Sub-Coulomb barrier penetration for a $^6\mathrm{Li}$ with a clustered and deformed ground-state

Salvatore Simone Perrotta[1,2,3,4,*], *Lorenzo* Fortunato[4,5], *José Antonio* Lay[2,6], and *Maria* Colonna[3,1]

[1]Università degli Studi di Catania – Catania, Italy
[2]Universidad de Sevilla – Seville, Spain
[3]Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud – Catania, Italy
[4]Università degli Studi di Padova – Padua, Italy
[5]Istituto Nazionale di Fisica Nucleare, Sezione di Padova – Padua, Italy
[6]Instituto Interuniversitario Carlos I de Física Teórica y Computacional – Seville, Spain

Abstract. The penetrability of the Coulomb barrier of ^{6}Li by a proton is studied using a quantum cluster model. We focus on the role of quadrupole deformations in the nucleus ground-state, in terms of which a $^6\mathrm{Li}-\mathrm{p}$ form factor with tensor components is computed. We find that the diagonal part of the tensor term reduces the average barrier penetrability of the system. However, the tensor interaction due only to the mechanism studied at present is very small, regardless of the specific adopted construction, and yields negligible effects.

1 Introduction

The dynamics of Coulomb-barrier penetration plays a primary role in nuclear reactions taking place at collision energies of astrophysical interest [1, ch. 2]. The process can also be relevant with regards to the "electron screening problem" [2], the excess of enhancement observed in the cross-section of several nuclear reactions of astrophysical interest, measured in fixed-target experiments, with respect to the expected effect of the electrons in the projectile and target. Cluster models have been found to represent an excellent framework for the study of reactions involving light nuclei. In the context of barrier-penetration phenomena, the implications of such a model were explored in ref. [2] within a classical formulation.

In this work, we represent the structure of the ^{6}Li nucleus through a quantum two-cluster non-spherical wave-function. The projectile-target tensor interaction arising from such description, of which we aim to study the properties, appears to be a more microscopical analogous of the coupling interaction that is sometimes employed to study the impact of nuclear deformation on barrier penetrability in heavy-ion fusion reactions [3]. Additional details and previous work on this topic can be found in refs. [4, 5].

2 Description of the model and input ingredients

Let $\left|\mathrm{Li}_{1,M}\right\rangle$ be the ^{6}Li 1^+ ground-state with spin projection M. This is modelled as an inert-cluster-model bound state of α and deuteron, whose wave-function is written, as in ref. [5,

*e-mail: perrotta@lns.infn.it

eq. 1], as the superposition of s- and d-wave components. In refs. [4, 5] these components were constructed phenomenologically and combined with weights adjusted on data. Here, instead, the full wave-function was computed, using the FRESCO code [6], as the ground state of the α−d potential reported in ref. [7], including a central, a spin-orbit and a rank-2 tensor interaction. The volume term was fitted on a Woods-Saxon, whose depth was subsequently increased by 0.8 % to reproduce the α+d experimental binding energy. Such state corresponds to an electric quadrupole moment of −2.97 mb for the ^{6}Li, which does not agree satisfactorily with the experimental value of −0.81 mb [8] but still constitutes a relevant improvement with respect to the prediction of a central α−d potential (2.86 mb). Determining an inert-two-cluster-model state accurately reproducing all structure observables of interest appears to be challenging (for more discussion on this topic see refs. [4, 5] for a phenomenological construction and ref. [9] for a more microscopical one).

Given a set of phenomenological potentials for the interaction between the proton projectile and each ^{6}Li cluster, $V_{\alpha\,\mathrm{p}}$ and $V_{\mathrm{d\,p}}$, if all couplings to ^{6}Li exited states are neglected, the ^{6}Li−p system can be described by just the ground-state form factor $V(M, M', \boldsymbol{R}) = \langle \mathrm{Li}_{1M'} | V_{\alpha\,\mathrm{p}} + V_{\mathrm{d\,p}} | \mathrm{Li}_{1M} \rangle$, where $\boldsymbol{R}$ is the distance between the centre of mass of projectile and target. Here, this was computed using the same potentials $V_{\alpha\,\mathrm{p}}$ and $V_{\mathrm{d\,p}}$ in ref. [5, sec. 3] and the present-work ^{6}Li wave-function. Even if the projectile-cluster potentials are central, the non-spherical ^{6}Li inter-cluster motion generates a tensor component in V, which can expressed as in ref. [4, sec. 5.2.2]. The qualitative features of the form factor computed here are similar to those found in ref. [5], but the weight of the tensor term is smaller (this is essentially because the norm of the ^{6}Li d-wave component is smaller here).

As in refs. [2, 4, 5], the barrier penetrability is evaluated approximately by neglecting the non-diagonal complex components of V (that is, selecting only $M = M'$) and computing the average, over each specific spin projection and orientation of the projectile-target displacement with respect to the quantization axis, of the WKB radial s-wave transmission coefficient (see e.g. ref. [3, eq. (3·60)] or [4, sec. 1.1, sec. 5]) for a central potential $V_{M,\theta}(R)$ equal to $V(M, M, \boldsymbol{R})$.

3 Results and conclusions

Figure 1 shows the average ^{6}Li−p penetrability computed as described in section 2, and compares it with the penetrability of the barrier corresponding to only the central part of $V(M, M, \boldsymbol{R})$, which is also equal to the average of V itself over all orientations and spin projections. The two calculations are practically indistinguishable. Having used a more microscopical description of the ^{6}Li cluster-model state, we thus confirm the result, mentioned in refs. [4, 5], that the diagonal part of the ^{6}Li−p tensor interaction generated solely by the non-sphericity of ^{6}Li ground state is too small to yield a measurable difference in the overall s-wave barrier penetrability. In order to strengthen the conclusion, it would be pertinent to add to the model the non-central components of the projectile-cluster potentials (in particular the tensor part of the deuteron interaction). Additionally, it may be important to improve the description of the barrier penetrability process, for instance taking into account the role of spin-flip processes allowed by the full form factor.

To investigate in greater detail the implications of this result, fig. 1 includes a numerical experiment (purple points) in which the tensor component of the form factor was rescaled by a factor of 20, without altering its shape (so that the average potential is unchanged): the associated penetrability is seen to be measurably smaller than in the previous cases. This is interesting, as the opposite result is frequently expected: nuclear deformations are often associated to fusion enhancement [3, sec. 3.1], and the average penetrability for a system

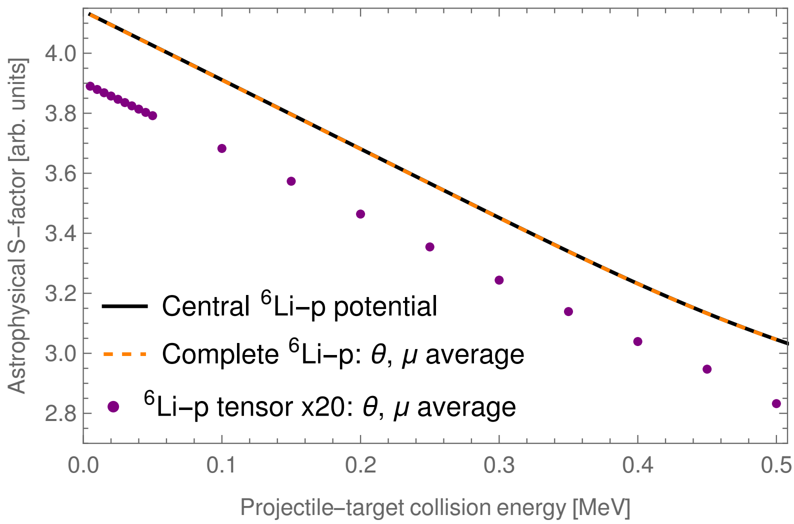

Figure 1. Astrophysical factor (see e.g. ref. [5, sec. 4] for the relevant definitions), in arbitrary units, for barrier penetration of the ^{6}Li$-$p system, computed as mentioned in section 2. The dashed orange line is the average over all configurations of the penetrability for the diagonal components of the present-work ^{6}Li$-$p form factor. The black solid line corresponds to only the central part of the same form factor. The purple points are the same as the dashed line but assuming a ^{6}Li$-$p tensor interaction 20 times bigger than computed in this work.

subject to atomic or plasma electron screening effects is always greater than the penetrability for the average screening potential [10, sec. 2.3]. We note that the outcome is sensitive to the shape of the perturbation to the potential barrier. Additionally, the present observation may in part be a consequence of the adopted approximations in the penetrability computation. As our preliminary results confirm, effects of nuclear origin can be non-trivial, and we plan to analyse them in greater detail in forthcoming works.

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