

Exercise – Renormalization in one-dimensional quantum mechanics

We seek a low-energy theorem for the scattering from a short-range potential in one spatial dimension. We take this potential to have a width of order a . We represent this potential in terms of distributions given by delta functions.

Consider the time-independent Schrödinger equation in one spatial dimension,

$$-\frac{1}{2} \Psi''(x) + V(x) \Psi(x) = E \Psi(x) , \quad (1)$$

where $E > 0$ and where $V(x)$ denotes a short-range potential given by the distribution

$$V(x) = c \frac{\delta(x+a) - \delta(x-a)}{2a} . \quad (2)$$

The parameter a is a short-distance cutoff. It defines a potential with width of order a . The parameter c is dimensionless.

We seek a solution of (1) of the form

$$\Psi(x) = \begin{cases} A e^{ipx} + B e^{-ipx} , & x < -a \\ \tilde{A} e^{ipx} + \tilde{B} e^{-ipx} , & -a < x < a \\ C e^{ipx} , & x > a \end{cases}$$

where $p = \sqrt{2E} > 0$.

a) Imposing continuity and the appropriate jump conditions at $x = -a$ and $x = a$, show that the transmission coefficient $T \equiv C/A$ is given by

$$\frac{1}{T} = 1 + \frac{c^2}{4a^2 p^2} (1 - e^{4iap}) . \quad (3)$$

b) Show that at low-energies, i.e. $pa \ll 1$, the transmission probability is given in terms of a renormalized parameter c_R as

$$|T|^2 = \frac{p^2}{c_R^2} . \quad (4)$$

Determine c_R and verify that it is dimensionful.

Thus, the dimensionless parameter c has been traded for a dimensionful parameter c_R . Verify that the result (4) is independent of the short-distance cutoff a in that scalings of a can be compensated by scalings of c .