Microscopic analysis of the ^{3}He(^{3}He,2p)^{4}He and ^{3}H(^{3}H,2n)^{4}He reactions in a three-cluster model

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The three-cluster generator coordinate method is used to investigate the ^{3}He(^{3}He,2p)^{4}He and ^{3}H(^{3}H,2n)^{4}He reactions at low energies. The three-body exit channels are simulated by distortion effects in the wave functions. We test the model through the experimental ^{3}He + ^{3}He elastic cross sections, and discuss the different contributions to the S factors. We show that, in the ^{3}He(^{3}He,2p)^{4}He cross section, the $(\alpha+p)+p$ sequential breakup dominates the $\alpha+(p+p)$ process. A systematic search for resonances in ^{6}Be and ^{6}He is carried out, but we do not find any evidence for a new resonance.

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The ^{3}He(^{3}He,2p)^{4}He low-energy reaction is expected to be the dominant source of ^{4}He in low-mass stars [1]. The ^{3}He + ^{3}He branch (chain I) represents about 86% of the pp chain and therefore significantly dominates the ^{3}He + ^{4}He branch (chains II and III, $\simeq$ 14%). In addition, it is well known that the observed solar-neutrino flux sensitively depends on the ^{3}He(^{3}He,2p)^{4}He cross section. More than 20 years ago, it has been suggested [2] that a narrow resonance, located close to the ^{3}He + ^{3}He threshold, might be present in the ^{6}Be spectrum. If so, this expected resonance might enhance the ^{3}He(^{3}He,2p)^{4}He reaction rate, and provide an explanation for the long-standing solar-neutrino problem.

Several experiments have been devoted to the measurement of the low-energy cross section, and to the search for a narrow resonance near the ^{3}He + ^{3}He threshold [3–5]. However, if recent experiments succeeded in measuring the cross section down to stellar energies ($\approx$ 20 keV for the sun), all attempts to observe a resonance failed up to now. It has been suggested [5] that this resonance might be located below the experimental lower limit (24.5 keV) and, consequently, that its width would be much lower than the energy resolution of current experiments.

In parallel, theoretical works [6–8] aimed at calculating the ^{3}He(^{3}He,2p)^{4}He S factor, but none of them discusses the possible existence of a low-energy resonance. Jarmie [6] uses the R-matrix method to extrapolate the existing data down to stellar energies. In 1991, Typel *et al.* [7] performed a resonating-group-method (RGM) calculation, applied to the ^{3}He(^{3}He,2p)^{4}He and ^{3}H(^{3}H,2n)^{4}He reactions simultaneously. However, the three-body exit channel is approximated by a two-cluster configuration, involving an α particle and a two-proton (or two-neutron) one-center cluster. The treatment of the three-body channel in Ref. [7] is therefore strongly simplified, in contradiction with experimental arguments [5]. In addition, the nucleon-nucleon interaction is chosen by a fit of the experimental data in the low-energy region, and the predictive power of the microscopic model is reduced. Winkler *et al.* [8] assume that the ^{3}He(^{3}He,2p)^{4}He cross section is essentially nonresonant, and analyze its energy dependence in the DWBA theory. This method is, however, unable to bring any information concerning the resonance problem.

In this paper we use the generator coordinate method (GCM—see Ref. [9] and references therein), equivalent to the RGM, to investigate the nuclear component of the ^{3}He(^{3}He,2p)^{4}He and ^{3}H(^{3}H,2n)^{4}He low-energy S factors. Screening effects are not taken into account here. A microscopic model, such as the GCM, presents a fairly strong predictive power since, except in the nucleon-nucleon interaction, there is no free parameter. Experimental data are not necessary, but are used as a validity test of the theory. The main characteristics of our work are the following: (i) the three-body exit channel is simulated by different $\alpha+p+p$ three-cluster configurations; (ii) the nucleon-nucleon force is determined from ^{3}He + ^{3}He elastic scattering [10] at different angles, which makes the ^{3}He(^{3}He,2p)^{4}He cross section independent of parameters; (iii) the mirror reaction ^{3}H(^{3}H,2n)^{4}He is investigated simultaneously, and is used as a consistency test of the theory. The present three-cluster model also offers the opportunity to describe resonances with a two-body or a three-body structure. We therefore aim here at searching for possible resonances close to the ^{3}He + ^{3}He threshold in ^{6}Be.

Let us first present the microscopic model. We start from a six-body Hamiltonian

$$H=\sum_{i=1}^{6}T_i+\sum_{i<j=1}^{6}V_{ij}\ , \tag{1}$$

where T_i is the kinetic energy of nucleon i and V_{ij} the nucleon-nucleon interaction. It involves the exact Coulomb force, the Volkov V2 interaction [11], and a zero-range spin-orbit force [12]. We take for the spin-orbit amplitude a reasonable value [12] S_0 = 40 MeV fm^5, which reproduces fairly well the experimental $\alpha+p$ elastic phase shifts [13] with the V2 central force. We determine the Majorana parameter m of the Volkov force from ^{3}He + ^{3}He elastic-scattering data [10]. For these data, the best agreement between theory and experiment is obtained with m = 0.580 (see Fig. 1).

Three-cluster GCM basis wave functions are constructed from an α cluster, defined in the harmonic os-

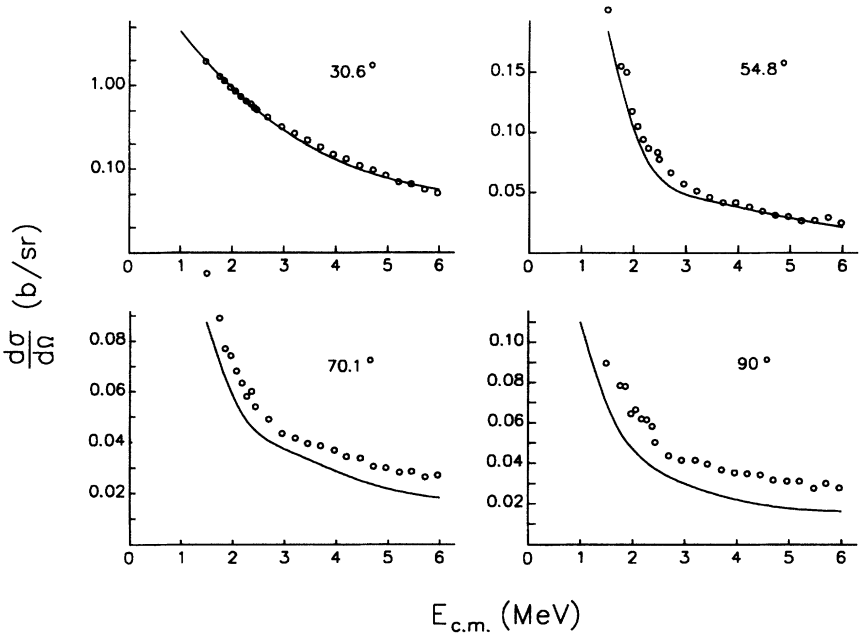

FIG. 1. ^{3}He + ^{3}He elastic cross sections for different c.m. angles. The data are from Ref. [10].

cillator model (b = 1.36 fm), and 2 protons. According to Fig. 2, two coupling modes are taken into account, in order to simulate as well as possible the three-body exit channel. In the first configuration, the two-proton wave function (with angular momentum $\ell = 0$) is described by 3 generator coordinates (R_2 = 0, 2, and 4 fm), and an approximation of the $3/2^-$ and $1/2^-$ ^{5}Li wave functions (second configuration) is obtained with R_2 = 2 fm, and angular momentum $\ell = 1$. Of course, the ^{3}He + ^{3}He two-cluster channel is coupled to these configurations. The mixing of 3 two-proton configurations introduces distortion effects. After diagonalization of the 3 × 3 problem, the two-proton wave functions yield the diproton resonance, and two excited states, often called pseudostates [14], which do not have a direct physical meaning, but simulate deformation effects during the collision. The generator coordinates R_1 are selected from 2.4 to 9.6 fm with a step of 1.2 fm.

We present in Fig. 3 the GCM ^{3}H(^{3}H,2n)^{4}He S factor, where partial waves up to J=4 are included. In our approach, the total S factor results from different two-channel contributions which, together, are expected to simulate three-body effects. In such a model, it is therefore possible to distinguish between a sequential breakup into n+^{5}He followed by the ^{5}He → ^{4}He+n decay, and a sequential breakup into (2n)+^{4}He with the subsequent decay (2n) → $n + n$. In Fig. 3 we display the contributions of the α+(n+n), (α+n)$^{3/2^-}$+n and (α+n)$^{1/2^-}$+n channels. It turns out that all of them have similar energy dependencies. This is not surprising since the energy dependence is mainly given by the ^{3}H + ^{3}H entrance channel. We find that the principal contribution arises from the (α+n)$^{1/2^-}$+n exit channel; the α+(n+n) channel represents about 1/3 of the total cross section. The $(\alpha + n)^{3/2^-} + n$ contribution is negligible in our model. The GCM total S factor is fairly consistent with the recent data [15,16], but we slightly overestimate the normalization. The comparison of the theoretical S factor with older data [17,18] is less good, but these data have been suggested to have large systematic errors [6].

Let us now discuss the ^{3}He(^{3}He,2p)^{4}He S factor, presented in Fig. 4. Except for the Coulomb force, the ingredients of the model are identical to those of the ^{3}H(^{3}H,2n)^{4}He investigation. Here also, the main contri-

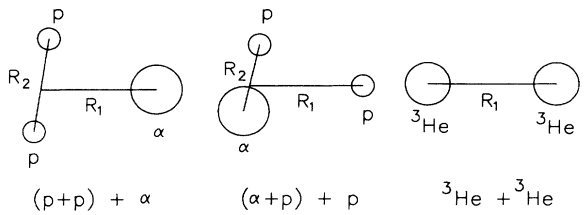

FIG. 2. Cluster configurations of ^{6}Be.

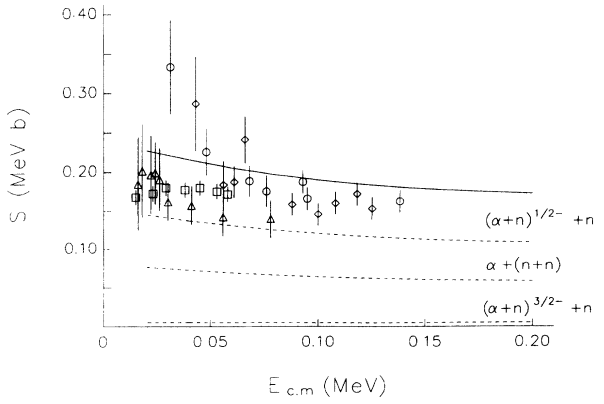

FIG. 3. ^{3}H(^{3}H,2n)^{4}He S factor (solid curve), with partial contributions (dashed curves). The data are from Ref. [15] (triangles), Ref. [16] (squares), Ref. [17] (rhombi), and Ref. [18] (circles).

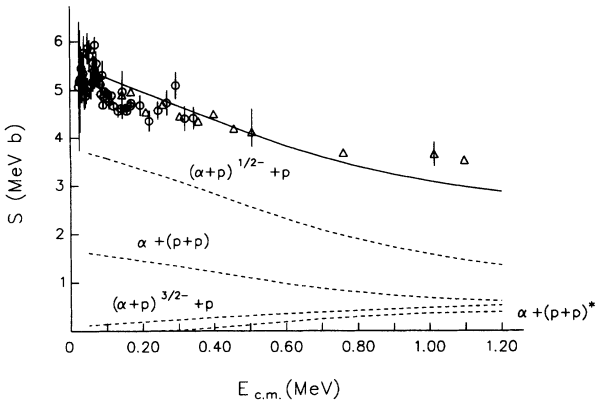

FIG. 4. ^{3}He(^{3}He,2p)^{4}He S factor (solid curves), with partial contributions (dashed curves). The data are from Ref. [19] (triangles) and Ref. [5] (circles).

bution arises from a sequential breakup into $(\alpha+p)^{1/2^-}+p$, which represents about 3/4 of the total cross section. At astrophysical energies, only the $\alpha+(p+p)$ channel is also significant. The $(\alpha+p)^{3/2^-}+p$ contribution amounts to 10% beyond 1 MeV only. In the ^{3}He(^{3}He,2p)^{4}He reaction, the first $p+p$ pseudostate, referred to as $(p+p)^*$, may contribute beyond 0.2 MeV. This contribution, as well as the $(\alpha+p)^{3/2^-}+p$ contribution yields a change in the energy dependence of the total S factor; from about 0.6 MeV, the slope of the GCM S factor is reduced, as it is observed in the data of Dwarakanath and Winkler [19].

After these tests of the microscopic model we have searched for resonances in ^{6}He and ^{6}Be. We use an extension of the microscopic R-matrix (MRM) method [20], based on an iterative procedure [21]. This method has been used in many two-cluster or three-cluster systems, and has been shown to be efficient and accurate. The best accuracy is obtained for narrow resonances, but this procedure can be reliably used for resonances whose width reaches about 1 MeV. Both for ^{6}He and ^{6}Be we have investigated partial waves from $J=0$ to $J=4$ for positive and negative parities. As expected, we found the 0^+ ground state, and the low-energy 2^+ resonance in ^{6}He and ^{6}Be. In ^{6}He, the ground-state binding energy with respect to the $\alpha+n+n$ threshold is -3.10 MeV and the 2^+ excitation energy is 2.78 MeV. These theoretical values do not differ very much from the experimental data (-0.98 MeV and 1.80 MeV, respectively). In ^{6}Be the ground state is found slightly bound (-0.68 MeV) and the 2^+ excited state is located at $E_x=3.19$ MeV. As for ^{6}He the GCM slightly overestimates the binding energy, since ^{6}Be is experimentally unbound (+1.37 MeV). These small differences with respect to experiment are not expected to significantly affect the wave functions near the ^{3}H + ^{3}H or ^{3}He + ^{3}He thresholds, which are located beyond 10 MeV in the ^{6}He or ^{6}Be spectra. However, there is no indication for a resonance (even for a broad structure) near the ^{3}H + ^{3}H threshold in ^{6}He or near the ^{3}He + ^{3}He threshold in ^{6}Be. This result has been confirmed by a careful analysis of the phase shifts. They are found quite monotonic, and characteristic from a pure nonresonant process, in good agreement with a recent experimental analysis of the Tübingen group [22].

Of course, the present work might be improved. For the sake of simplicity we have assumed that all the clusters (α, ^{3}He, ^{3}H) have the same harmonic-oscillator parameter $b=1.36$ fm. This choice minimizes the α binding energy with the V2 force, but is slightly too small for minimizing ^{3}He or ^{3}H binding energies. We neglect the tensor component and use the V2 nucleon-nucleon interaction which is probably the most "popular" force in microscopic cluster theories. It is obvious that these assumptions might affect some details of our results, such as the amplitude of the S factors. However, without any fitting procedure, the ^{3}H(^{3}H,2n)^{4}He and ^{3}He(^{3}He,2p)^{4}He GCM S factors are in fair agreement with the data. We think that the presence (or absence) of new resonances does not depend on these assumptions. Our work suggests that a low-energy resonance in the ^{3}He(^{3}He,2p)^{4}He reaction should not be a solution to the solar-neutrino problem.

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