COUPLED CHANNEL EFFECTS IN THE SCATTERING OF ^{6,7}Li BY ^{58}Ni ☆

J. GOMEZ-CAMACHO[1], M. LOZANO
Departamento de Fisica Atomica y Nuclear, Facultad de Fisica, Universidad de Sevilla, Apartado 1065, 41080 Sevilla, Spain

and

M.A. NAGARAJAN
SERC, Daresbury Laboratory, Daresbury, Warrington W4A 4AD, England

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Using a single-particle description of ^{6,7}Li and Woods–Saxon generated wavefunctions for ^{58}Ni matter density distribution, the diagonal and transition densities are calculated. Folding these densities with the M3Y effective interaction, the coupling and diagonal potentials are obtained. Coupled channel calculations for ^{6,7}Li on ^{58}Ni at bombarding energies in a range from 12 to 74 MeV are performed. It is shown that the predictions of the coupled channel calculations are consistent with those of optical model calculations using folded potentials renormalized by a factor 0.6 in the entire range of energies.

In recent years the scattering of light heavy ions such as ^{6,7}Li and ^{9}Be have received considerable interest. This is due to the failure of the double folding potential [1] obtained from an effective nucleon–nucleon interaction [2], which have to be renormalized by a factor around 0.6 in order to fit the elastic scattering data for these nuclei.

This anomaly has been attributed to break-up effects which become important due to the low break-up threshold of these nuclei [3]. This idea has been confirmed by calculations describing ^{6}Li and ^{7}Li, respectively, as $(\alpha + \alpha)$ and $(\alpha + t)$ systems. It is found that to reproduce the elastic scattering data of ^{6,7}Li in terms of the optical potentials of the target with the fragments of the projectile, the break-up states must be considered. The cluster model is also successful in explaining the behavior of polarized projectiles. It is shown [4] that the coupling effects between the cluster-described excited states have a very important effect on the tensor analyzing powers, even at very low energy. Of particular interest is the work of Sakuragi et al. [5], who use a detailed cluster description of ^{6}Li, discretizing the continuum of break-up states in several bins for each relevant partial wave. The diagonal and transition potentials are obtained from an effective nucleon–nucleon interaction convoluted with the target density and the corresponding projectile diagonal and transition density. It is shown that the main contribution on the elastic scattering comes from the resonances which affect mainly the real potential.

Recently we have developed a single-particle description of ^{7}Li [6], assuming a $(0s)^4(0p)^3$ configuration in a single-particle well for the relevant states of ^{7}Li. The different negative parity states of this nucleus are obtained by diagonalizing a residual hamiltonian, and the diagonal and

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[1] Currently at Daresbury Laboratory, Daresbury, Warrington W4A 4AD, England.

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transition densities are found to be related with the single-particle wavefunctions. We have shown that a coupled channel calculation including the relevant states explains the experimental data of ^{7}Li + ^{40,48}Ca at 89 MeV.

In this work we use the same formalism to analyze the elastic scattering of ^{6}Li and ^{7}Li by ^{58}Ni over a wide range of energies.

The intermediate coupling model [7] has explained successfully the structure of the 0p nuclei. It is shown that the effective nucleon–nucleon interaction for the 0p shell has a large Majorana component which favours the states with maximum spatial symmetry. When the spin–orbit force is small, as happens in the first half of the shell, the different states can be labelled with the irreducible representations of the permutation group of spatial symmetry $[\lambda]$ to which they belong, as well as by the orbital (L), spin (S) and total (J) angular momenta and the isospin (T).

For ^{6}Li all the low-lying states belong to the configuration $(0s)^4(0p)^2$ with the maximum spatial symmetry [2]. The ground state is assumed to be labelled by $L=0$, $S=1$, $T=0$ and the multiplet with $J=3,2,1$ corresponds to $L=2$, $S=1$, $T=0$.

For ^{7}Li the low-lying states correspond to the $(0s)^4(0p)^3$ configurations, with the maximum spatial symmetry $[\lambda]=[3]$. The ground state ($3/2^-$) and the first excited state ($1/2^-$) correspond to $L=1$, $S=1/2$, $T=1/2$ and the $7/2^-_1$ and $5/2^-_1$ states correspond to the $L=3$, $S=1/2$, $T=1/2$ doublet.

The density operator can be written as

$$\hat{\rho}(r)=\sum_{l_i l_j}\sum_{\lambda}\left[O^{l_i l_j}_{\lambda}\cdot Y_{\lambda}(\hat{r})\right]\cdot R^{*}_{l_i}(r)R_{l_j}(r), \qquad (1)$$

where

$$O^{l_i l_j}_{\lambda}=\left[a^{+}_{l_j}\cdot a_{l_i}\right]^{\lambda}\cdot(l_j\|Y_{\lambda}\|l_i). \qquad (2)$$

$a^{+}_{l_j}$ (a_{l_i}) is the creation (annihilation) operator of a particle in the shell labelled by l_j (l_i), and $R_{l_j}(r)$ ($R_{l_i}(r)$) the corresponding radial wavefunction. When only states of the $(0s)^4(0p)^n$ configurations are allowed, then eq. (1) can be rewritten as

$$\hat{\rho}(r)=\rho_0(r)+\left[\hat{O}_2\cdot Y_2(\hat{r})\right]\rho_2(r), \qquad (3)$$

Table 1
Reduced matrix elements for ^{6}Li.

	1^+	3^+	2^+	1^+_2
1^+	0	−0.6750	−0.5705	−0.4419
3^+	−0.6750	−0.7394	−0.4773	−0.3375
2^+	0.5705	0.4773	−0.3773	0.4465
1^+_2	−0.4419	−0.3375	−0.4465	−0.3458

Table 2
Reduced matrix elements for ^{7}Li.

	$3/2^-$	$1/2^-$	$7/2^-$	$5/2^-$
$3/2^-$	−0.4841	0.4841	−0.6454	0.2635
$1/2^-$	−0.4841	0	0	−0.4930
$7/2^-$	−0.6454	0	−0.7469	0.2587
$5/2^-$	−0.2635	−0.4930	−0.2587	−0.6338

where

$$\rho_0(r)=(1/4\pi)\left[4R^2_{0s}(r)+nR^2_{0p}(r)\right], \qquad (4)$$

$$\hat{O}_2=(6/4\pi)^{1/2}|a^{+}_{0p}\cdot a_{0p}|^{\lambda=2}, \qquad (5)$$

$$\rho_2(r)=R^2_{0p}(r). \qquad (6)$$

The matrix elements of $\hat{O}_2$ between the relevant states of ^{6}Li and ^{7}Li are shown in tables 1 and 2. In order to fit the quadrupole moment and B(E2) of ^{7}Li we had to introduce an additional charge of $0.215e$ for each one of the 0p shell nucleons, and from that, we justified the inclusion of an additional mass of 0.43 for each nucleon in the 0p shell [6]. This is maintained for ^{6}Li also in this work.

The density of ^{58}Ni was obtained from a single-particle description [8] which agrees with electron and proton scattering data.

The effective nucleon–nucleon interaction [2] is of the form

$$V(r)=7999\exp(-4r)/4r - 2134\exp(-2.5)/2.5-262\,\delta(r). \qquad (7)$$

The density distribution for ^{7}Li is described elsewhere [6]. For ^{6}Li, we have just taken off ^{7}Li one neutron from the 0p shell, keeping the same single-particle wavefunctions.

With these densities and effective nucleon–nucleon interaction the real potentials for the

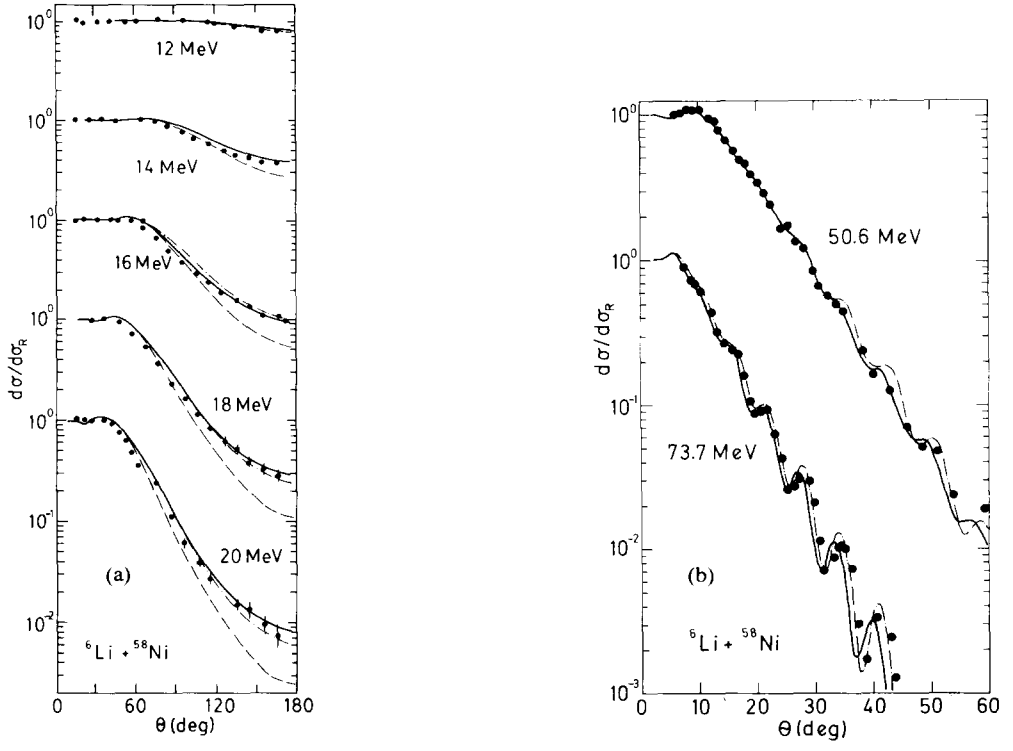

Fig. 1. (a) Elastic cross sections of ^{6}Li with ^{58}Ni at 12, 14, 16, 18 and 20 MeV. The dashed fine line is obtained including only the elastic channel with the folding potential without renormalization. The dot-dashed fine line correspond to the folding potential renormalized by a factor 0.6. The continuous line is the full coupled channel calculation. The experimental data are from ref [9]. (b) Same as (a) but at 50.6 MeV (experiments from ref. [10]) and 73.7 MeV (experiments from ref. [11]) bombarding energies. Predictions of the unrenormalized potential are not shown because the total disagreement with the data.

reactions ^{6}Li + ^{58}Ni and ^{7}Li + ^{58}Ni are determined. Following the procedure of Sakuragi et al. [5] we fix the imaginary potentials as 0.6 times the real ones. This is equivalent to assuming an imaginary effective nucleon–nucleon interaction which is 0.6 times that of expression [7]. We compare the experimental data with (a) the predictions of the double folded potential without renormalization, (b) the predictions of the double folded potential renormalized by a factor 0.6 and (c) the predictions of the coupled channel calculations without any renormalization. These comparisons are shown in figs. 1a and 1b for the elastic scattering of ^{6}Li by ^{58}Ni at a range of energies from 12 MeV to 74 MeV. It was observed that for ^{6}Li energies greater than 20 MeV, the energy difference between the states forming the triplet ($L = 2, S = 1$) can be ignored. Thus, treating these as degenerate the results of a coupled channel calculation with two channels or four channels yields the same result. (In the two-channel calculation, the $L = 2$ level is fixed at the centroid of the triplet). For energies below 20 MeV, it was observed that the dominant coupled channel effect arose from the 3^+ member of the triplet. However, the other two states (2^+ and 1^+) could not be totally ignored when large angle scattering was considered.

The analyses of the elastic scattering of ^{7}Li by ^{58}Ni are shown in fig. 2 for projectile energies from 14.2 to 20.3 MeV. It was found that the effect of the $5/2^-$ state of ^{7}Li on the elastic scattering was negligible at all the energies and at energies below 20 MeV, the coupling effect of the $7/2^-$

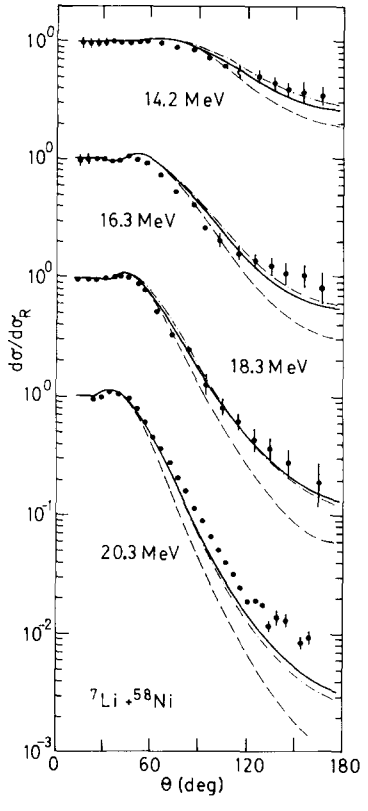

Fig. 2. Elastic cross sections of ^{7}Li with ^{58}Ni at 14.2, 16.3, 18.3 (experiments from ref. [9]) and 20.3 (experiments from ref. [12]) MeV. The lines have the same meaning as in fig. 1a.

state on the elastic scattering was also small. Thus, in the energy range from 12 to 20 MeV, the only strong coupling arises from the $1/2^-$ state at 470 keV. It can be seen in both cases of elastic scattering of ^{6}Li and ^{7}Li that the results of the coupled channel calculations are almost identical to those of the double folded potential renormalized by a complex constant factor (0.6 + 0.6i).

From the figures it is seen that whereas agreement between the coupled channel calculations and the experimental data is very good, at the lower energies ($E \lesssim 20$ MeV) we see discrepancy between theory and experiment at large angles. These may be due to our choice of the same geometry for the real and imaginary potential. These results confirm what was suggested in a previous paper [6], this is, that the renormalization of the real potential can be explained with a single-particle excitation mechanism, which does not take into account the continuum nature of the break-up states, but which allows for a complex effective interaction.

It seems necessary to have more precise experimental data at low energy in order to decide if there is a change in the characteristics of the ^{6}Li and ^{7}Li optical potentials. Such a change in the characteristics have been observed by Lilley et al. [13] in the elastic scattering of ^{16}O on ^{208}Pb at energies close to the Coulomb barrier.

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