

Disentangling the transfer and breakup contributions from the inclusive ${}^8\text{Li}+{}^{208}\text{Pb}$ reaction

A. M. Moro and R. Crespo

Departamento de Física, Instituto Superior Técnico, 1049-001 Lisboa, Portugal

H. García-Martínez, E. F. Aguilera and E. Martínez-Quiroz

Departamento del Acelerador, ININ, A.P. 18-1027, C. P. 11801, México, D. F.

J. Gómez-Camacho

Departamento de FAMN, Universidad de Sevilla, Apdo. 1065, 41080 Sevilla, Spain

F. M. Nunes

Universidade Fernando Pessoa, Praça 9 de Abril, 4200, Porto, Portugal

Abstract

An analysis of the ${}^8\text{Li}+{}^{208}\text{Pb}$ reaction at energies around the Coulomb barrier is presented. The study is focused on the elastic and one-neutron removal channels. For the elastic scattering, an optical model analysis of the experimental data is performed. The observed ${}^7\text{Li}$ is interpreted as the superposition of the one-neutron transfer reaction, ${}^{208}\text{Pb}({}^8\text{Li}, {}^7\text{Li}){}^{209}\text{Pb}$, and the breakup reaction. The separate contribution of each one of these processes has been calculated within the DWBA formalism. The sum of both contributions explains adequately the experimental angular distribution of ${}^7\text{Li}$.

Keywords: reactions with weakly bound nuclei, optical model and DWBA analysis, elastic scattering, transfer and breakup reactions.

Presentamos un análisis de la reacción ${}^8\text{Li}+{}^{208}\text{Pb}$ a energías en torno a la barrera coulombiana. El estudio se centra en los canales de sección eficaz elástica y de separación de un neutrón. Para la dispersión elástica, se ha efectuado un análisis de modelo óptico de los datos experimentales. El ${}^7\text{Li}$ observado ha sido interpretado como una superposición de la reacción de transferencia de un neutrón, ${}^{208}\text{Pb}({}^8\text{Li}, {}^7\text{Li}){}^{209}\text{Pb}$, y la reacción de fragmentación. La distribución de cada uno de estos procesos se ha calculado dentro del formalismo DWBA. La suma de ambas contribuciones explica adecuadamente la distribución angular del ${}^7\text{Li}$ medido.

Descriptores: reacciones con núcleos poco ligados, análisis de modelo óptico y DWBA, dispersión elástica, reacciones de transferencia y ruptura.

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I. INTRODUCTION

During nearly two decades a considerable amount of experimental data of nuclear reac-

tions with radioactive beams has been accumu-

lated. These data have constituted our main source of knowledge of exotic nuclei. Due to the experimental techniques used in the production of these beams, most of these experiments correspond to medium and high energies (tens or hundreds of MeV per nucleon). At low energies, however, the scarce amount of data and the theoretical difficulties turn the situation more uncertain. Many important questions concerning the relevance of the different reaction mechanisms or the effect of the weakly bound nature of exotic nuclei on the scattering observables remain unanswered. For instance, a problem that has been subject of exhaustive theoretical and experimental work [? ? ? ? ?] but does not seem to be fully clarified is the possible role of the halo nucleon/s on the enhancement or suppression of the fusion cross section in subbarrier reactions. Another question that requires further analyses is the apparent absence of the threshold anomaly in weakly bound systems [?]. Another striking result is the large transfer/breakup cross section observed in the ${}^6\text{He}+{}^{209}\text{Bi}$ reaction at energies below the barrier [? ?].

In a recent experiment performed in the RNB facility at Notre-Dame, the scattering of ${}^8\text{Li}$ on ${}^{208}\text{Pb}$ at bombarding energies around the Coulomb barrier was measured [?]. This experiment holds interesting repercussions within the context of the previous discussion, since it involves the weakly bound nucleus ${}^8\text{Li}$. As a distinctive feature, this reaction displays a prominent ${}^7\text{Li}$ group. The large cross section associ-

ated with this group is interpreted as an enhancement of the one-neutron removal channel due to the weak binding of the valence neutron in ${}^8\text{Li}$. This result resembles the strong ${}^4\text{He}$ group observed in the ${}^6\text{He}+{}^{209}\text{Bi}$ reaction [?]. However, while in the ${}^6\text{He}$ case a realistic description of the transfer and breakup mechanisms would require a three-cluster model, in the case of the ${}^8\text{Li}$ projectile a two-cluster model (${}^7\text{Li}$ core plus a valence neutron) may be adequate for this problem. Thus, it is expected that the analysis of the ${}^8\text{Li}+{}^{208}\text{Pb}$ reaction is significantly easier and can permit the extraction of useful physical information about the relevant reaction mechanisms.

In this work, we present an analysis of the referred experiment, with special emphasis on the elastic and single-neutron removal channels. We first study the elastic angular distributions, in terms of optical potentials. From this analysis we can conclude on the relevance of non-elastic channels. The obtained optical potentials will also be used in the analysis of the transfer and breakup channels. For these, DWBA calculations will be performed.

II. ANALYSIS OF ELASTIC SCATTERING DATA

The study of the elastic scattering by means of optical potentials (OP) provides information on the nature of the interaction between the colliding nuclei and on the importance of non-elastic channels.

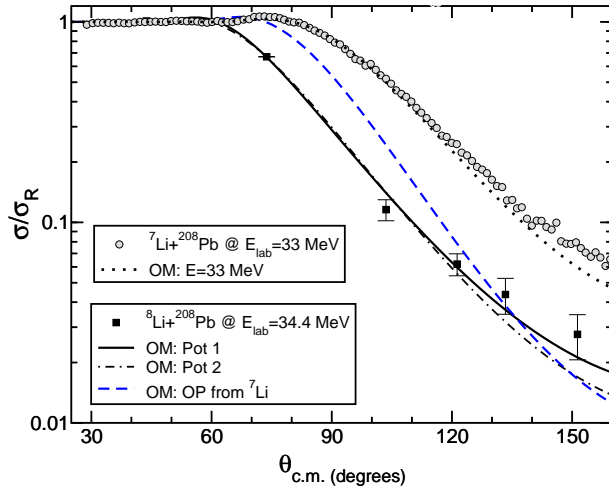


Figure 1: Comparative study for the elastic scattering of ^8Li and ^7Li on ^{208}Pb . See text and labels for details.

In previous works [? ?], the similitude between the scattering of ^8Li and ^7Li has been made apparent. In these works, it is shown that the same potentials that fit the ^7Li scattering on ^{12}C and ^{58}Ni give also a good agreement for the ^8Li scattering on the same targets and at similar energies.

We examine this result in the present reaction. For this purpose, we compare in Fig. 1 the experimental data for $^8\text{Li}+^{208}\text{Pb}$ at 34.4 MeV with the data for $^7\text{Li}+^{208}\text{Pb}$ at $E_{\text{lab}}=33$ MeV, reported in [?]. The latter can be accurately described using the OP listed in Table I and represented by the dotted line in Fig. 1. Using these parameters we performed an OM calculation for $^8\text{Li}+^{208}\text{Pb}$ at $E_{\text{lab}}=34.4$ MeV. This calculation, shown by the dashed line in Fig. 1, clearly fails to reproduce the data, particularly at angles around the rainbow. The quality of the fit can be im-

proved by using a more absorptive potential. In Fig. 1 we show the result obtained with two different optical potentials: the first one, labeled as “Pot 1” in Table 1 and plotted with the solid line, was obtained by fitting the depths and the imaginary diffuseness to the data. This procedure leads to a very deep imaginary potential. Due to the strong absorption, the calculations are not very sensitive to the real potential. We found that keeping the same real part of the interaction as that for $^7\text{Li}+^{208}\text{Pb}$, a good fit to the experimental data could also be achieved using a diffuse imaginary potential (“Pot 2” in Table 1). The corresponding elastic angular distribution is given by the dotted-dashed line in Fig. 1. These calculations suggest a more absorptive nature in the case of ^8Li , in apparent contradiction with previous results [? ?]. This discrepancy might be explained by noting that at energies around the barrier the OP depends significantly on the energy and also that the ^8Li and ^7Li barriers differ by about 4 MeV [?].

It is worthwhile to note that the reported elastic data contains a contribution from the 1^+ excited state of the ^8Li nucleus ($\epsilon_x=0.98$ MeV), which could not be separated in the experiment. This inelastic contribution can be extracted in a model dependent way by performing a coupled channels (CC) calculation in which the ground and excited states are included explicitly, and coupled to all orders. For the coupling matrix elements we took the reported values for the electric transition probability, $B(E2; 2^+ \rightarrow 1^+)$, and

Table I: Optical potential parameters used in the analysis of ${}^7\text{Li}+{}^{208}\text{Pb}$ elastic scattering at $E_{lab}=33$ MeV and ${}^8\text{Li}+{}^{208}\text{Pb}$ at $E_{lab}=34.4$ MeV. In all cases, $r_0 = r_w=1.3$ fm, $a_0=0.65$ fm and $r_C = 1.25$ fm. The last column gives the chi square per data point.

	V_0	W	a_w	σ_R	χ^2
	(MeV)	(MeV)	(fm)	(mb)	
${}^7\text{Li}+{}^{208}\text{Pb}$	15.4	13.2	0.65	-	-
${}^8\text{Li}+{}^{208}\text{Pb}$ (Pot 1)	37.1	154	0.57	1231	1.11
${}^8\text{Li}+{}^{208}\text{Pb}$ (Pot 2)	15.4	58.4	0.70	1275	1.51

the deformation parameter, β [?]. Further details of this calculation are given in [?]. The main conclusion is that there is an important contribution from inelastic events at large angles.

We extended the optical model analysis to lower energies. The extracted optical potential parameters, given in [?], indicate that very absorptive potentials are also required at energies down to $E_{cm}=24.4$ MeV.

III. THE TRANSFER/BREAKUP REACTION

As observed in previous reactions involving ${}^8\text{Li}$ as a projectile, the present experiment shows a large cross section for the ${}^7\text{Li}$ yield, coming from the one-neutron removal channel. This phenomenon is a consequence of (i) the weak binding of the valence neutron ($\epsilon_0=2.03$ MeV), which results in a positive Q value, and (ii) the 2^+ spin of the ${}^8\text{Li}$ ground state, which allows multiple angular momentum transfers. According to Q value

arguments, both the one-neutron and breakup channels are energetically favoured so, in principle, both processes can contribute substantially to the measured ${}^7\text{Li}$ yield.

One of the objectives of this work is to evaluate the relative contributions of both mechanisms, and to verify that their sum explains the total measured yield.

A. Single-neutron transfer

Within the post form of the Distorted Wave Born Approximation (DWBA), the one-neutron transfer amplitude for our reaction reads

$$T = \langle \chi_{[{}^7\text{Li}, {}^{209}\text{Pb}]} \phi_{[n, {}^{208}\text{Pb}]} | V_{trans} | \chi_{[{}^8\text{Li}, {}^{208}\text{Pb}]} \phi_{[n, {}^7\text{Li}]} \rangle \quad (1)$$

with the transfer operator $V_{trans} = V_{[n, {}^7\text{Li}]} + U_{[{}^7\text{Li}, {}^{208}\text{Pb}]} - U_{[{}^7\text{Li}, {}^{209}\text{Pb}]}$. For the interaction $V_{[n, {}^7\text{Li}]}$, that binds the neutron to the ${}^7\text{Li}$ core, we took the ${}^8\text{B}$ binding potential used in [?], with the depth modified to reproduce the binding energy. In Eq. (1), $\chi_{[{}^8\text{Li}, {}^{208}\text{Pb}]}$ and $\chi_{[{}^7\text{Li}, {}^{209}\text{Pb}]}$ are the distorted waves describing the elastic scattering in the entrance and exit channels, respectively. The former was generated with the potential ‘‘Pot 1’’ of Table I, and the latter with the ${}^7\text{Li}+{}^{209}\text{Pb}$ optical potential, also given in this table. The functions $\phi_{[n, {}^{208}\text{Pb}]}$ and $\phi_{[n, {}^7\text{Li}]}$ represent the overlap integrals (${}^{209}\text{Pb}|{}^{208}\text{Pb}$) and (${}^8\text{Li}|{}^7\text{Li}$) between internal states. The transfer was calculated to all bound states in ${}^{209}\text{Pb}$ (see Fig. 2). These states were described using pure single-particle configurations, with the quantum num-

bers and spectroscopic factors taken from the literature. In the case of ${}^8\text{Li}$, we assume a core plus valence neutron structure with the components

$$\begin{aligned}
\text{(a)} \quad & \left[|{}^7\text{Li}(3/2^-) \rangle \otimes |p_{3/2} \rangle \right]_{2^+}, \\
\text{(b)} \quad & \left[|{}^7\text{Li}(3/2^-) \rangle \otimes |p_{1/2} \rangle \right]_{2^+}, \\
\text{(c)} \quad & \left[|{}^7\text{Li}(1/2^-) \rangle \otimes |p_{3/2} \rangle \right]_{2^+}. \quad (2)
\end{aligned}$$

Therefore, the relevant spectroscopic amplitudes for the ground state of ${}^8\text{Li}$ are $A_{3/2} = CFP(2^+|3/2^-, 1p_{3/2})$, $A_{1/2} = CFP(2^+|3/2^-, 1p_{1/2})$, and $B_{3/2} = CFP(2^+|1/2^-, 1p_{3/2})$, where we have used the definition

$$CFP(J|J_7, nlj) = \frac{\langle {}^8\text{Li}(J) || a_{nlj}^+ || {}^7\text{Li}(J_7) \rangle}{\sqrt{2J+1}}, \quad (3)$$

with the $3j$ phase convention of [?].

We adopted the values: $A_{3/2} = \sqrt{8/9}$, $A_{1/2} = \sqrt{2/9}$ and $B_{3/2} = -\sqrt{2/9}$, which are derived in Ref. [?] making use of Wigner supermultiplet scheme. Note that the component (c) in (2) corresponds to a ${}^8\text{Li}$ configuration with the ${}^7\text{Li}$ core in the excited state $1/2^-$ at $\epsilon_x=0.48$ MeV. Since the energy resolution of the present experiment did not permit the separation of both states, this component has to be included in the calculation of the ${}^7\text{Li}$ cross section. The calculated cross sections are shown in Fig. 3. The thick dashed line represents the so called elastic transfer, where the ${}^7\text{Li}$ is emitted in the ground state. The thin dashed line is the inelastic transfer, coming from the component (c) in Eq. (2). We see that the elastic transfer accounts for most of the observed

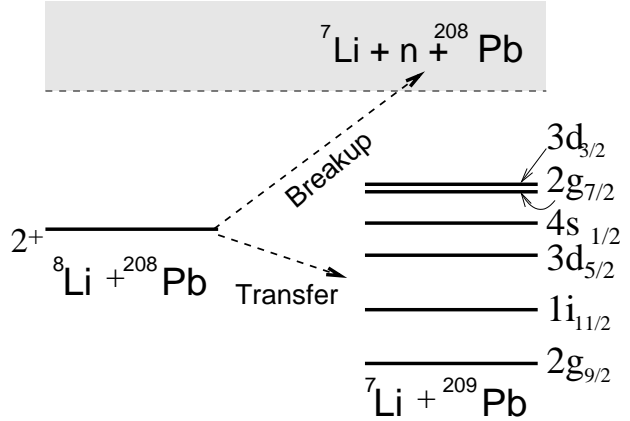


Figure 2: Coupling scheme used in the DWBA calculations for one-neutron transfer and breakup.

${}^7\text{Li}$, while the inelastic transfer gives a small (but non negligible) contribution.

B. The breakup reaction

The breakup process can be visualized as a transfer of the valence neutron to the target continuum (see Fig. 2): ${}^{208}\text{Pb}({}^8\text{Li}, {}^7\text{Li})n{}^{208}\text{Pb}$. Within this approach, the breakup cross section can be calculated using the expression (1), just by replacing the ${}^{209}\text{Pb}$ bound state wave functions by n - ${}^{208}\text{Pb}$ scattering functions. Since the continuum spectrum contains an infinite set of states in both energy and relative angular momentum, a procedure of discretization was performed. For this purpose, for each partial wave the continuum was divided into $N = 3$ energy bins of equal width and up to $\epsilon = 6$ MeV for the maximum relative energy between n and ${}^{208}\text{Pb}$. Only the partial waves $0 \leq \ell \leq 6$ were retained in the calculation. Test calculations showed that the contribution from higher partial waves gives

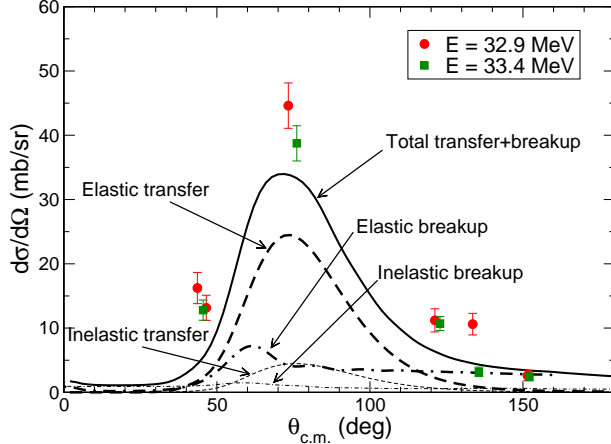


Figure 3: Angular distribution for the ${}^7\text{Li}$ yield produced in the ${}^8\text{Li} + {}^{208}\text{Pb}$ reaction at $E_{\text{lab}}=34.4$ MeV. The dots and squares correspond to the experimental data of Ref. [?]. The lines correspond to our DWBA calculations for the transfer and breakup contributions, as indicated by the labels.

a small contribution to the breakup. As in the case of the transfer, the final ${}^7\text{Li}$ can be produced in the ground or excited state, giving rise to *elastic* and *inelastic* breakup contributions, respectively.

The angular distributions calculated for the elastic and inelastic breakup cross sections are represented in Fig. 3 by the thick and thin dotted-dashed lines, respectively. Also shown is the sum of the calculated transfer and breakup contributions, given by the thick solid line. As it can be seen, it gives a fairly good agreement with the experimental data, reproducing the shape of the angular distribution and its normalization. According to our calculations, the transfer channel accounts for about 80% of the observed ${}^7\text{Li}$ yield. However, it is interesting to note that

for scattering angles above 120 degrees, there is an inversion of the relative importance of both mechanisms. In this region, the ${}^7\text{Li}$ particles are mainly produced through the elastic breakup of the projectile.

IV. SUMMARY AND CONCLUSIONS

In summary, we have analyzed the recently measured reaction ${}^8\text{Li} + {}^{208}\text{Pb}$ at energies slightly above the Coulomb barrier. Experimentally, this reaction shows, as a remarkable feature, a strong yield of ${}^7\text{Li}$ particles, which is attributed to the weak binding of the valence neutron in the ${}^8\text{Li}$ nucleus. An optical model analysis of the elastic differential cross sections reflects a very absorptive nature for the process, probably due to the loss of flux in the elastic channel leading to the production of ${}^7\text{Li}$ and ${}^4\text{He}$. Our DWBA calculations indicate that the transfer cross section is the main mechanism responsible for the one-neutron removal channel, although there is also an important contribution coming from the breakup channel, which is actually the dominant mechanism at backward angles. The sum of both contributions accounts quite well for the measured ${}^7\text{Li}$ angular distribution in both shape and absolute magnitude. Other effects, such as the importance of the 1^+ excited state on the transfer cross section and the effect of the transfer channels on the elastic cross sections are now under study and will be published elsewhere [?].

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