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Distorted-wave Born approximation study of the ^{11}Li(p,t)^{9}Li reaction

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Abstract. The reaction ^{11}Li(p,t)^{9}Li(gs) at an incident energy of 4 MeV is treated in terms of a simplistic distorted-wave Born approximation transfer. The halo neutrons involved in the reaction are treated as a di-neutron cluster transferred in a simultaneous process. This appears to be a good approximation of the mechanism. The dominant contribution to the reaction comes from the known $(1s_{1/2})^2$ structure component of the ground state of ^{11}Li, and the cross section angular distribution seems to be relatively insensitive to the fact that ^{11}Li has an anomalously large radius due to its Borromean halo properties. Significantly this simple treatment of the reaction is in much better agreement with the experimental angular distribution than a more sophisticated calculation.

1. Introduction

Proton-induced two-nucleon transfer represents a convenient method to study an exotic nucleus such as ^{11}Li [1, 2]. The Borromean character of the target system when viewed as a two-neutron halo bound to a ^{9}Li core promises to be of special interest. The short lifetime of about 8 ms of ^{11}Li causes a slight experimental complication to the measurement of cross section angular distributions for a two-neutron pickup reaction, which is then properly written as ^{1}H(^{11}Li, ^{9}Li)^{3}H to reflect the inverse kinematics required for a radioactive beam. In order to emphasize the transfer of the halo component of the nucleus of interest, we write this reaction consistently as ^{11}Li(p,t)^{9}Li. However, this latter alternative convention is a personal preference and it is of no consequence or further significance.

In order to extract information regarding the prominence of two-nucleon correlations in ^{11}Li from experimental measurements of the (p,t) reaction, the distorted-wave Born approximation (DWBA) promises to be a useful tool. Although DWBA theory has been thoroughly studied over many years, several issues remain somewhat obscure. Of these, the prominence of a sequential [3, 4] pickup process is the most controversial. The motivation for the importance of a sequential, two-step mechanism in nucleon-induced two-nucleon transfer is inspired by concerns that the absolute magnitude of the cross sections predicted by the DWBA seems to be much too low when compared with some experimental values. Also, in the ^{208}Pb(p,t)^{206}Pb(3^+) reaction to the ground state, which involves an unnatural parity transition, a zero-range first order DWBA is forbidden. Nevertheless, Nagarajan *et al.* [5] show that a careful finite range, simultaneous transfer DWBA estimation for this reaction provides the correct absolute magnitude. On the

other hand, Igarashi *et al.* [6] argue that addition of a two-step sequential transfer mechanism to the direct pickup in DWBA is essential to describe the cross section magnitude of the ^{208}Pb(p,t)^{206}Pb(3^+) reaction. The controversy of sequential versus a simultaneous mechanism has not been satisfactorily clarified up to date, and this may partly be because the absolute cross section magnitude of a reaction such as (p,t) suffers from severe momentum mismatch between the incident and exit channels. This causes the cross section to be proportional to the square of the momentum wave function of the bound di-nucleon system which participates in the pickup process. At the large momenta involved in the transfer, the magnitude of the wave functions of the neutrons constituting the picked-up pair are not known well, hence a large uncertainty in cross section magnitude follows.

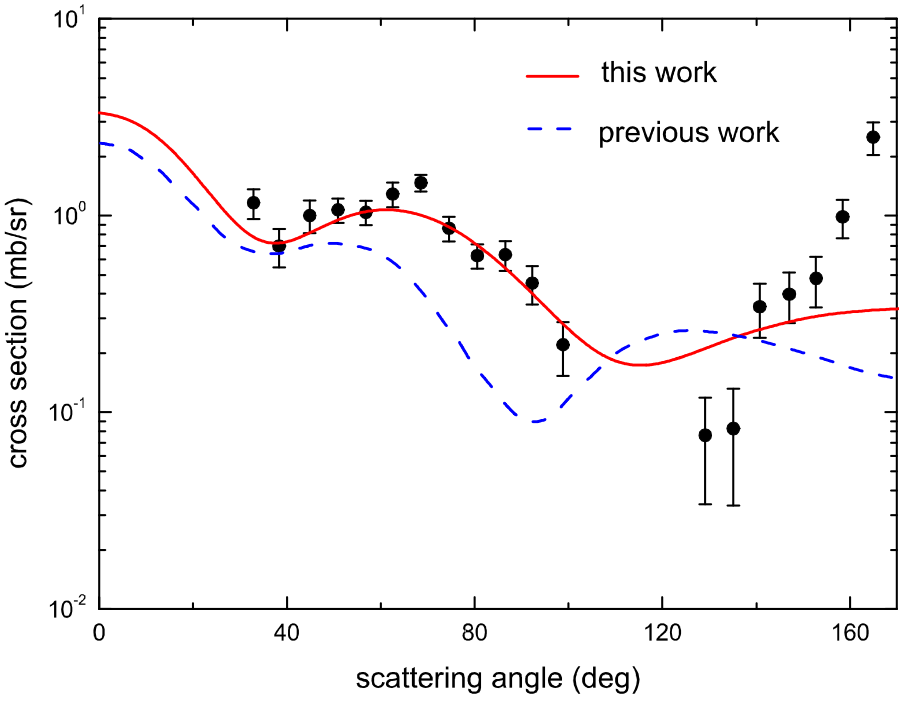

Figure 1. Angular distribution for the reaction ^{11}Li(p,t)^{9}Li(gs) at an incident energy of 4.4A MeV. The solid curve represents a DWBA calculation as described in the text and the dashed curve (*reproduced with permission*) is a preliminary results of Thompson [7]. Experimental data were measured at TRIUMF and are available in Ref. [7].

2. Sophisticated and alternative simplistic DWBA approaches

Because earlier sophisticated DWBA approaches, in which all the known properties of ^{11}Li were incorporated, were not particularly successful [1, 7] , the present work approaches the problem differently. Instead of *ab initio* attempting to reproduce the absolute magnitude of the ^{11}Li(p,t)^{9}Li cross section, we at first explore a simplistic zero-range, simultaneous di-neutron cluster transfer process. The di-neutron cluster is assumed to be bound in a standard best-value geometry as suggested by Meijer *et al.* [8, 9, 10] for stable target nuclei. Thus the di-neutron bound state is calculated with a geometry of radius parameter r_0=1.15 and diffuseness

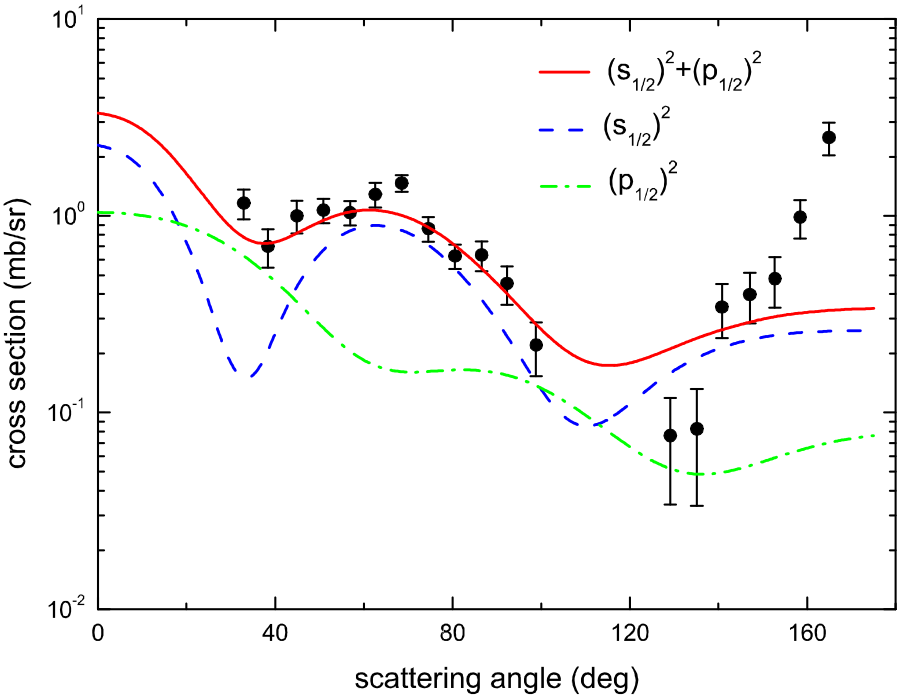

Figure 2. Contributions from angular momentum transfers of L=0 and L=2 to the ^{11}Li(p,t)^{9}Li(gs) cross section at an incident energy of 4.4A MeV. These components originate from $(s_{1/2})^2$ and $(p_{1/2})^2$ configurations. Normalizations have been chosen independently and arbitrarily in order that the incoherent sum of the two contributions should best reproduce the experimental data. (From figure in Ref. [11]).

Table 1. Optical potential parameters used in the DWBA calculations.

Channel	Ref.	V	r_v	a_v	W	W_D	r_W	a_W	V_{SO}	r_{SO}	a_{SO}
p+^{11}Li	[1]	54.06	1.17	0.75	2.37	16.87	1.32	0.82	6.2	1.01	0.75
t+^{9}Li	[1]	1.42	1.16	0.78	28.2	0	1.88	0.61	0		
bound state	[8]	adjusted	1.15	0.78							

Definition of optical potentials in Table 1 (with strengths in MeV and geometrical sizes in fm):

$$V(r) = -Vf(r,r_v,a_v) - Wf(r,r_v,a_v) + W_D 4a_W \frac{d}{dr} f(r,r_W,a_W) + W_{SO}\sigma.\ell\lambda\!\!\!^{-2} \frac{1}{r}\frac{d}{dr} f(r,r_{SO},a_{SO})$$

$$\text{with } f(r,r_i,a_i) = [1+\exp(\tfrac{r-r_i A^{\frac{1}{3}}}{a_i})]^{-1}$$

a=0.76 in a Woods-Saxon well, adjusted to reproduce the cluster binding energy with quantum numbers based on oscillator-well energy conservation. Consequently this means that in such an approach the extended spatial extent of ^{11}Li is not taken into account. Distorted waves, derived from optical potentials for the incident and exit channels, are identical to those of the earlier sophisticated calculations [1, 7], and parameter values are provided in Table 1. As was already mentioned, possible sequential pickup of the two neutrons is excluded and core excitations are also neglected. Of course, in our approach, all information regarding absolute magnitude of the cross section scale is lost, but the shape reproduction of the angular distribution now becomes

crucial as a criterion for successful reproduction of the experimental data.

As shown in Fig. 1 for the ^{11}Li(p,t)^{9}Li reaction at an incident energy of 4.4MeV, the simplistic DWBA calculation from the present work gives a result which is in vastly superior agreement in angular-distribution shape to the earlier preliminary work of Thompson [7]. This is also true when compared with published results [1] at a lower incident energy of 3 MeV. Although we have arbitrarily normalized the DWBA prediction to the experimental distribution, as the loss of information on cross-section magnitude inherent to the simplistic calculation requires, it should be noted that the sophisticated calculation cannot be further improved by a similar adjustment. The surprising superiority of a standard, simplistic DWBA calculation over a more sophisticated treatment needs to be understood, and this is investigated further in the following sections.

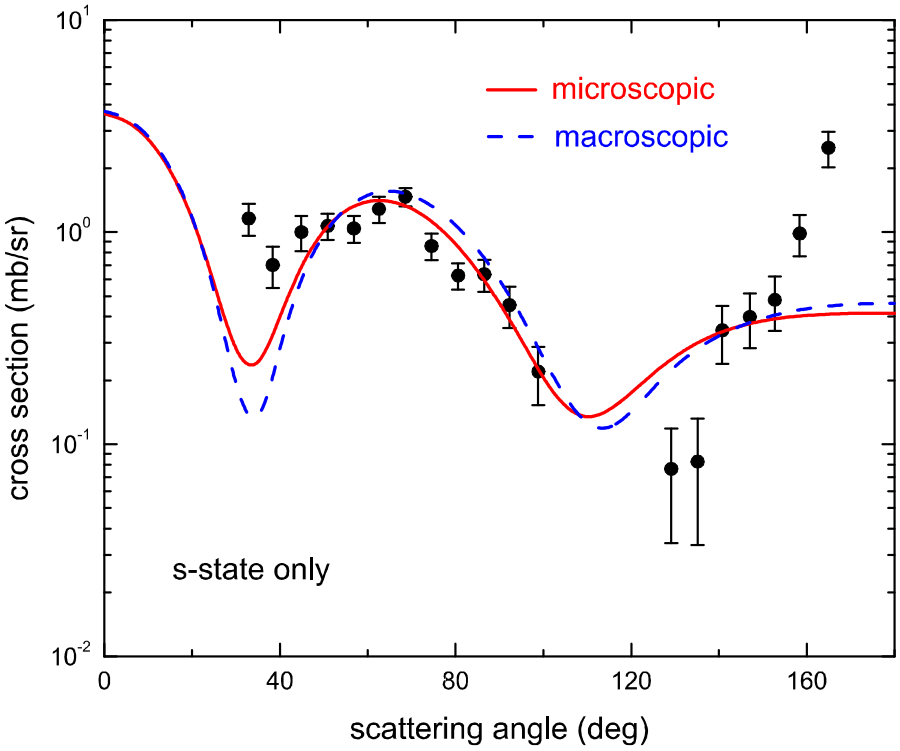

Figure 3. Comparison between macroscopic and microscopic calculations for ^{11}Li(p,t)^{9}Li(gs) at an incident energy of 4.4A MeV. In the microscopic case a pure $(s_{1/2})^2$ configuration is assumed, whereas for the macroscopic calculation a di-neutron cluster and an angular momentum transfer of L=0 are introduced. The normalizations to the experimental data are arbitrary. (From figure in Ref. [11]).

3. Influence of ground state structure of ^{11}Li and di-neutron approach

As is known, the wave function φ of the two halo neutrons in the ground state of ^{11}Li may be expressed [12, 13] as

$$\varphi = 0.45 \left| s^2_{1/2}(0) \right\rangle + 0.55 \left| p^2_{1/2}(0) \right\rangle + 0.04 \left| d^2_{5/2}(0) \right\rangle , \quad (1)$$

where the base wave functions are indicated in a standard notation.

The component where both neutrons are in the $2s$-state dominate, and the contributions of the cross sections of the s- and p-states to the summed value (with a neligible contribution from the d-state occupation) is shown in Fig. 2. Angular momentum transfers are $L = 0$ and $L = 2$ for s- and p-states, respectively. Relative magnitudes are adjusted to reproduce the overall shape of the angular distribution best, and added incoherently. If only the dominant s-state is considered, the comparison of the DWBA prediction and the experimental angular distributions is still reasonable, as shown in Fig. 3. Furthermore, as shown in Fig. 3, a macroscopic treatment of the two halo neutrons as a di-neutron, instead of a realistic microscopic formulation, is of no consequence.

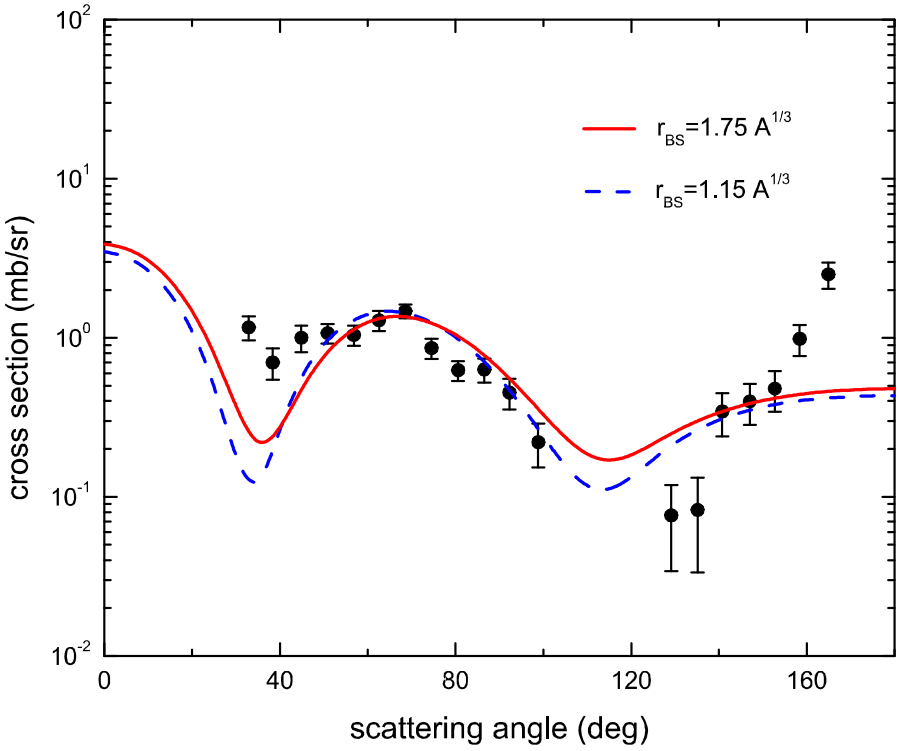

Figure 4. Macroscopic calculations for ^{11}Li(p,t)^{9}Li(gs) at an incident energy of 4.4A MeV with different values of the bound state radius of the di-neutron cluster. The solid line corresponds to a radius which corresponds to the rms size of ^{11}Li, and the dashed line to a number appropriate for stable nuclei in general.

4. Influence of bound state geometry

Variation of the geometry of the bound state serves as a crude approximation to the influence of the extended range of the halo mass distribution of the ^{11}Li nucleus. This is shown in Fig. 4 where the radius of the bound state is increased from $R = 1.15A^{1/3}$ to $R = 1.75A^{1/3}$, where A is the mass number of the core system ^{9}Li. The latter radius value corresponds to the actual rms radius of ^{11}Li. Clearly no significant difference is observable, and similar insensitivity is shown to the diffuseness parameter.

5. Sensitivity to distorting potentials

As is evident from the discussion thus far, the crucial issue which still needs to be investigated is the sensitivity of the DWBA results to the distorting potentials which are employed in the incident and exit channels. As the global potentials used in the present work were extracted based on target nuclei at or near the line of stability, those parameters are unlikely to be optimized for a nuclear species such as ^{11}Li. In fact, it is known that the present optical parameters do not reproduce elastic scattering of protons from ^{11}Li well in the incident energy range of interest [14].

In Fig. 5 a comparison is shown of a preliminary attempt to use a modified parameter set for the incident channel. The dashed curve corresponds to the standard global proton potentials of Table 1, whereas the solid curve is based on a set [14] which describes elastic scattering of protons from ^{11}Li well, except that the real radius parameter had to be arbitrarily adjusted (from r_0=1.09 to r_0=1.69) for better overall agreement with the experimental data. Hence the only useful purpose that this exercise serves is to suggest that further improvement to our understanding of the ^{11}Li$(p,t)^{9}$Li reaction should follow from a further investigation of the influence of the distorting potentials.

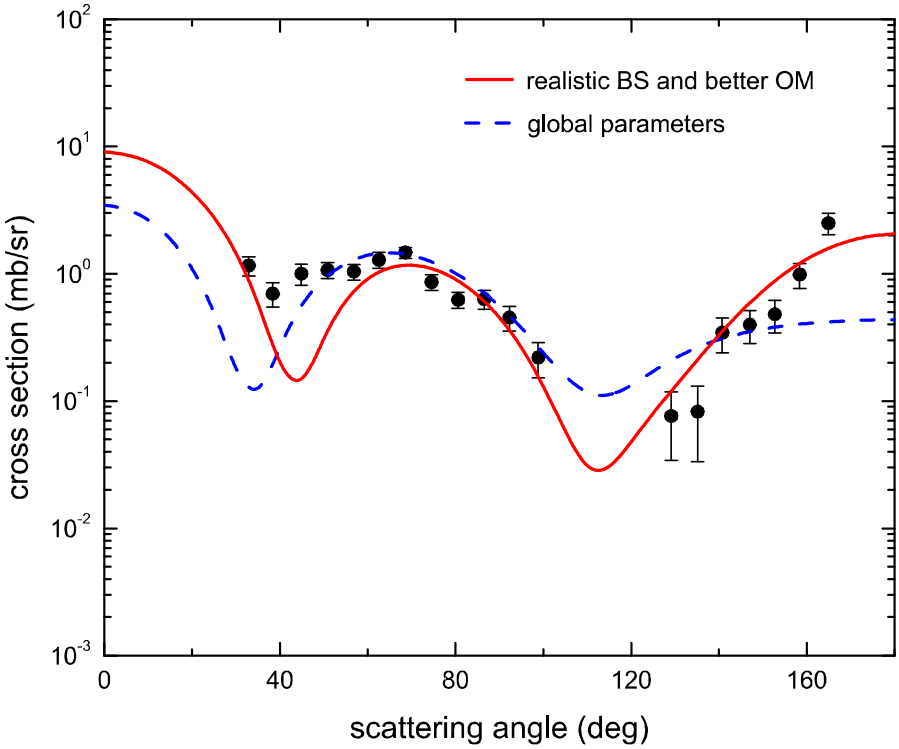

Figure 5. Comparison between macroscopic calculations for ^{11}Li$(p,t)^{9}$Li(gs) at an incident energy of 4.4A MeV with different optical potentials for the distorted waves an bound state geometry. The solid line is applicable to more realistic optical potentials and bound state geometry, as discussed in the text.

6. Summary and Conclusions

The DWBA prediction of a simplistic calculation for the reaction ^{11}Li(p,t)^{9}Li(gs) at an incident energy of 4.4A MeV was investigated. Such a DWBA was shown to give a reasonably good reproduction of the cross section angular distribution. Results from the present study were found to be superior to those from more sophisticated analyses at the same or lower incident energy. The present results are independent of whether di-neutron cluster transfer is assumed, or a more realistic microscopic two-particle mechanism is considered. The response to the transfer reaction is similar to that of nuclear species of normal rms size, and the extended halo structure of ^{11}Li does not seem to be influence the shape of the (p,t) angular distribution. Alternative optical potentials which specifically attempts to reproduce the elastic scattering of protons from ^{11}Li, as opposed to global optical parameters, appear to hold the promise of even better agreement with existing experimental data.

The simplicity of the theoretical treatment, combined with its ability to reproduce the main characteristics of experimentally observed angular distributions, is encouraging. Clearly this needs to be investigated further.

Acknowledgement

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