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Microscopic description of \( \alpha + \alpha \) bremsstrahlung from a realistic nucleon-nucleon interaction

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Abstract. The \( \alpha + \alpha \) bremsstrahlung is studied in a microscopic cluster approach with the Generator Coordinate Method associated with the Microscopic R-matrix Method. Two effective nucleon-nucleon interactions are considered: the Minnesota potential and a potential derived from the realistic Argonne AV18 potential by the Unitary Correlation Operator Method. The influence of the nucleon-nucleon interactions are discussed and the results are compared with experimental data.

1. Introduction

For a long time, microscopic approaches have been used to describe nuclear collisions [1, 2]. They were based on effective nucleon-nucleon (NN) interactions adapted to the cluster model and including one or two parameters fitted for each collision. In recent years, realistic NN interactions were developed and many efforts were done to base collision models on them. These realistic potentials have the feature to reproduce with a high precision the properties of two-nucleon systems. However, for three- or more-nucleon systems, a good agreement with experiment cannot be achieved without three-body forces and/or renormalization techniques.

In Ref. [3], we proposed to describe the \( \alpha + N \), \( \alpha + ^3\text{He} \), and \( \alpha + \alpha \) elastic scatterings in a microscopic cluster model based on the UCOM-AV18 potential obtained from the two-body realistic potential Argonne AV18 [4] by the Unitary Correlation Operator Method (UCOM)[5, 6]. A rather good agreement with the experimental phase shifts was obtained. However, scattering data only depend on the asymptotic part of the scattering wave function. To probe the inner part of the scattering wave function, the study of bremsstrahlung is relevant, in particular for unbound systems.

Microscopic descriptions of the \( \alpha + \alpha \) bremsstrahlung were previously performed [7, 8]. The scattering wave functions were obtained from a Schrödinger equation based on effective NN potentials: the Volkov [9] and Minnesota potentials [10]. In this contribution, we follow a very similar approach but based on the realistic effective UCOM-AV18 potential [3]. The obtained results are compared with the experimental data and with results from a microscopic cluster model based on the Minnesota effective NN interaction.

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2. Microscopic bremsstrahlung model

An α particle moving in the z-direction with the energy \( E_\alpha \) collides a second α particle initially at rest. Then, a photon is emitted in the direction \( \Omega_\gamma = (\theta_\gamma, \varphi_\gamma) \) and the α particles are scattered in the directions \( \Omega_1 = (\theta_1, \varphi_1) \) and \( \Omega_2 = (\theta_2, \varphi_2) \). In the coplanar Harvard geometry which is considered here and in the experiments [11, 12], the α particles are detected only if \( \varphi_1 = \varphi_2 = 0 \).

Evaluating the differential bremsstrahlung cross sections requires calculating the matrix element of the photon-emission operator \( H_e \) between the incoming initial and outgoing final states. In this cluster approach, the wave function is assumed to be written as

\[
\Psi = A \phi_{\alpha_1} \phi_{\alpha_2} g(\rho)
\]  

(1)

where \( A \) is the antisymmetrization projector, \( \phi_{\alpha_1} \) and \( \phi_{\alpha_2} \) are the internal wave functions of the α particles, \( g \) is the relative wave function, and \( \rho \) is the vector between the c.m. of the nuclei. The α wave functions are obtained by removing a c.m. factor from the \( (0s)^4 \) state of the harmonic oscillator shell model. The initial and final relative wave functions \( g(\rho) \) are calculated from the microscopic Schrödinger equation for eight nucleons

\[
H \Psi(1, 2, \ldots, 8) = E_{\text{tot}} \Psi(1, 2, \ldots, 8),
\]  

(2)

with

\[
H = \sum_{i=1}^{8} t_i - T_{\text{c.m.}} + \sum_{i<j}^{8} \left[ v_{ij}^N + v_{ij}^C \right],
\]  

(3)

where \( E_{\text{tot}} \) is the energy of the nuclear system in the c.m. framework, \( t_i \) is the kinetic energy of nucleon \( i \), \( T_{\text{c.m.}} \) is the c.m. kinetic energy, \( v_{ij}^N \) is the nuclear interaction (the UCOM-AV18 potential or the Minnesota potential with the exchange parameter \( u = 0.9474 \)) and \( v_{ij}^C \) is the Coulomb potential. Following the principle of the Microscopic R-matrix Method [13], the configuration space is divided in two regions at the channel radius \( a \): an internal region \( (\rho < a) \) where the wave function is described by the Generator Coordinate Method [14, 2] and an external region \( (\rho > a) \) where the antisymmetrization between nuclei is neglected and the \( \alpha \alpha \) interaction is considered purely Coulombic. The wave functions are evaluated by solving the Schrödinger equation (2) on the internal region requiring the continuity of the wave function at the channel radius \( a \). They are insensitive to the value of \( a \) if \( a \) is chosen large enough.

The photon-emission operator is limited to the E2 transitions because they dominate greatly for the \( \alpha + \alpha \) system. As in Ref. [7], we take only the convection current into account to evaluate the photon-emission operator. The long-wavelength approximation is not performed and the Siegert theorem is not used because it would lead to divergent integrals as the initial and final states are in the continuum, so not square-integrable [7]. Therefore, the spin-isospin-scalar part of the photon-emission operator reads [7]

\[
H_e = \frac{ie\sqrt{\pi}}{2\sqrt{15}m_Nck_\gamma} \sum_{\mu=-2}^{2} \left[ D^2_{\mu-1}(R_\gamma) + D^2_{\mu1}(R_\gamma) \right] \sum_{i=1}^{8} \chi_{\mu}(k_\gamma, r_i - R_{\text{c.m.}}) \cdot (p_i - A^{-1} P_{\text{c.m.}}),
\]  

(4)

where \( m_N \) is the nucleon mass, \( k_\gamma \) is the photon wave number, \( D \) is the rotation matrix element depending on the Euler angles \( R_\gamma = (\varphi_\gamma, -\theta_\gamma, 0) \), \( r_i \) and \( p_i \) are respectively the coordinate and momentum of nucleon \( i \), \( R_{\text{c.m.}} \) and \( P_{\text{c.m.}} \) are the c.m. coordinate and momentum, and \( \chi_{\mu} \) is given by

\[
\chi_{\mu}(k, r) = \left( k^2 r + \nabla \frac{\partial}{\partial r} r \right) j_2(kr) Y_2^\mu(kr).
\]  

(5)
3. Results and discussions

The theoretical and experimental differential bremsstrahlung cross sections $d^2\sigma/d\Omega_1d\Omega_2$ as a function of the incident $\alpha$ energy are displayed at Fig. 1 for the Harvard coplanar configurations $\theta_1 = \theta_2 = 35^\circ$ (a) and $\theta_1 = \theta_2 = 37^\circ$ (b). They are the only configurations for which experimental data are available.

In the range of energy where experimental data are available, differences between models are weak compared to the experimental error bars. At higher energies, differences become much larger. New bremsstrahlung experiments at higher energy are thus required to probe the models.

To conclude, let us note that differences between models come from the differences not only in the inner part of the wave functions but in their external part too since the phase shifts are not exactly equal for both models [3]. Indeed, for the lowest values of the relative orbital angular momentum $l = 0$ and $l = 2$, theoretical and experimental phase shifts are in a rather good agreement but from $l = 4$, the model based on the UCOM-AV18 potential does not reproduce anymore the experimental phase shifts as well as the model based on the Minnesota potential. This discrepancy between the models in the $\alpha + \alpha$ elastic phase shifts is partially responsible for their discrepancy in the description of $\alpha + \alpha$ bremsstrahlung. The contribution of the external part deserves to be investigated in further works.

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