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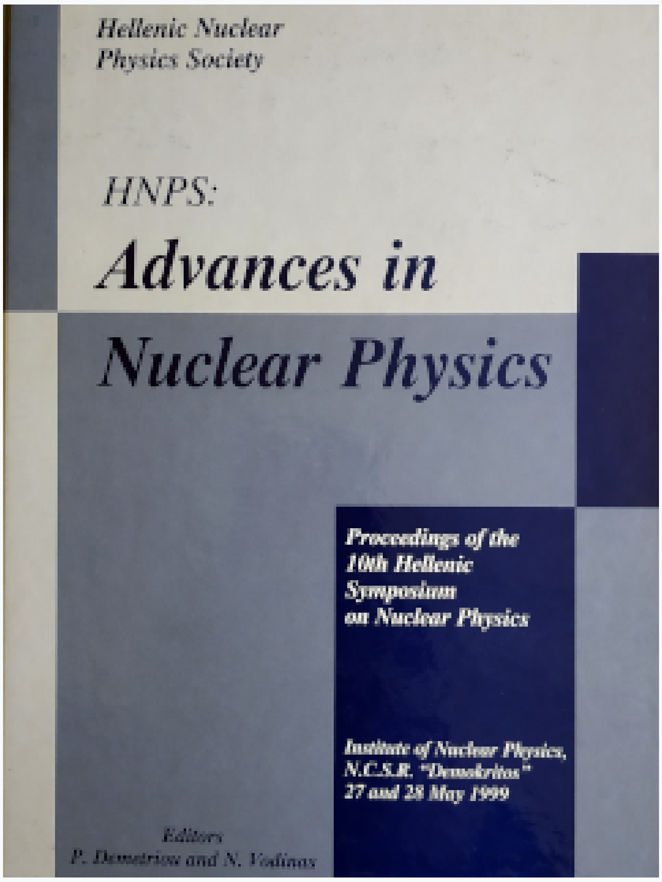

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Statistical model calculations of the $^7Li +^{11} B$ reaction

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Abstract

The $^7Li +^{11} B$ reaction has been studied in the energy range from a little below to about three times the Coulomb barrier by measuring the cross section of the γ- ray transitions in the residual nuclei produced. Statistical compound nucleus calculations have been performed in order to interpret the experimental data as well as to extract cross sections of the individual exit channels. The statistical compound nucleus theory can reproduce rather well the absolute γ- ray and the various reaction channel excitation functions.

1 Introduction

The light heavy-ion reactions have attracted in recent years a great deal of experimental and theoretical efforts. Theoretical studies have investigated reactions with light loosely bound nuclei [1,2]. In this case the probability of opening of direct channels and break up processes becomes important, leading to hindrance of the fusion cross section. On the other hand, in cases where halo nuclei are used as projectiles in light heavy ion collisions, exotic features lead to an enhancement of the fusion cross section. Another interesting feature associated with light heavy-ion reactions is the observation of the break up of dinuclear system resulting to strongly damped inelastic processes [3]. Concerning the limitation of the fusion cross section and the collision dynamics responsible for it, contradictory results have been reported in several light heavy-ion systems. In the $^{6,7}Li +^9 Be$ and $^{6,7}Li +^{12} C$ [4] fusion reactions a strong inhibition of the fusion cross section has been observed attributed to break up processes. In $^7Li +^{12,13} C$ system, however, no evidence has been reported for fusion cross section limitation near the Coulomb barrier [5]. In $^{9}Be +^{9} Be$ [6] the fusion cross section is not seen to deviate from the reaction cross section, while the $^{7}Li +^{11} B$ [6] is found to be less than the reaction cross section at energies close and above the Coulomb barrier. Thus, it is obvious that further investigations are needed in order to shed more light to the complexity of these open questions.

2 Experiment

The $^{7}Li +^{11} B$ system has been measured by detecting γ- ray cascades from the various possible residual nuclei. Beams of ^{7}Li ions provided by the Tandem accelerator of the NRC Demokritos at energies $5.5 - 19.0 MeV$ in $0.5 MeV$ steps, were used to bombard a $323 \mu g/cm^2$ thick ^{11}B target evaporated on $100 mg/cm^2$ Ta backing. Two Ge(Li) detectors placed at 125^0 and 95^0 relative to the beam direction were employed to detect characteristic γ- rays originating from the reactions. A cold trap has been placed on top of the scattering chamber to keep it at liquid nitrogen temperature to avoid carbon build up on the target. Measurements at $15.5 MeV$ were repeated every 6 hours during the experiment and showed that no significant carbon has been built up on the target. The yield of the Coulomb excitation γ- rays from the backing was used for the absolute normalization of the data.

3 Experimental results

The resulting absolute cross sections σ_γ of the γ- rays from the low-lying states of the evaporation residues are presented as a function of the c.m. energy in Fig.1. Excitation functions of observed γ- rays have been compared with statistical model calculations by using a modified version of the code STAPRE [7] and will be discussed in the next section. The calculations helped also to extract from the individual γ- rays the cross sections $\sigma(k)$ corresponding to the formation of the residual nucleus k for the various reaction channels by determining the theoretical branching factors F_k which represent the contribution of each γ- ray to the total cross section of the channel. The calculated F-factors for the exit channels are presented in Fig. 2 and the extracted channel cross sections are shown in Fig 3. This reaction has also been studied by Mukherjee et al. [6] from threshold to $6 MeV$ incident beam energy. In the overlapping energy range the experimental data of the fusion cross section of reference [6] seem to coincide with the results presented here. In addition the extracted F-factor values are in a good agreement with the values of the present work, even though the calculations have been performed with different statistical model codes using other set of the adjustable input parameters.

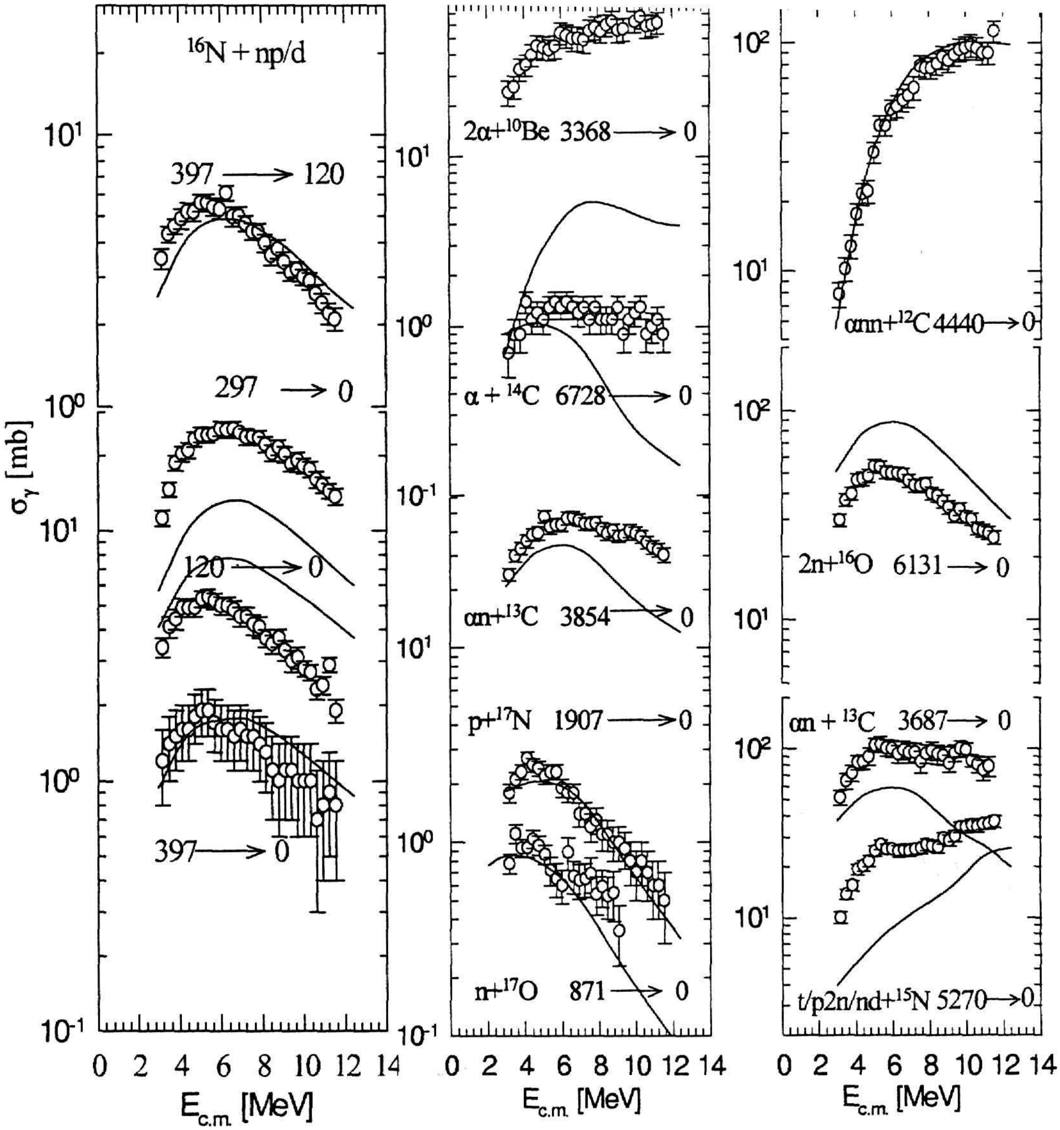

Fig. 1. Excitation function for observed transitions in the final state of the reaction $^{7}Li +^{11} B$. The solid lines are the corresponding theoretical predictions from statistical model calculations.

4 Statistical model calculations

The theoretical calculations have been performed by using a modified version of the statistical model code STAPRE [6], which is designed to estimate energy -averaged cross sections for particle induced reactions assuming sequential evaporation of several emitted particles and γ -rays. The code requires some fixed and some adjustable parameters. The fixed parameters are the level schemes [8], the nuclear masses [9],

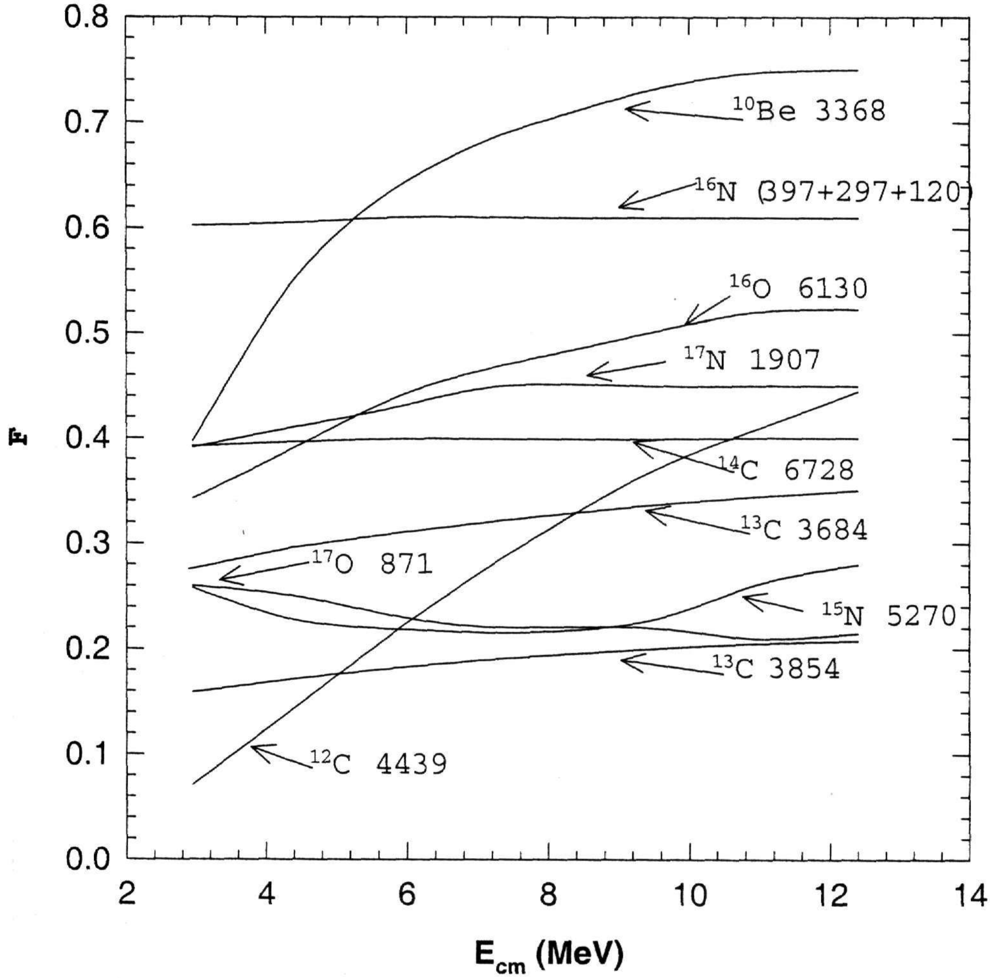

Fig. 2. Calculated F-factors for the γ- rays employed in the reduction of the data.

the physical properties of the ground state, the incident ion beam energy and the reaction chains. The adjustable parameters are optical potential parameters (in order to calculate transmission coefficients for neutrons, protons, deuterons, tritons and alpha particles) and level density parameters. Transimission coefficients were obtained from optical nuclear potentials as proposed in literature [10-13] respectively for n, p, d, t and α. The density of levels of the nuclei in the continuum was calculated using the Back-Shifted Fermi Gas model with the Lang formula [14]. The parameters used for this model are the single particle level density α, the fictive ground state position Δ and the effective moment of inertia was taken equal to that of a rigid rotor.

An extensive investigation has been undertaken with regards to the influence of these

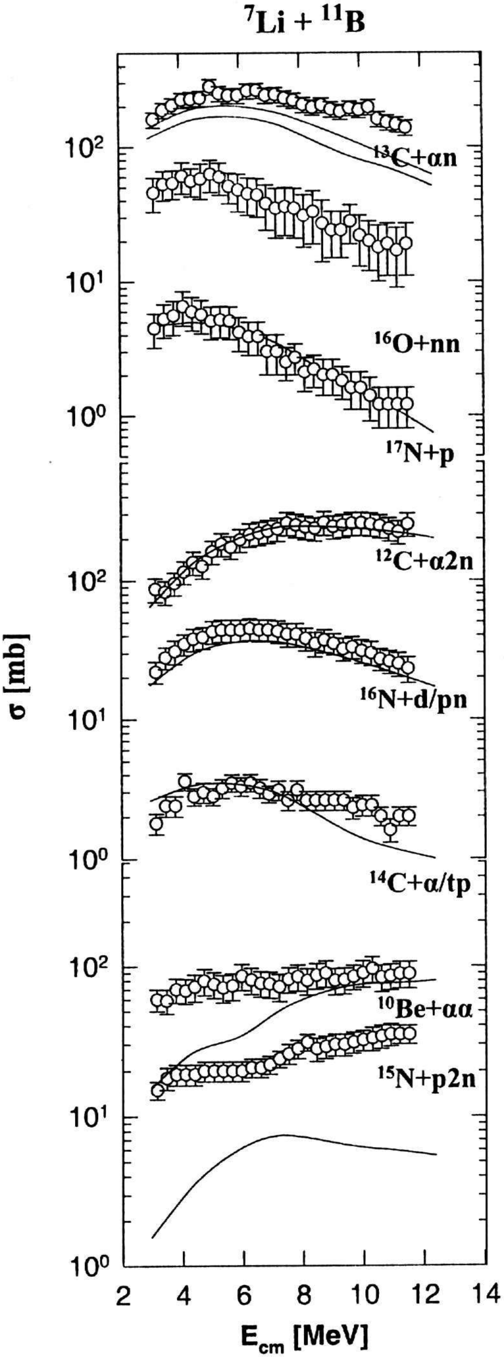

Fig. 3. Measured cross section of evaporation channels in the reaction $^7Li + ^{11}B$. The solid lines are the corresponding theoretical predictions of the statistical model calculations.

parameters to the values of the F-factors and test their reliability. The influence of the transmission coefficients for light particle emission as well as for the entrance channel was estimated to produce a variation of less than 3% in the F-factor values. In addition, several tests have been conducted by using different sets of values of α and Δ taken from the literature. The variation of the F-factors ranged between 5% and 12%. The uncertainties of the F-factors deduced from this investigation were included in the values of the corresponding cross section and the resulting errors varied between 5% and 15%. It should be noted, that the above mentioned variation of the input parameters, although producing substantial differences in the calculated γ -ray and channel cross sections, affected the corresponding F-factors to a much lesser degree. The final values of the parameters entering the code and used in the calculations presented in Figs. 1 and 3, are given in Table 1.

Table 1
Level density parameters

Nucleus	α	Δ	*Reference*
^{18}O	2.46	1.16	[5]
^{17}O	2.04	−0.80	[5]
^{16}O	1.72	3.46	[5]
^{17}N	2.26	−0.60	$A/10$
^{17}N	1.70	−0.60	$A/7.5$
^{16}N	1.93	−2.10	[5]
^{15}N	1.60	−0.17	[5]
^{14}C	1.71	2.83	[5]
^{13}C	1.73	−2.02	$A/10$
^{13}C	1.30	−2.02	$A/7.5$
^{12}C	1.60	0.65	$A/10$
^{12}C	1.20	0.65	$A/7.5$
^{10}Be	1.00	−2.20	$A/10$
^{10}Be	1.33	−2.20	$A/7.5$

As a further test of the reliability of the results the cross sections of the $^{13}C + \alpha n$ and $^{16}N + np/d$ channels have been deduced from two and four different γ- rays, respectively, de-exciting the two residual nuclei. The results from the alternate γ-rays estimates were found to agree within the experimental errors for both channels.

5 Discussion

5.1 *Comparison of the γ- ray cross section with the calculations*

The statistical model calculations together with the experimental data for each γ-ray emitted from the residual nuclei of the reaction $^7Li + ^{11}B$ are shown in Fig 1. The γ- ray cross section of ^{17}O, ^{17}N, ^{12}C residual nuclei are found to agree quite nicely with the statistical model calculations. In addition the calculations of the 277 and 397 keV transitions from ^{16}N seem to reproduce very well the experimental data. In contrary the 297 keV transition of the ^{16}N is underestimated by 25% and the 120 keV is overestimated by 25% relative to the experimental values. Noticeable enhancement of the γ- ray cross section relative to the calculations was observed for 3854 keV and 3687 keV of ^{13}C and for 6728 keV of ^{14}C especially at high energies. This enhancement could be attributed to the transfer reaction processes. The transition 3368 keV γ- ray of ^{10}Be shows also an enhancement by a factor of ~ 10 over the statistical model calculations in the energy range covered in this experiment. Similar behaviour of the 2α exit channels has been observed previously in different, but relatively light compound systems [5,15]. The upslopping behaviour of 5270 keV γ- ray cross section of the ^{15}N could be attributed to the multiparticle emission (p2n,dn) of the compound system which become important at higher energies than the t production. This is also corroborated by the statistical statistical model calculations which reveal the same qualitative behavior with the experimental data, but quantitatively the experimental values are underestimated by a factor ~ 2. This discrepancy could also result from non compound contributions, like α-transfer.

5.2 *Comparison of the channel cross section with the calculations*

The statistical model calculations are shown in Fig. 3 together with the experimental values for various exit channels of the $^7Li + ^{11}B$ reaction. In general the theoretical calculations seem to reproduce quite well most of the channel excitation functions. For the p, αn, α2n, d/np and α/tp channels the calculated cross section data are consistent with the experimental values. However the p2n and nn channel calculated cross sections show an enhancement by a factor of ~ 2, while for the 2α channel the calculations underestimate the data by about one order of magnitude. It should be mentioned that the same behavior has also been observed in neighboring systems such as $^{13}C + ^{16}O$, $^7Li + ^{12}C$ and $^7Li + ^{13}C$ [15,5]. In these systems the statistical model calculations are also seen to overestimate the experimental values for neutron evaporation at the expense of flux for α emission. In order to investigate this systematic bahavior, several tests have been performed by using different input values in the code. However no progress has been achieved in this direction.

6 Summary and conclusions

The cross section for populating evaporation channels in the $^7Li+^{11}B$ system have been measured through the observation of singles γ -rays over the energy range from below to three times the Coulomb barrier. The excitation functions of both γ-rays deexciting the residual nuclei and the reaction channel cross sections behave smoothly with energy. The overall trend of the experimental excitation functions was satisfactorily accounted for by statistical model calculations. The theoretical values, however, seem to overestimate the experimental cross section for neutron evaporation channels at the expense of flux for alpha particle emission.

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