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A NEW HEAVY FLAVOUR GENERATOR IN $\epsilon - p$ COLLISIONS.

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Abstract

The reaction of boson-gluon fusion $V^*g \to Q\bar{Q}'$ has been implemented in the framework of the QCD inspired Monte Carlo, HERWIG, and results have been obtained for the energy of HERA, the $\epsilon - p$ collider at DESY. The backward evolution of the initial gluon leg, as well as the coherence in timelike and spacelike parton cascades, can be both described in HERWIG. The new implementation shows consistently differences at the level of the parton shower and the fragmented hadrons in comparison with the previous boson-gluon fusion generator, AROMA, from the Lund package. The program, namely HARHEA, will be available within the next releases of the HERWIG Monte Carlo.

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1. Introduction

The HERA $\epsilon - p$ collider will provide the physics community with new interesting data hopefully next year, 1991. Deep Inelastic Scattering is the dominant reaction of physical interest together with the Boson-Gluon Fusion (BGF), which will produce $q\bar{q}$ pairs via charged ($W^{\pm}$) or neutral currents (γ and Z_0) coupled to a gluon emitted from the incoming proton (fig. 1).

The physical interest for the BGF reaction is strongly enhanced by the possibility to obtain high yields of $c\bar{c}$ and $b\bar{b}$ pairs, up to $\mathcal{O}(10^8)$ and $\mathcal{O}(10^6)$ events per year respectively, with the expected HERA luminosity. The *top* quark will be looked for, even if its mass is probably beyond the maximum HERA BGF limit ($\sim 80\ GeV/c^2$); an independent lower limit from $\epsilon - p$ reactions will anyway be obtained.

Until now the only available Monte Carlo generator for BGF in $\epsilon - p$ collisions has been that provided by G. Ingelman and G. A. Schuler [1,2], called AROMA (main routine HFLGEN). This generator starts from the hard subprocess matrix element at order $\alpha^2\alpha_s$ as computed by G. A. Schuler [3] and subsequently develops the parton showers from the outgoing heavy quark legs. This approach is not satisfactory since it takes into account only the timelike cascade, neglecting the initial gluon possible radiation. AROMA then treats the hadronization process of the final partons (included the proton remnant) with the Lund string model.

The HERWIG Monte Carlo [4] considers the QCD gluon radiation properly; it takes into account the leading collinear singularities as well as the leading infrared ones by the ordering in emission angles. A further difference from AROMA is the cluster hadronization model which contains fewer free parameters than the string model.

The next section describes the program implementation, while section 3 shows some results. Section 4 deals with the problem of the independence from the cluster mass parameter. Section 5 reports on conclusions. The appendix contains some technical details on the mathematical implementation of the subprocess.

2. The program HARHEA

(HARd HEAvy flavour production)

The hard process is chosen in HERWIG via the variable IPROC, defined in the main program. A total of 7 new values for IPROC have been defined for the Heavy Flavour pair production via Boson-Gluon Fusion, namely:

19200: Charged Current $s\bar{c}$
19300: Charged Current $b\bar{c}$
19400: Neutral Current $c\bar{c}$
19500: Neutral Current $b\bar{b}$
19600: Neutral Current $t\bar{t}$
19700: Charged Current $s\bar{t}$
19800: Charged Current $b\bar{t}$

The choice has to be made in the main program, before the call to the subroutine HWEPRO which handles the generation of the elementary subprocess. Once entered in the main routine of the BGF subprocess, HWHBGF, kinematics and colour connections are developed to connect the inner tree Feynman graph to the framework of the HERWIG parton shower evolution. The appendix describes in details such a development.

The link with HERWIG is obtained by the vectors of the /HEPEVT/ common: IDHEP(4:9), ISTHEP(4:9), JMOHEP(1:2,4:9), JDAHEP(1:2,4:9), PHEP(1:5,4:9). Actually the essential feature of our implementation stays in its full compatibility with HERWIG, once the hard process is chosen. It also follows the new criteria stated in ref. [5] for the standard event description of the High Energy Physics Monte Carlo's.

The program is 739 lines long in FORTRAN 77, corresponding to 206 *kbytes*. The routines outline is as follows:

SUBROUTINE HWHBGF
Main subroutine. Is is called by HWEPRO, following a setting of IPROC to 19200 ÷ 19800. After some initializations, it calls HWRBGF and HWUBGF subsequently.

SUBROUTINE HWRBGF
It generates randomly a point in the phase space (y, Q^2, η, z, ϕ) and it returns the corresponding ***Jacobian*** factor for the transformation between the Monte Carlo variables, covering the 5-dimensional unitary hypercube, and the 5 physical variables. The 5-dimensional phase space describes the elementary subprocess $e^- g \to l Q\bar{Q}'$, following the explicit calculation of ref. [3].

SUBROUTINE HWUBGF
It evaluates the differential cross section in (y, Q^2, η, z, ϕ), where y and Q^2 have their usual meaning in DIS. η is the gluon momentum fraction, z is related to the angle of the $Q\bar{Q}'$ axis with respect to the boson–gluon axis in the $Q\bar{Q}'$ rest frame, ϕ is the azimuthal

angle between the lepton and hadron planes around the boson axis.

SUBROUTINE HWEBGF
It is called by HWHBGF and it handles all the kinematics necessary to transport the 5 particles of the hard subprocess from the $Q\bar{Q}'$ rest frame where they are generated to the laboratory frame from where HERWIG works.

SUBROUTINE HWEPRO
It is a slightly modified version of the corresponding routine in HERWIG, to allow an entry point for HWHBGF.

PROGRAM HWIGPR
It is an example of main program for the generation of heavy quark events at HERA via BGF. It calls HWEPRO.

3. Results

The coding of the differential cross section for the hard subprocess has been checked by comparison with AROMA. Then the full HERWIG mechanism has been switched on and successively results have been obtained from the two programs for $b\bar{b}$ production at the HERA energies (see figs. 2÷5). The resulting differences are not cancelled by changing either the heavy flavour or the energy range. The problem of the "cluster" approach in HERWIG, described in the next section, has been solved by a phenomenological solution*.

An acceptance angular cut for the beam pipe of HERA is considered and magnifies the (detector dependent) differences between the predictions of the two generators. As one expects, the fact that the initial gluon can radiate and consequently owns a transverse p_T different from zero, leads to a greater activity in the detectable quantities. This is evident for the charged multiplicity distribution (fig. 2) as well as for the total energy and the transverse energy of the global flow (figs. 3 and 4). With respect to the previous Monte Carlo, an increase of roughly 50% is obtained for the charged multiplicity, while 70% more energy is visible in the detector. Obviously these results may differently constrain the detection tuning at HERA, e.g. for trigger conditions.

Furthermore the BGF reaction in the HERWIG implementation enhances the important contribution due to the u-channel in the backward direction with respect to the

* *B.R. Webber and one of us (G.A.) have found that introducing a light $q\bar{q}$ pair in the proton remnant, in such a way to decouple the hard process from the underlying soft event, provides more physical features to the following process of clustering.*

incident proton (fig. 5). This result supports the REAR instrumentation for the HERA detectors, that was first suggested by a study using AROMA [6].

More on the results obtained by HARHEA is reported in reference [7].

4. Clusters in the hadronization process

The cluster approach for the hadronization process relies on the preconfinement hypothesis [8]. This suggests that at the end of the showers development the outgoing partons collect in colour singlets each in a small phase space region.

The cluster model has fewer parameters than the Lund string model, since it leaves the formation of hadrons only constrained by phase space factors. However it contains a completely free parameter, M_C^{max}, the maximum mass a cluster can have to allow two-body hadron decays. The splitting of single clusters heavier than M_C^{max} into two lighter ones is then forced. It has been well demonstrated that physics results do not strongly depend on the different choices for M_C^{max} if only timelike processes are considered, as in e^+e^- reaction [9], since in this case only a small fraction of the clusters needs to be split.

We have studied the M_C^{max} dependence for our BGF process, but the presence of the spacelike evolution for the initial gluon sets severe limits to this "cluster" approach (see table I*a*). Going from 3 GeV/c^2 up to ∞ for M_C^{max} (∞ meaning no splitting), the physical observables are subject to strong variations. The problem arises from the formation of a "central" cluster which connects together a parton from the radiation of one of the heavy quarks or even one of the heavy quark legs and the proton remnant. This cluster is quite heavy and it has almost always to be split several times in a single event. As inferred from table I*a*, these splittings strongly influence the physical variables.

The released version 4.3 of HERWIG contains for all processes the phenomenological solution already quoted and a default value for M_C^{max} of 3 GeV/c^2. Looking at table I*b*, the provided modification is not completely satisfactory, as e.g. the charged multiplicity and the $< p_T >$ still display some dependence on M_C^{max}. This is probably related to problems in the *small–x* region of the spacelike cascade, where perturbative QCD predicts a different behaviour from what is reproduced by the program at the moment. However HERWIG is planned to include a full treatment of this region, according to the formulation of ref. [10]. This would have particular relevance for the heavy quark photoproduction, as it has been shown in ref. [11].

5. Conclusions

The Boson–Gluon Fusion reaction in $e - p$ collisions at HERA will be a fruitful source of heavy flavour quark pairs, essentially of $c\bar{c}$ and $b\bar{b}$. The analysis and the study of these processes need a reliable QCD inspired and constrained Monte Carlo generator. The HERWIG package provides such a suitable framework, with parton cascade for both timelike and spacelike (backward) evolutions.

The lack of a specific BGF generator in HERWIG has led us to provide for it. A next release of HERWIG will contain our implementation which will be under management of HERWIG for future versions.

Acknowledgments

We are grateful to Giuseppe Marchesini and Bryan Webber for the helpful collaboration and also for the kind hospitality received in Parma and in Cambridge, where part of the work was performed. We thank Silvia Limentani for a careful reading of the paper.

Appendix

Two technical aspects are described for the implementation of the BGF reaction inside HERWIG.

The cross section for the process $e^- g \rightarrow lQ\bar{Q}'$ has been computed in the $Q\bar{Q}'$ rest frame [3], while HERWIG requires the laboratory frame. Let us then consider the initial four-momenta of the incident electron, the incident gluon* and the virtual boson parametrized as:

$$
\begin{aligned}
p_e &= E_e(1, \sin\vartheta, 0, \cos\vartheta) \\
p_g &= (E_g, 0, 0, p_0) \\
q &= (E_V, 0, 0, -p_0)
\end{aligned}
$$

* *We remind the reader that HERWIG assigns a virtual mass of* 0.65 GeV/c^2 *to the gluon, to put an infrared cut-off.*

where:

$$p_0 = \sqrt{\frac{\hat{s}^2 + Q^4 + m_g^4 + 2\hat{s}Q^2 + 2Q^2 m_g^2 - 2\hat{s}m_g^2}{4\hat{s}}}$$
$$E_g = \sqrt{p_0^2 + m_g^2} = \frac{\hat{s} + Q^2 + m_g^2}{2\sqrt{\hat{s}}}$$
$$E_V = \sqrt{p_0^2 - Q^2} = \frac{\hat{s} - Q^2 - m_g^2}{2\sqrt{\hat{s}}}$$

A set of Lorentz transformations are then applied to transform the above fourmomenta to the laboratory, taking care of the two different possibilities for $\cos\beta >$ or < 0. Defining:

$$(E_{cm}, \vec{p}_{cm}) = p_e + p_g = (E_e + E_g, E_e \sin\beta, 0, E_e \cos\beta + p_0)$$

the first two transformations (a rotation around the y-axis and a boost along z) lead the fourmomenta to the $e-g$ center of mass. A further rotation around y alignes the momenta of the electron and the gluon with the z-axis and finally a boost gives the correct energy to the electron in the laboratory frame. More details are reported in ref. [12]. The complete transformation is given by the following Lorentz matrix ($c \equiv \cos$, $s \equiv \sin$, $sh \equiv \sinh$, $ch \equiv \cosh$):

$$\Lambda =$$
$$\begin{pmatrix} ch\sigma\cdot ch\nu + sh\sigma\cdot c\rho\cdot sh\nu & ch\sigma\cdot sh\nu\cdot s\mu + sh\sigma(s\rho\cdot c\mu + c\rho\cdot ch\nu\cdot s\mu) & 0 & ch\sigma\cdot sh\nu\cdot c\mu + sh\sigma(-s\rho\cdot s\mu + c\rho\cdot ch\nu\cdot c\mu) \\ -s\rho\cdot sh\nu & c\rho\cdot c\mu - s\rho\cdot ch\nu\cdot s\mu & 0 & -c\rho\cdot s\mu - s\rho\cdot ch\nu\cdot c\mu \\ 0 & 0 & 1 & 0 \\ sh\sigma\cdot ch\nu + ch\sigma\cdot c\rho\cdot sh\nu & sh\sigma\cdot sh\nu\cdot s\mu + ch\sigma(s\rho\cdot c\mu + c\rho\cdot ch\nu\cdot s\mu) & 0 & sh\sigma\cdot sh\nu\cdot c\mu + ch\sigma(-s\rho\cdot s\mu + c\rho\cdot ch\nu\cdot c\mu) \end{pmatrix}$$

where:

$$\cos\mu = \frac{p_{cm}^z}{p_{cm}}, \quad \sin\mu = \frac{p_{cm}^x}{p_{cm}}$$
$$\cosh\nu = \frac{E_{cm}}{M}, \quad \sinh\nu = -\frac{p_{cm}}{M}$$
$$\cos\rho = \frac{p_z^*}{p^*}, \quad \sin\rho = \frac{p_x^*}{p^*}$$
$$\tanh\sigma = -\frac{1 - (\frac{E_{lab}}{p^*})^2}{1 + (\frac{E_{lab}}{p^*})^2}$$

with:

$$p_x^* = E_e \frac{p_0 \sin\beta}{p_{cm}}$$
$$p_z^* = -E_e \frac{(E_g - E_e)(E_g - p_0\cos\beta) - m_g^2}{M p_{cm}}$$

the components of the spatial momentum of the electron after the first two Lorentz transformations and $p^* = \sqrt{(p_x^*)^2 + (p_z^*)^2}$. $M = \sqrt{E_{cm}^2 - p_{cm}^2}$ is the electron-gluon invariant mass, E_{lab} the electron energy in the laboratory frame.

Another point is the colour structure of the hard subprocess. In our implementation, as usually in HERWIG, the gluon line is considered as a colour–anticolour combination represented by a double line, see fig. 6. This is correct as far as the colour singlet contribution is negligible. Then, starting from a coloured gluon, it is evident that the colour connection to the $Q\bar{Q}'$ pair is unique and it is described by the arrows of fig. 6. In each generated event it remains to fix the colour connected partner for the gluon, which influences the following evolution of the spacelike cascade. According to the standard method adopted in HERWIG the choice is done randomly with equal probability for the Q or the $\bar{Q}'$.

Table I*a*

	M_C^{max} (GeV/c^2)			
	3	5	10	∞
$< n_{ch} >$	23.8	22.6	20.3	14.4
$< p_T > (GeV/c)$	0.55	0.59	0.72	1.83
$< \sum_i E_i > (GeV)$	126.	132.	152.	323.
$< \sum_i E_{T_i} > (GeV)$	24.5	25.3	28.0	52.0
$< N_{jet} >$	2.09	2.15	2.39	2.84

Table I*b*

	M_C^{max} (GeV/c^2)			
	3	5	10	∞
$< n_{ch} >$	20.4	19.7	18.2	15.7
$< p_T > (GeV/c)$	0.59	0.62	0.72	1.09
$< \sum_i E_i > (GeV)$	102.	105.	113.	134.
$< \sum_i E_{T_i} > (GeV)$	22.0	22.4	23.9	30.1
$< N_{jet} >$	2.02	2.03	2.15	2.45

Table I : mean values of some relevant quantities as function of the hadronization parameter M_C^{max}, for $M_C^{max} = 3, 5, 10, \infty$ respectively. The reported quantities are, from the top to the bottom of the tables, the charged multiplicity, the transverse momentum of the charged particles, the total "visible" energy, the transverse energy and the reconstructed number of jets. All the quantities are obtained after an acceptance cut corresponding to the HERA beam pipe. *a*) old version of HERWIG (4.2); *b*) new version of HERWIG (4.3).

References

[1] G.Ingelman, G.A.Schuler, AROMA 1.2, DESY preprint in preparation.

[2] G.Ingelman, G.A.Schuler, Z. Phys. C40 (1988) 299.

[3] G.A.Schuler, Nucl. Phys. B299 (1988) 21.

[4] G.Marchesini, B.R.Webber, Nucl. Phys. B310 (1988) 461;
I.G.Knowles, Nucl. Phys. B310 (1988) 571.

[5] T.Sjostrand et al., in "Z Physics at LEP 1", G.Altarelli, R.Kleiss and C.Verzegnassi editors, CERN Yellow Report 89-08, vol. 3, pag. 325.

[6] A.Ali et al., Proceedings of the HERA workshop, R.D.Peccei editor (1987) vol. 1, pag. 395, and DESY 88-119 (1988);
F.Barreiro et al., DESY 89-116 (1989).

[7] G.Abbiendi, L.Stanco, DESY preprint in preparation.

[8] D.Amati, G.Veneziano, Phys. Lett. B83 (1979) 87;
G.Marchesini, L.Trentadue, G.Veneziano, Nucl. Phys. B181 (1981) 335.

[9] B.R.Webber, Nucl. Phys. B238 (1984) 492.

[10] S.Catani, F.Fiorani, G.Marchesini, Nucl. Phys. B336 (1990) 18.

[11] S.Catani, M.Ciafaloni, F.Hautmann, preprint Cavendish-HEP 90/3 (1990).

[12] G.Abbiendi, Tesi di Laurea, unpublished.

Figure Caption

Fig. 1 Lowest order QCD diagrams for boson-gluon fusion into a quark-antiquark pair.

Fig. 2 Charged multiplicity distribution ($b\bar{b}$ production) after an angular cut of $100 mrad$ around the beam pipe. Full and dotted lines correspond to HARHEA and AROMA outputs, respectively.

Fig. 3 Total energy distribution ($b\bar{b}$ events) within the calorimeter acceptance of the ZEUS detector ($3.5^0 \leq \theta \leq 177.8^0$, with respect to the electron beam direction). Full and dotted lines correspond to HARHEA and AROMA outputs, respectively.

Fig. 4 Same as fig. 3, for the total transverse energy.

Fig. 5 Angular distribution of the energy flow for $b\bar{b}$ events. Full and dotted lines correspond to HARHEA and AROMA outputs, respectively.

Fig. 6 Colour structure for the hard subprocess $V^* g \to Q\bar{Q}'$.

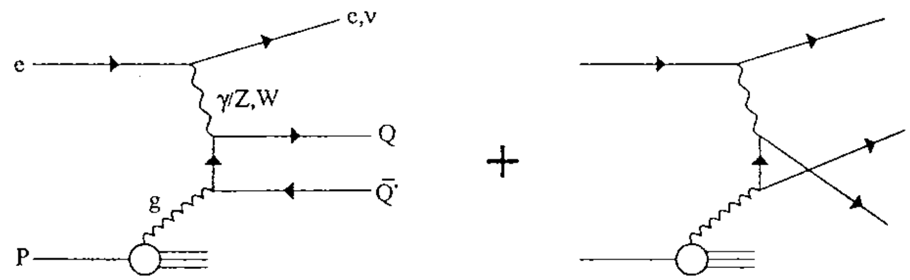

figure 1

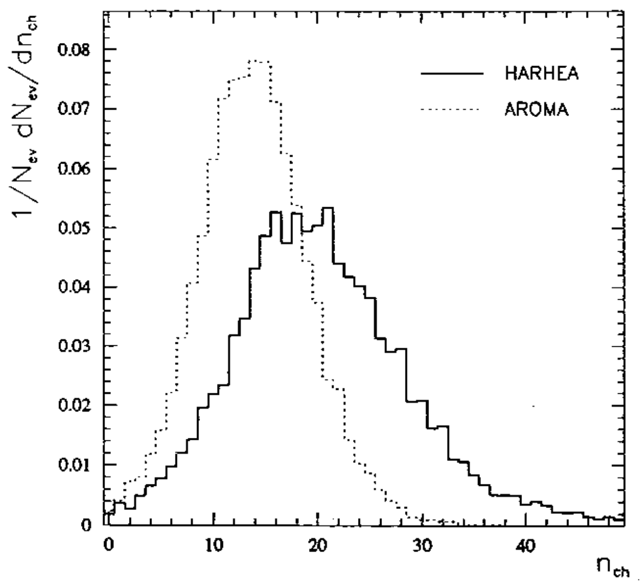

figure 2

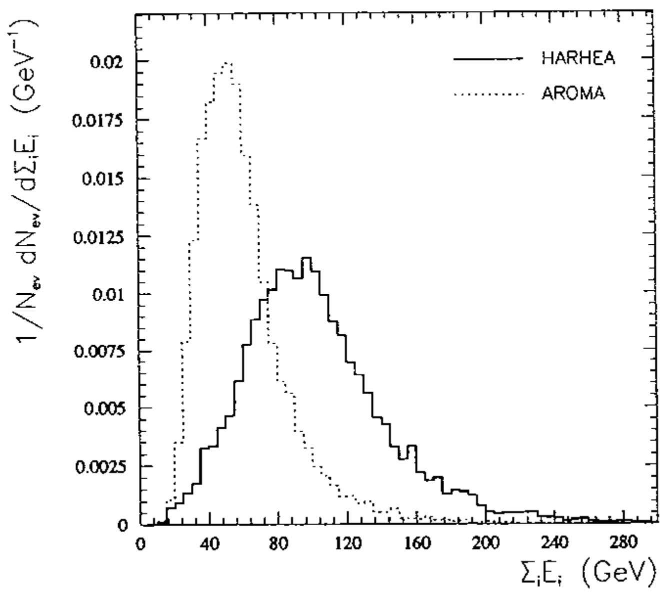

figure 3

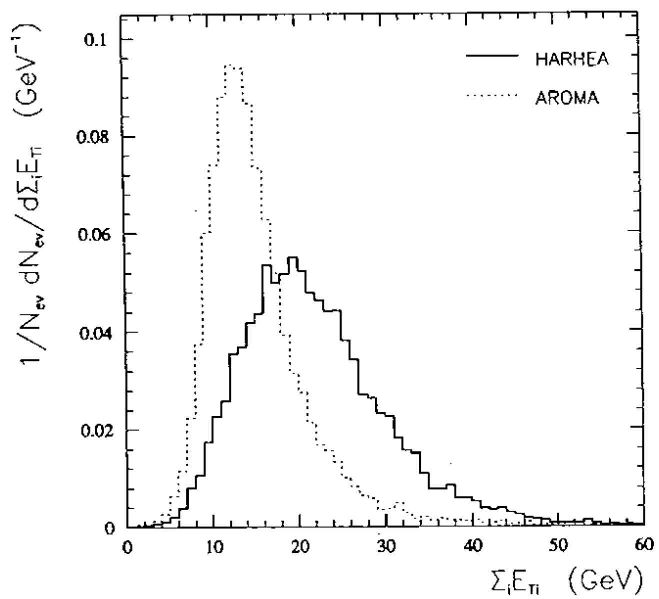

figure 4

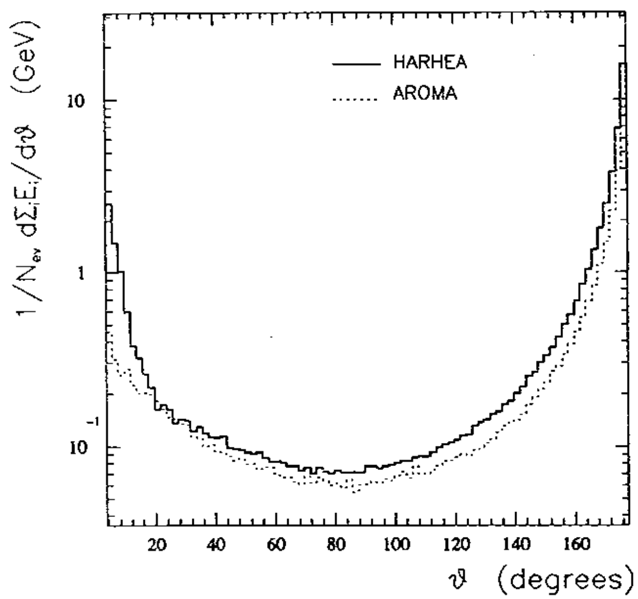

figure 5

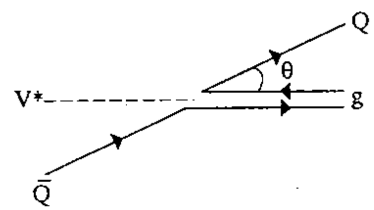

figure 6