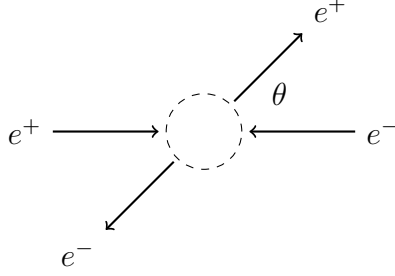


# Bhabha scattering

Bhabha scattering is the process  $e^- + e^+ \rightarrow e^- + e^+$ .



The following center-of-mass momentum vectors have  $E = \sqrt{p^2 + m^2}$ .

$$p_1 = \begin{pmatrix} E \\ 0 \\ 0 \\ p \end{pmatrix}_{e^+ \rightarrow} \quad p_2 = \begin{pmatrix} E \\ 0 \\ 0 \\ -p \end{pmatrix}_{\leftarrow e^-} \quad p_3 = \begin{pmatrix} E \\ p \sin \theta \cos \phi \\ p \sin \theta \sin \phi \\ p \cos \theta \end{pmatrix}_{e^+ \nearrow} \quad p_4 = \begin{pmatrix} E \\ -p \sin \theta \cos \phi \\ -p \sin \theta \sin \phi \\ -p \cos \theta \end{pmatrix}_{\nwarrow e^-}$$

Spinors for  $p_1$ .

$$v_{11} = \frac{1}{\sqrt{E+m}} \begin{pmatrix} p \\ 0 \\ E+m \\ 0 \end{pmatrix}_{\text{spin up}} \quad v_{12} = \frac{1}{\sqrt{E+m}} \begin{pmatrix} 0 \\ -p \\ 0 \\ E+m \end{pmatrix}_{\text{spin down}}$$

Spinors for  $p_2$ .

$$u_{21} = \frac{1}{\sqrt{E+m}} \begin{pmatrix} E+m \\ 0 \\ -p \\ 0 \end{pmatrix}_{\text{spin up}} \quad u_{22} = \frac{1}{\sqrt{E+m}} \begin{pmatrix} 0 \\ E+m \\ 0 \\ p \end{pmatrix}_{\text{spin down}}$$

Spinors for  $p_3$ .

$$v_{31} = \frac{1}{\sqrt{E+m}} \begin{pmatrix} p_{3z} \\ p_{3x} + ip_{3y} \\ E+m \\ 0 \end{pmatrix}_{\text{spin up}} \quad v_{32} = \frac{1}{\sqrt{E+m}} \begin{pmatrix} p_{3x} - ip_{3y} \\ -p_{3z} \\ 0 \\ E+m \end{pmatrix}_{\text{spin down}}$$

Spinors for  $p_4$ .

$$u_{41} = \frac{1}{\sqrt{E+m}} \begin{pmatrix} E+m \\ 0 \\ p_{4z} \\ p_{4x} + ip_{4y} \end{pmatrix}_{\text{spin up}} \quad u_{42} = \frac{1}{\sqrt{E+m}} \begin{pmatrix} 0 \\ E+m \\ p_{4x} - ip_{4y} \\ -p_{4z} \end{pmatrix}_{\text{spin down}}$$

The scattering amplitude  $\mathcal{M}_{abcd}$  for spin state  $abcd$  is

$$\mathcal{M}_{abcd} = \mathcal{M}_{1abcd} + \mathcal{M}_{2abcd}$$

where

$$\mathcal{M}_{1abcd} = -\frac{e^2}{t} (\bar{v}_{1a} \gamma^\mu v_{3c}) (\bar{u}_{4d} \gamma_\mu u_{2b}), \quad \mathcal{M}_{2abcd} = \frac{e^2}{s} (\bar{v}_{1a} \gamma^\nu u_{2b}) (\bar{u}_{4d} \gamma_\nu v_{3c})$$

scattering                      annihilation

Symbols  $s$  and  $t$  are Mandelstam variables.

$$s = (p_1 + p_2)^2$$

$$t = (p_1 - p_3)^2$$

Expected probability density  $\langle |\mathcal{M}|^2 \rangle$  is the sum over squared amplitudes divided by the number of inbound states.

$$\langle |\mathcal{M}|^2 \rangle = \frac{1}{4} \sum_{abcd} |\mathcal{M}_{abcd}|^2$$

Expand the summand and label the terms. By positivity  $\boxed{2} = \boxed{3}$ .

$$\langle |\mathcal{M}|^2 \rangle = \frac{1}{4} \sum_{abcd} (\mathcal{M}_{1abcd} \mathcal{M}_{1abcd}^* + \mathcal{M}_{1abcd} \mathcal{M}_{2abcd}^* + \mathcal{M}_{2abcd} \mathcal{M}_{1abcd}^* + \mathcal{M}_{2abcd} \mathcal{M}_{2abcd}^*)$$

$\boxed{1}$                        $\boxed{2}$                        $\boxed{3}$                        $\boxed{4}$

The following Casimir trick uses matrix arithmetic to sum over spin states.

$$\begin{aligned} \sum_{abcd} \boxed{1} &= \frac{e^4}{t^2} \text{Tr} \left[ (\not{p}_1 - m) \gamma^\mu (\not{p}_3 - m) \gamma^\nu \right] \text{Tr} \left[ (\not{p}_4 + m) \gamma_\mu (\not{p}_2 + m) \gamma_\nu \right] \\ \sum_{abcd} \boxed{2} &= -\frac{e^4}{st} \text{Tr} \left[ (\not{p}_1 - m) \gamma^\mu (\not{p}_2 + m) \gamma^\nu (\not{p}_4 + m) \gamma_\mu (\not{p}_3 - m) \gamma_\nu \right] \\ \sum_{abcd} \boxed{4} &= \frac{e^4}{s^2} \text{Tr} \left[ (\not{p}_1 - m) \gamma^\mu (\not{p}_2 + m) \gamma^\nu \right] \text{Tr} \left[ (\not{p}_4 + m) \gamma_\mu (\not{p}_3 - m) \gamma_\nu \right] \end{aligned}$$

Probability density  $\langle |\mathcal{M}|^2 \rangle$  can be reformulated as

$$\langle |\mathcal{M}|^2 \rangle = \frac{e^4}{4} \left( \frac{f_{11}}{t^2} + \frac{2f_{12}}{st} + \frac{f_{22}}{s^2} \right)$$

with Casimir trick terms

$$\begin{aligned} f_{11} &= \text{Tr} \left[ (\not{p}_1 - m) \gamma^\mu (\not{p}_3 - m) \gamma^\nu \right] \text{Tr} \left[ (\not{p}_4 + m) \gamma_\mu (\not{p}_2 + m) \gamma_\nu \right] \\ f_{12} &= -\text{Tr} \left[ (\not{p}_1 - m) \gamma^\mu (\not{p}_2 + m) \gamma^\nu (\not{p}_4 + m) \gamma_\mu (\not{p}_3 - m) \gamma_\nu \right] \\ f_{22} &= \text{Tr} \left[ (\not{p}_1 - m) \gamma^\mu (\not{p}_2 + m) \gamma^\nu \right] \text{Tr} \left[ (\not{p}_4 + m) \gamma_\mu (\not{p}_3 - m) \gamma_\nu \right] \end{aligned}$$

The following formulas are equivalent to the Casimir trick. (Recall that  $a \cdot b = a^\mu g_{\mu\nu} b^\nu$ )

$$\begin{aligned} f_{11} &= 32(p_1 \cdot p_2)^2 + 32(p_1 \cdot p_4)^2 - 64(p_1 \cdot p_2)m^2 + 64(p_1 \cdot p_4)m^2 \\ f_{12} &= 32(p_1 \cdot p_4)^2 + 64(p_1 \cdot p_4)m^2 \\ f_{22} &= 32(p_1 \cdot p_3)^2 + 32(p_1 \cdot p_4)^2 + 64(p_1 \cdot p_3)m^2 + 64(p_1 \cdot p_4)m^2 \end{aligned}$$

In Mandelstam variables

$$\begin{aligned}f_{11} &= 8u^2 + 8s^2 - 64um^2 - 64sm^2 + 192m^4 \\f_{12} &= 8u^2 - 64um^2 + 96m^4 \\f_{22} &= 8u^2 + 8t^2 - 64um^2 - 64tm^2 + 192m^4\end{aligned}$$

For  $E \gg m$  a useful approximation is to set  $m = 0$  and obtain

$$\begin{aligned}f_{11} &= 8u^2 + 8s^2 \\f_{12} &= 8u^2 \\f_{22} &= 8u^2 + 8t^2\end{aligned}$$

For  $m = 0$  the Mandelstam variables are

$$\begin{aligned}s &= 4E^2 \\t &= -2E^2(1 - \cos \theta) \\u &= -2E^2(1 + \cos \theta)\end{aligned}$$

Hence

$$\begin{aligned}\langle |\mathcal{M}|^2 \rangle &= \frac{e^4}{4} \left( \frac{f_{11}}{t^2} + \frac{2f_{12}}{st} + \frac{f_{22}}{s^2} \right) \\&= 2e^4 \left( \frac{u^2 + s^2}{t^2} + \frac{2u^2}{st} + \frac{u^2 + t^2}{s^2} \right) \\&= e^4 \left( \underbrace{\frac{2(1 + \cos \theta)^2 + 8}{(1 - \cos \theta)^2}}_{\text{scattering}} - \underbrace{\frac{2(1 + \cos \theta)^2}{1 - \cos \theta}}_{\text{interference}} + \underbrace{1 + \cos^2 \theta}_{\text{annihilation}} \right)\end{aligned}$$

The expected probability density can be written more compactly as

$$\langle |\mathcal{M}|^2 \rangle = e^4 \left( \frac{\cos^2 \theta + 3}{\cos \theta - 1} \right)^2$$

## Cross section

The differential cross section is

$$\frac{d\sigma}{d\Omega} = \frac{\langle |\mathcal{M}|^2 \rangle}{4(4\pi\epsilon_0)^2 s}$$

where

$$s = (p_1 + p_2)^2 = 4E^2$$

For high energy experiments we have

$$\langle |\mathcal{M}|^2 \rangle = e^4 \left( \frac{\cos^2 \theta + 3}{\cos \theta - 1} \right)^2$$

Hence

$$\frac{d\sigma}{d\Omega} = \frac{e^4}{4(4\pi\varepsilon_0)^2 s} \left( \frac{\cos^2 \theta + 3}{\cos \theta - 1} \right)^2$$

Noting that

$$e^2 = 4\pi\varepsilon_0\alpha\hbar c$$

we have

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2(\hbar c)^2}{4s} \left( \frac{\cos^2 \theta + 3}{\cos \theta - 1} \right)^2$$

Noting that

$$d\Omega = \sin \theta d\theta d\phi$$

we also have

$$d\sigma = \frac{\alpha^2(\hbar c)^2}{4s} \left( \frac{\cos^2 \theta + 3}{\cos \theta - 1} \right)^2 \sin \theta d\theta d\phi$$

Let  $S(\theta_1, \theta_2)$  be the following integral of  $d\sigma$ .

$$S(\theta_1, \theta_2) = \int_0^{2\pi} \int_{\theta_1}^{\theta_2} d\sigma$$

The solution is

$$S(\theta_1, \theta_2) = \frac{\pi\alpha^2(\hbar c)^2}{2s} [I(\theta_2) - I(\theta_1)]$$

where

$$I(\theta) = \frac{16}{\cos \theta - 1} - \frac{\cos^3 \theta}{3} - \cos^2 \theta - 9 \cos \theta - 16 \log(1 - \cos \theta)$$

The cumulative distribution function is

$$F(\theta) = \frac{S(a, \theta)}{S(a, \pi)} = \frac{I(\theta) - I(a)}{I(\pi) - I(a)}, \quad a \leq \theta \leq \pi$$

Angular support is reduced by an arbitrary angle  $a > 0$  because  $I(0)$  is undefined.

The probability of observing scattering events in the interval  $\theta_1$  to  $\theta_2$  is

$$P(\theta_1 < \theta \leq \theta_2) = F(\theta_2) - F(\theta_1)$$

The probability density function is

$$f(\theta) = \frac{dF(\theta)}{d\theta} = \frac{1}{I(\pi) - I(a)} \left( \frac{\cos^2 \theta + 3}{\cos \theta - 1} \right)^2 \sin \theta$$