Annihilating States in Close-Coupling Method for Collisions between Hadronic and Ordinary Atoms

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Traditional close-coupling method for atomic and nuclear collisions supposes an expansion of the total wave function in terms of inner stationary states of colliding subsystems. In the case of hadronic atoms, a similar expansion has to involve *inter alia* the low angular-momentum states (ns, np) with large annihilation (nuclear absorbtion) widths Γ_{nl} and small life times $\tau_{nl} = \hbar/\Gamma_{nl}$. These states can disappear during collision. The parameter $\nu_{nl} = \Gamma_{nl} R_i/\hbar v$ (the ratio of the collision time $\tau_{coll} = R_i/v$ to the life time) gives a criterion of the state non-stationarity during collisions: at $\nu \ll 1$ the annihilation during collision is negligible, whereas at $\nu \gtrsim 1$ it is appreciable. The annihilation during collisions was considered previously within semiclassical approximations (see, e.g., [1, 2]). As far as we know, the single attempt to consider this effect within the quantum close-coupling method was done in the paper [3] for the collisions of $(\pi^- p)_{nl}$ with H atom. However the authors of [3] use an artificial assumption that the Γ_{nl} is turned off at distances between two atoms $r > R_0 = 5a_0$ that contradicts to the physical reality.

In order to consider close-coupling equations with account for annihilating states correctly, we divide the total space of N channels into the subspace α of the stationary states and the subspace β of the annihilating states, and construct two types of the $(N \times N)$ matrix solutions $X(r)$ and $Y(r)$, which are defined by the asymptotic forms at $r \to \infty$: X_{ij}, $Y_{ij} \to 0$ at $i \neq j$, X_{ii} and Y_{ii} at $i \in \alpha$ tend to ordinary incoming and outgoing waves, whereas at $i \in \beta$ they tend to *damping* incoming and outgoing waves, respectively. The damping of the both latter waves is provided by the complex conjugation of the complex wave numbers in two waves, $k_\beta^{(-)} = (k_\beta^{(+)})^*$, and $\mathrm{Im} k_\beta^{(+)} > 0$. Total matrix of solutions with the correct asymptotic behaviour is $F(r) = [X(r) - Y(r)C]A$. At a small $r = r_s$ it has to be sewed with the $(N \times N)$ matrix of regular solutions $U(r)$ obtained by a standard way with account for the complex energy shifts in the annihilating channels. This procedure yields the $(N \times N)$ matrix C. The submatrix $C_{\alpha\alpha} = S$ is the S-matrix of the transitions between the states in the subspace α, whereas other elements of the C don't have a real physical meaning. The S-matrix is not unitary, because the hamiltonian of the problem is non-hermitian. The 'unitary defect' $(1 - \sum_{j\in\alpha} |S_{ji}|^2)$ gives the cross section of induced annihilation for the initial state $i \in \alpha$.

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[2] T.P. Terada and R.S. Hayano, Phys. Rev. **C 55**, 73 (1997).
[3] T.S. Jensen and V.E. Markushin, Eur. Phys. J. **D 19**, 165 (2002).