5 Perturbations and Approximation Methods

In this chapter we study methods of approximation frequently used to solve quantum mechanical problems that are too difficult (or impossible) to solve analytically. We will cover both stationary (i.e., time-independent) and time-dependent perturbation techniques involving perturbations of small enough amplitude compared to the unperturbed Hamiltonian of such systems.

Some of the material presented in this chapter is taken from Auletta, Fortunato and Parisi, Chap. 10 and Cohen-Tannoudji, Diu and Laloë, Vol. II, Chaps. XI and XIII.

5.1 The Theory of Stationary Perturbations

It is very often the case in quantum mechanics that the Hamiltonian of a system is not explicitly a function of time. These are cases where we need to solve the time-independent form of the Schrödinger equation (see equation (1.56) in Chapter 1). Unfortunately, in most cases it is not possible to solve Schrödinger equation exactly to obtain analytical solutions. Physicists must then resort to methods of approximations in order to develop solutions of increasing accuracy by considering higher orders of perturbations.

We consider the case of a quantum mechanical system with an Hamiltonian such that

$$ H = H_0 + W'', \tag{5.1} $$

where H_0 is the unperturbed Hamiltonian, for which we know the eigenvectors and eigenvalues, and W' is a perturbation such that $W'' \ll H_0$ (but see below). We assume that both H_0 and W'' are independent of time. This lack of dependence on time and the difference in importance between the two components of the Hamiltonian is the basis for the *theory of stationary perturbations*.

Given the relative smallness of the perturbation we normalize it in relation to H_0 and introduce a real parameter $\lambda \ll 1$ such that

$$ W'' = \lambda W \tag{5.2} $$

and

$$ H(\lambda) = H_0 + \lambda W. \tag{5.3} $$

We will assume that the unperturbed Hamiltonian H_0 possesses a set of eigenvectors $\{|u_n^i\rangle\}$, which also forms a basis (i.e., $\langle u_n^i | u_m^j \rangle = \delta_{nm}\delta_{ij}$ and $\sum_{n,i} |u_n^i\rangle\langle u_n^i|$), and

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