisations of $f_{G/\gamma}(x,Q^2)$ [10] as shown in fig. 6.

Jet production in $ep$ (or equivalently $\gamma p$) collisions also has two contributions: ‘direct’ and ‘resolved’. High energy photons are effectively avail-
able at the HERA collider at DESY, in the collision of a 30 GeV $e$ beam with a 820 GeV $p$ beam. This corresponds to a c.m. energy $\leq 300$ GeV, which in turn corresponds to $E_\gamma \leq 50$ TeV. Our calculations [11] showed that here also the photo-production of jets is dominated by the ‘resolved’ contributions up to $p_T = 40$ GeV. The ‘resolved’ contributions are expected to have ‘spectator’ jets in the direction of the $\gamma$ (i.e. the electron). This rate also depends strongly on $f_{G/\gamma}(x,Q^2)$, $f_{q/\gamma}(x,Q^2)$ and hence can be used to get information about these. Recent measurements at HERA [12, 13] have indeed confirmed all the features of the predictions and have provided unequivocal proof for the ‘resolved’ processes. Fig. 7 shows one of the experimental evidence.

Thus these observations have provided a confirmation (in addition to the DIS measurements) of the ideas about $F_2^\gamma$ and these experiments will continue to add to our knowledge of the $f_{G/\gamma}(x,Q^2)$, $f_{q/\gamma}(x,Q^2)$.

5. Beamstrahlung induced backgrounds at the next linear colliders

The above discussion explains in what sense one says that the photon has hadronic structure. The discussion also shows that the effects of hadronic structure of the photon increase with increasing photon energy. This makes it clear that the existence and study of the ‘resolved’ processes at the current colliders is necessary to understand the interactions of very high energy photons. One such source of high energy photon is the phenomenon of ‘beamstrahlung’ that will exist at the next generation linear colliders.
5.1. BEAMSTRAHLUNG

As explained in section 2, the next generation of $e^+e^-$ colliders will operate at much higher luminosities than those of the current ones. This is partly necessiated by the reduction of the annihilation cross-section with increasing energy. More importantly, due to the severe synchrotron radiation losses at high energies, it is not possible to build a circular $e^+e^-$ collider beyond $\sqrt{s} \geq 200$ GeV. The higher energy colliders under planning have to be therefore linear colliders, which operate in single pass mode as opposed to the circular colliders where a bunch passes an interaction point a number of times (e.g. at LEP this number is $\sim 10^8$). Hence to achieve the much higher luminosity that is needed the $e^+/e^-$ bunches will have to be extremely dense which in turn causes the $e^-/e^+$ to see very high electromagnetic fields due to the dense $e^+/e^-$ bunch. This causes ‘bremsstrahlung’ radiation. This radiation caused by the coherent interactions of all $e^-/e^+$ with the $e^+/e^-$ bunch, is termed ‘beamstrahlung’ [14]. The energy spectrum of the beamstrahlung photons depends critically on the machine parameters and its calculation is an art in itself. Fortunately approximate analytic expressions given by Chen [15] are applicable for almost all the machine designs currently under consideration [16]. The beamstrahlung parameter $\Upsilon$ is proportional to the effective magnetic field of the bunches and for
Gaussian beams the mean value of Υ is given by

$$\Upsilon = \frac{5r_e^2 EN}{6\alpha_{em}\sigma_z m_e (\sigma_x + \sigma_y)}.$$  (8)

where E is the beam energy, N is the number of electrons/positrons per bunch, σx and σy are the transverse bunch dimensions, re is the classical electron radius. The expression shows that the beamstrahlung parameter is larger for round bunches than for flat, ribbon–like bunches. For a given luminosity and bunch dimensions, the beamstrahlung can be reduced by introducing more bunches. So beamstrahlung can thus be controlled by spatial/temporal shaping of the bunches. There is also a suggestion [17] to convert the e+e− linear colliders into γγ colliders by using the backscattered lasers from the e+/e−. The photons in both these cases are ‘real’ as opposed to the ‘quasi-real’ bremsstrahlung photons. Fig. 8 shows that

Figure 8. Photon spectra for $\sqrt{s} = 500$ GeV for the different proposed machine designs. WW is the Weizsäcker Williams spectrum of the quasi–real bremsstrahlung photons, and Laser shows the spectrum for the photons obtained from a backscattered laser, taken from ref. [16]

the beamstrahlung spectra are quite different for different machine designs all of which correspond to roughly the same luminosity.

5.2. HADRON PRODUCTION IN $\gamma\gamma$ COLLISIONS AND BEAMSTRAHLUNG

The net effect of beamstrahlung therefore is that associated with e+e− collision there is also a simultaneous $\gamma\gamma$ collision. The jet production in
\( \gamma \gamma \) collisions will have ‘direct’ as well as the ‘1-res’ and ‘2-res’ contributions as said before. The ‘resolved’ contributions rise in importance with increasing photon energies. This rise in \( \sigma(\gamma \gamma \rightarrow \text{jets}) \) has been experimentally confirmed in the laboratory as described in the earlier sections. If one therefore now extrapolates these calculations to this situation, one finds a most unusual result. A calculation [16] shows that the cross–sections for the production of jets with very small \( p_T \) in these \( \gamma \gamma \) collisions is very large indeed. Table 2 gives the integrated semi–hard, inclusive cross–section

\[
\int_{p_T,\text{min}} d\sigma(\gamma \gamma \rightarrow \text{jets}) \frac{d\sigma}{dp_T} \text{ for } p_{T,\text{min}} = 1.6 \text{ GeV along with the ‘soft’ cross–section that is expected on the basis of the VMD picture mentioned earlier. The last column gives the number of events containing small } p_T \text{ ‘jets’ that will occur per ‘effective’ bunch crossings, i.e., bunch crossings which can not be distinguished from each other. For the Laser machine the two numbers correspond to the TESLA and Palmer-G design of the } e^+e^- \text{ collider which is used to produce the } \gamma \gamma \text{ collider. What this table tells us is that simultaneous to the effective } e^+e^- \text{ event there will be production of hadrons in the } \gamma \gamma \text{ collision and these hadrons will carry considerable energy (e.g. for P-G machine they will carry } \simeq 24 \times (1.6 \times 2 + 2) \simeq 125 \text{ GeV } ) \text{ which has nothing to do with the } e^+e^- \text{ collision and thus produce an underlying event at an } e^+e^- \text{ collider which is totally unheard of. Luckily, as the table shows, the number of the underlying events depend very much on the beamstrahlung and hence on the machine parameters. The machine designs can be changed to reduce the beamstrahlung induced background. Eventhough the inclusive cross-section that we have computed is not a measure of the total } \gamma \gamma \text{ cross–section and also suffers from uncertainties due to the poor knowledge of the gluon content of the photon, it still gives a measure of the ‘messiness’ that would be caused by the underlying event at the linacs. So this table underlies the need of studying hadron production in } \gamma \gamma \text{ collisions and controlling the beamstrahlung induced backgrounds at the linacs [18].}
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