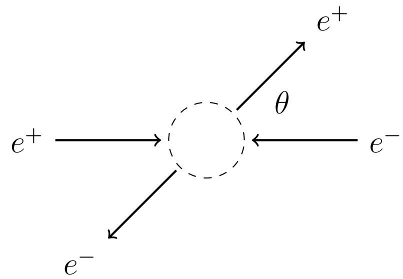
Bhabha scattering

Bhabha scattering is the interaction $e^- + e^+ \to e^- + e^+$.



Define the following momentum vectors and spinors. Symbol p is incident momentum. Symbol E is total energy $E = \sqrt{p^2 + m^2}$ where m is electron mass. Polar angle θ is the observed scattering angle. Azimuth angle ϕ cancels out in scattering calculations.

$$p_1 = \underset{\text{inbound } e^+}{\begin{pmatrix} E \\ 0 \\ 0 \\ p \end{pmatrix}} \qquad v_{11} = \underset{\substack{\text{inbound } e^+ \\ \text{spin up}}}{\begin{pmatrix} p \\ 0 \\ E+m \\ 0 \end{pmatrix}} \qquad v_{12} = \underset{\substack{\text{inbound } e^+ \\ \text{spin down}}}{\begin{pmatrix} 0 \\ -p \\ 0 \\ E+m \end{pmatrix}}$$

$$p_2 = \underset{\text{inbound } e^-}{\begin{pmatrix} E \\ 0 \\ 0 \\ -p \end{pmatrix}} \qquad u_{21} = \underset{\substack{\text{inbound } e^- \\ \text{spin up}}}{\begin{pmatrix} E+m \\ 0 \\ -p \\ 0 \end{pmatrix}} \qquad u_{22} = \underset{\substack{\text{inbound } e^- \\ \text{spin down}}}{\begin{pmatrix} 0 \\ E+m \\ 0 \\ p \end{pmatrix}}$$

$$p_3 = \underset{\text{outbound } e^+}{\begin{pmatrix} E \\ p\sin\theta\cos\phi \\ p\sin\theta\sin\phi \\ p\cos\theta \end{pmatrix}} \qquad v_{31} = \underset{\substack{\text{outbound } e^+ \\ \text{spin up}}}{\begin{pmatrix} p_3^z \\ p_3^x + ip_3^y \\ E+m \\ 0 \end{pmatrix}} \qquad v_{32} = \underset{\substack{\text{outbound } e^+ \\ \text{spin down}}}{\begin{pmatrix} p_3^x - ip_3^y \\ -p_3^z \\ 0 \\ E+m \end{pmatrix}}$$

$$p_4 = \underset{\text{outbound } e^-}{\begin{pmatrix} E \\ -p\sin\theta\cos\phi \\ -p\sin\theta\sin\phi \\ -p\cos\theta \end{pmatrix}} \qquad u_{41} = \underset{\substack{\text{outbound } e^- \\ \text{spin up}}}{\begin{pmatrix} E+m \\ 0 \\ p_4^z \\ p_4^x + ip_4^y \end{pmatrix}} \qquad u_{42} = \underset{\substack{\text{outbound } e^- \\ \text{spin down}}}{\begin{pmatrix} 0 \\ E+m \\ p_4^x - ip_4^y \\ -p_4^z \end{pmatrix}}$$

The spinors are not individually normalized. Instead, a combined spinor normalization constant $N = (E+m)^4$ will be used.

This is the probability density for spin state *abcd*. The formula is derived from Feynman diagrams for Bhabha scattering.

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

Symbol e is electron charge and

$$s = (p_1 + p_2)^2 = 4E^2$$
$$t = (p_1 - p_3)^2 = (p_1 - p_3)^\mu g_{\mu\nu}(p_1 - p_3)^\nu$$

Let

$$a_1 = (\bar{v}_{1a}\gamma^\mu v_{3c})(\bar{u}_{4d}\gamma_\mu u_{2b}), \quad a_2 = (\bar{v}_{1a}\gamma^\nu u_{2b})(\bar{u}_{4d}\gamma_\nu v_{3c})$$

Then

$$\begin{aligned}
|\mathcal{M}_{abcd}|^2 &= \frac{e^4}{N}\left|-\frac{a_1}{t} + \frac{a_2}{s}\right|^2 \\
&= \frac{e^4}{N}\left(-\frac{a_1}{t} + \frac{a_2}{s}\right)\left(-\frac{a_1}{t} + \frac{a_2}{s}\right)^* \\
&= \frac{e^4}{N}\left(\frac{a_1 a_1^*}{t^2} - \frac{a_1 a_2^*}{st} - \frac{a_1^* a_2}{st} + \frac{a_2 a_2^*}{s^2}\right)
\end{aligned}$$

The expected probability density $\langle|\mathcal{M}|^2\rangle$ is computed by summing $|\mathcal{M}_{abcd}|^2$ over all spin states and then dividing by the number of inbound states. There are four inbound states.

$$\begin{aligned}
\langle|\mathcal{M}|^2\rangle &= \frac{1}{4}\sum_{a=1}^{2}\sum_{b=1}^{2}\sum_{c=1}^{2}\sum_{d=1}^{2}|\mathcal{M}_{abcd}|^2 \\
&= \frac{e^4}{4N}\sum_{a=1}^{2}\sum_{b=1}^{2}\sum_{c=1}^{2}\sum_{d=1}^{2}\left(\frac{a_1 a_1^*}{t^2} - \frac{a_1 a_2^*}{st} - \frac{a_1^* a_2}{st} + \frac{a_2 a_2^*}{s^2}\right)
\end{aligned}$$

The Casimir trick uses matrix arithmetic to compute sums.

$$\begin{aligned}
f_{11} &= \frac{1}{N}\sum_{abcd} a_1 a_1^* = \operatorname{Tr}\left((\not{p}_1 - m)\gamma^\mu(\not{p}_3 - m)\gamma^\nu\right)\operatorname{Tr}\left((\not{p}_4 + m)\gamma_\mu(\not{p}_2 + m)\gamma_\nu\right) \\
f_{12} &= \frac{1}{N}\sum_{abcd} a_1 a_2^* = \operatorname{Tr}\left((\not{p}_1 - m)\gamma^\mu(\not{p}_2 + m)\gamma^\nu(\not{p}_4 + m)\gamma_\mu(\not{p}_3 - m)\gamma_\nu\right) \\
f_{22} &= \frac{1}{N}\sum_{abcd} a_2 a_2^* = \operatorname{Tr}\left((\not{p}_1 - m)\gamma^\mu(\not{p}_2 + m)\gamma^\nu\right)\operatorname{Tr}\left((\not{p}_4 + m)\gamma_\mu(\not{p}_3 - m)\gamma_\nu\right)
\end{aligned}$$

Hence

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

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

$$\begin{aligned}
f_{11} &= 32(p_1 \cdot p_2)^2 + 32(p_1 \cdot p_4)^2 - 64m^2(p_1 \cdot p_3) + 64m^4 \\
f_{12} &= -32(p_1 \cdot p_4)^2 - 32m^2(p_1 \cdot p_2) + 32m^2(p_1 \cdot p_3) - 32m^2(p_1 \cdot p_4) - 32m^4 \\
f_{22} &= 32(p_1 \cdot p_3)^2 + 32(p_1 \cdot p_4)^2 + 64m^2(p_1 \cdot p_2) + 64m^4
\end{aligned}$$

For Mandelstam variables

$$\begin{aligned} s &= (p_1 + p_2)^2 \\ t &= (p_1 - p_3)^2 \\ u &= (p_1 - p_4)^2 \end{aligned}$$

the formulas are

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

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

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

Hence

$$\begin{aligned} \langle |\mathcal{M}|^2 \rangle &= \frac{e^4}{4} \left(\frac{f_{11}}{t^2} - \frac{f_{12}}{st} - \frac{f_{12}^*}{st} + \frac{f_{22}}{s^2} \right) \\ &= \frac{e^4}{4} \left(\frac{8s^2 + 8u^2}{t^2} - \frac{-8u^2}{st} - \frac{-8u^2}{st} + \frac{8t^2 + 8u^2}{s^2} \right) \\ &= 2e^4 \left(\frac{s^2 + u^2}{t^2} + \frac{2u^2}{st} + \frac{t^2 + u^2}{s^2} \right) \end{aligned}$$

For $m = 0$ the Mandelstam variables are

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

and it can be shown that

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

Cross section

The differential cross section is

$$\frac{d\sigma}{d\Omega} = \frac{\langle |\mathcal{M}|^2 \rangle}{4(4\pi\varepsilon_0)^2 s}$$

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 for high energy experiments

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

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 surface integral of $d\sigma$.

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

The solution is

$$S(\theta_1,\theta_2) = \frac{2\pi\alpha^2(\hbar c)^2}{4s}\big(I(\theta_2)-I(\theta_1)\big)$$

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

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

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

The probability of observing scattering events in the interval θ_1 to θ_2 is

$$P(\theta_1\le\theta\le\theta_2) = F(\theta_2)-F(\theta_1)$$

Let N be the total number of scattering events from an experiment. Then the number of scattering events in the interval θ_1 to θ_2 is predicted to be

$$NP(\theta_1\le\theta\le\theta_2)$$

The probability density function is

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

Data from SLAC SPEAR experiment

The following Bhabha scattering data is from SLAC-PUB-1501.

k	x_k	x_{k+1}	y
1	0.6	0.5	4432
2	0.5	0.4	2841
3	0.4	0.3	2045
4	0.3	0.2	1420
5	0.2	0.1	1136
6	0.1	0.0	852
7	0.0	−0.1	656
8	−0.1	−0.2	625
9	−0.2	−0.3	511
10	−0.3	−0.4	455
11	−0.4	−0.5	402
12	−0.5	−0.6	398

Column k is the bin number, column y is the number of scattering events, and

$$x_k = \cos\theta_k$$

The cumulative distribution function for this experiment is

$$F(\theta) = \frac{I(\theta) - I(\theta_1)}{I(\theta_{13}) - I(\theta_1)}$$

where

$$\theta_{13} = \arccos(-0.6), \quad \theta_1 = \arccos(0.6)$$

The scattering probability P_k is

$$P_k = F\left(\arccos(x_{k+1})\right) - F\left(\arccos(x_k)\right)$$

Multiply P_k by total scattering events to obtain predicted number of events $\hat{y}_k$.

$$\sum y_k = 15773, \quad \hat{y}_k = 15773\, P_k$$

The following table shows the predicted scattering events $\hat{y}$.

k	x_k	x_{k+1}	y	$\hat{y}$
1	0.6	0.5	4432	4598
2	0.5	0.4	2841	2880
3	0.4	0.3	2045	1955
4	0.3	0.2	1420	1410
5	0.2	0.1	1136	1068
6	0.1	0.0	852	843
7	0.0	−0.1	656	689
8	−0.1	−0.2	625	582
9	−0.2	−0.3	511	505
10	−0.3	−0.4	455	450
11	−0.4	−0.5	402	411
12	−0.5	−0.6	398	382

The coefficient of determination R^2 measures how well predicted values fit the data.

$$R^2 = 1 - \frac{\sum(y - \hat{y})^2}{\sum(y - \bar{y})^2} = 0.997$$

The result indicates that $F(\theta)$ explains 99.7% of the variance in the data.

Data from DESY PETRA experiment

See www.hepdata.net/record/ins191231, Table 3, 14.0 GeV.

x	y
-0.7300	0.10115
-0.6495	0.12235
-0.5495	0.11258
-0.4494	0.09968
-0.3493	0.14749
-0.2491	0.14017
-0.1490	0.18190
-0.0488	0.22964
0.0514	0.25312
0.1516	0.30998
0.2520	0.40898
0.3524	0.62695
0.4529	0.91803
0.5537	1.51743
0.6548	2.56714
0.7323	4.30279

Data x and y have the following relationship with the cross section formula.

$$x = \cos\theta, \quad y = \frac{d\sigma}{d\Omega} \text{ in units of nanobarns}$$

The cross section formula is

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

To compute predicted values $\hat{y}$, multiply by 10^{37} to convert square meters to nanobarns.

$$\hat{y} = \frac{\alpha^2}{4s}\left(\frac{x^2 + 3}{x - 1}\right)^2 \times (\hbar c)^2 \times 10^{37}$$

The following table shows predicted values $\hat{y}$ for $s = (14.0\,\text{GeV})^2$.

x	y	$\hat{y}$
−0.7300	0.10115	0.110296
−0.6495	0.12235	0.113816
−0.5495	0.11258	0.120101
−0.4494	0.09968	0.129075
−0.3493	0.14749	0.141592
−0.2491	0.14017	0.158934
−0.1490	0.18190	0.182976
−0.0488	0.22964	0.216737
0.0514	0.25312	0.264989
0.1516	0.30998	0.335782
0.2520	0.40898	0.443630
0.3524	0.62695	0.615528
0.4529	0.91803	0.907700
0.5537	1.51743	1.451750
0.6548	2.56714	2.609280
0.7323	4.30279	4.615090

The coefficient of determination R^2 measures how well predicted values fit the data.

$$R^2 = 1 - \frac{\sum(y-\hat{y})^2}{\sum(y-\bar{y})^2} = 0.995$$

The result indicates that the model $d\sigma$ explains 99.5% of the variance in the data.

Notes

Here are a few notes about how the Eigenmath scripts work. In component notation the trace operators of the Casimir trick become sums over the repeated index α.

$$\begin{aligned}
f_{11} &= \left((\not{p}_1 - m)^\alpha{}_\beta \gamma^{\mu\beta}{}_\rho (\not{p}_3 - m)^\rho{}_\sigma \gamma^{\nu\sigma}{}_\alpha\right)\left((\not{p}_4 + m)^\alpha{}_\beta \gamma_\mu{}^\beta{}_\rho (\not{p}_2 + m)^\rho{}_\sigma \gamma_\nu{}^\sigma{}_\alpha\right) \\
f_{12} &= (\not{p}_1 - m)^\alpha{}_\beta \gamma^{\mu\beta}{}_\rho (\not{p}_2 + m)^\rho{}_\sigma \gamma^{\nu\sigma}{}_\tau (\not{p}_4 + m)^\tau{}_\delta \gamma_\mu{}^\delta{}_\eta (\not{p}_3 - m)^\eta{}_\xi \gamma_\nu{}^\xi{}_\alpha \\
f_{22} &= \left((\not{p}_1 - m)^\alpha{}_\beta \gamma^{\mu\beta}{}_\rho (\not{p}_2 + m)^\rho{}_\sigma \gamma^{\nu\sigma}{}_\alpha\right)\left((\not{p}_4 + m)^\alpha{}_\beta \gamma_\mu{}^\beta{}_\rho (\not{p}_3 - m)^\rho{}_\sigma \gamma_\nu{}^\sigma{}_\alpha\right)
\end{aligned}$$

To convert the above formulas to Eigenmath code, the γ tensors need to be transposed so that repeated indices are adjacent to each other. Also, multiply γ^μ by the metric tensor to lower the index.

$\gamma^{\beta\mu}{}_\rho \quad \rightarrow \quad$ `gammaT = transpose(gamma)`

$\gamma^\beta{}_{\mu\rho} \quad \rightarrow \quad$ `gammaL = transpose(dot(gmunu,gamma))`

Define the following 4×4 matrices.

$$
\begin{aligned}
(\not{p}_1 - m) &\quad\rightarrow\quad \texttt{X1 = pslash1 - m I} \\
(\not{p}_2 + m) &\quad\rightarrow\quad \texttt{X2 = pslash2 + m I} \\
(\not{p}_3 - m) &\quad\rightarrow\quad \texttt{X3 = pslash3 - m I} \\
(\not{p}_4 + m) &\quad\rightarrow\quad \texttt{X4 = pslash4 + m I}
\end{aligned}
$$

Then for f_{11} we have the following Eigenmath code. The contract function sums over α.

$$
\begin{aligned}
(\not{p}_1 - m)^\alpha{}_\beta \gamma^{\mu\beta}{}_\rho (\not{p}_3 - m)^\rho{}_\sigma \gamma^{\nu\sigma}{}_\alpha &\quad\rightarrow\quad \texttt{T1 = contract(dot(X1,gammaT,X3,gammaT),1,4)} \\
(\not{p}_4 + m)^\alpha{}_\beta \gamma_\mu{}^\beta{}_\rho (\not{p}_2 + m)^\rho{}_\sigma \gamma_\nu{}^\sigma{}_\alpha &\quad\rightarrow\quad \texttt{T2 = contract(dot(X4,gammaL,X2,gammaL),1,4)}
\end{aligned}
$$

Next, multiply then sum over repeated indices. The dot function sums over ν then the contract function sums over μ. The transpose makes the ν indices adjacent as required by the dot function.

$$
f_{11} = \operatorname{Tr}(\cdots \gamma^\mu \cdots \gamma^\nu) \operatorname{Tr}(\cdots \gamma_\mu \cdots \gamma_\nu) \quad\rightarrow\quad \texttt{f11 = contract(dot(T1,transpose(T2)))}
$$

Follow suit for f_{22}.

$$
\begin{aligned}
(\not{p}_1 - m)^\alpha{}_\beta \gamma^{\mu\beta}{}_\rho (\not{p}_2 + m)^\rho{}_\sigma \gamma^{\nu\sigma}{}_\alpha &\quad\rightarrow\quad \texttt{T1 = contract(dot(X1,gammaT,X2,gammaT),1,4)} \\
(\not{p}_4 + m)^\alpha{}_\beta \gamma_\mu{}^\beta{}_\rho (\not{p}_3 - m)^\rho{}_\sigma \gamma_\nu{}^\sigma{}_\alpha &\quad\rightarrow\quad \texttt{T2 = contract(dot(X4,gammaL,X3,gammaL),1,4)}
\end{aligned}
$$

Hence

$$
f_{22} = \operatorname{Tr}(\cdots \gamma^\mu \cdots \gamma^\nu) \operatorname{Tr}(\cdots \gamma_\mu \cdots \gamma_\nu) \quad\rightarrow\quad \texttt{f22 = contract(dot(T1,transpose(T2)))}
$$

The calculation of f_{12} begins with

$$
\begin{aligned}
&(\not{p}_1 - m)^\alpha{}_\beta \gamma^{\mu\beta}{}_\rho (\not{p}_2 + m)^\rho{}_\sigma \gamma^{\nu\sigma}{}_\tau (\not{p}_4 + m)^\tau{}_\delta \gamma_\mu{}^\delta{}_\eta (\not{p}_3 - m)^\eta{}_\xi \gamma_\nu{}^\xi{}_\alpha \\
&\qquad\rightarrow\quad \texttt{T = contract(dot(X1,gammaT,X2,gammaT,X4,gammaL,X3,gammaL),1,6)}
\end{aligned}
$$

Then sum over repeated indices μ and ν.

$$
f_{12} = \operatorname{Tr}(\cdots \gamma^\mu \cdots \gamma^\nu \cdots \gamma_\mu \cdots \gamma_\nu) \quad\rightarrow\quad \texttt{f12 = contract(contract(T,1,3))}
$$