

## R-matrix Analysis for the $^8\text{Be}$ System and Features in the $p+^7\text{Li}$ Reaction Over Resonance Region

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**Abstract.** A comprehensive R-matrix analysis is currently underway for the  $^8\text{Be}$  compound system toward a consistent evaluation of the  $p+^7\text{Li}$  reaction cross-sections over the resonance energy region. In this analysis, the energy eigenvalues are fixed to the level energies given in ENSDF, and we searched for values of the boundary condition parameters as well as the reduced-width amplitudes. It is found that some additional levels are necessary to fit the resonant shape of experimental cross-sections. Besides, the channel radii obtained may be consistent with well-known physical pictures of the atomic nucleus.

### 1 Introduction

Resonant peaks are observed in the nuclear reaction cross-sections in the lower-energy range where the level structure of compound nucleus shows its very unique character. It is not easy to theoretically predict such resonant cross-sections explicitly as it is still at the stage of scientific challenge. Hence, at this moment, experimental researches are essential to come close to the true values. R-matrix [1] is rigorous and straightforward to the quantum mechanical theory, which relates the nature of the compound nucleus to the S-matrix (hence the cross-sections) under a certain boundary condition at the channel surface. That is, once we measured cross-sections, a consistent data evaluation could be made through the R-matrix analysis. Indeed, a number of analyses have been reported especially for light systems in the world to evaluate cross-sections and/or to understand the nature of the compound nuclei.

In this study, we focus on the analysis of  $^8\text{Be}$  compound system toward a complete evaluation of the  $p+^7\text{Li}$  cross-sections. It is essentially because the  $^7\text{Li}(p,n)^7\text{Be}$  reaction is a promising neutron source to be used in the nuclear science and engineering. Indeed, this reaction is drawing attention also in the medical field as it could be a candidate of neutron-generator in Boron Neutron Capture Therapy [2]. Also, we are interested in the astrophysics, as the  $^7\text{Li}(p,\alpha)^4\text{He}$  reaction has an important role in determining the amount of  $^7\text{Li}$ -depletion in a pre-main sequence phase [3]. Therefore, those reaction cross-sections should be quantitatively known over the relevant energy range.

Let's look at the present status of the  $p+^7\text{Li}$  data evaluation in the world. Although the cross-sections have been measured over the years for those reactions, in-depth evaluation works have not necessarily been reported. The worst situation is found, e.g., in JENDL-4 [4] (or JENDL/HE-2007 [5]) where the  $p+^7\text{Li}$  cross-section is not given at all in spite of its importance. The TENDL library [6]

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contains cross-sections virtually for any reactions including  $p+{}^7\text{Li}$ . However, the  $p+{}^7\text{Li}$  cross-sections are estimated with the optical and the statistical model, which are beyond the applicable limit for resonant region and also for the few-body system itself. ENDF/B-VII.1 [7] certainly has  $p+{}^7\text{Li}$  cross-section over a resonance range ( $E_p \leq 10$  MeV), in which the data were evaluated though a R-matrix analysis. It is consistent with a number of measurements at around the first peak of  ${}^7\text{Li}(p,n_0){}^7\text{Be}$  cross-sections (around  $E_p = 2$  MeV), however, there are serious discrepancies above  $E_p = 3$  MeV. Indeed, it is not easy to achieve a consistent R-matrix analysis over a wide energy range due to a significant number of possible channels and unknown background contributions from bound/distant levels and/or the direct reactions.

A comprehensive R-matrix analysis is currently underway for the  ${}^8\text{Be}$  compound system to evaluate the  $p+{}^7\text{Li}$  cross-sections over the resonance energy region. In this analysis, the energy eigenvalues are fixed to the level energies given in Evaluated Nuclear Structure Data File (ENSDF) [8, 9], instead we search for values of the boundary condition parameters and the reduced-width amplitudes where the unknown background contributions are assumed to be supplemented by putting pseudo levels far above the relevant energy range. We preliminary achieved reasonable fits to measured cross-sections of different reactions simultaneously. Investigating the values of the R-matrix parameters and sources of the resonances, we may obtain a better understanding of natures in the  $p+{}^7\text{Li}$  reactions.

## 2 Overview of R-matrix formalism and our computational code

### 2.1 Short summary of the R-matrix formalism and parameters

The R-matrix approach is a quantum mechanical formalism which connects the nature of the compound system to the scattering observables such as the cross-sections. To be more precise, the internal and external wave-functions are matched at the channel surface under a certain boundary condition, then S-matrix/collision-matrix is calculated as follows.

$$U_{cc'} = e^{-i(\varphi_c + \varphi_{c'})} \left[ \delta_{cc'} + 2i \sqrt{P_c P_{c'}} \left( \frac{\mathbf{R}}{\mathbf{I} - \mathbf{R}\mathbf{L}} \right)_{cc'} \right], \quad (1)$$

with

$$L_{cc'} = (S_c + iP_c - B_c) \delta_{cc'}. \quad (2)$$

Where the symbol  $\varphi_c$  denotes the hard-sphere scattering phase-shift, while  $P_c$  and  $S_c$  stand for the penetration and shift factors at the channel surface, respectively. The boundary condition number  $B_c$  is virtually the logarithmic derivative of the wave function. It should be noted that the channel is defined explicitly, viz.,  $c \equiv (\alpha, l, s; J)$  where the symbol  $\alpha$  is the partition (the pair of particle and nucleus),  $l$  for the angular momentum of the pair,  $s$  for the channel spin, and  $J$  is the spin of the eigenstates. The matrix  $\mathbf{R}$  includes structural information of the compound system, which is necessary to calculate resonant cross-sections. The matrix element is given as follows,

$$R_{cc'} = \sum_{\lambda} \frac{\gamma_{\lambda c} \gamma_{\lambda c'}}{E_{\lambda} - E}, \quad (3)$$

where the symbol  $E_{\lambda}$  denotes the energy eigenvalue for each eigenstate  $\lambda$  and  $\gamma_{\lambda c}$  is the reduced-width amplitude for each explicit channel. They are normally treated as the parameters to be deduced from the experimental cross-sections under a certain boundary condition.

## 2.2 Computational code AMUR

AMUR [10, 11] is a multichannel and multilevel R-matrix code to be used for the analysis of the experimental cross-sections, hence for the nuclear data evaluation. Substantial features of the code are listed as follows.

- The code is based on the Wigner-Eisenbud's formalism [12] which is an exact expression of the R-matrix theory. One exception is for the  $\gamma$ -ray channels which we optionally treated by the Reich-Moore approximation [13].
- Both the neutron and charged-particle cross-sections are calculated. It is true also for the differential cross-sections including those for the charged-particle elastic-scattering where the total amplitude is calculated as the sum of the T-matrix element and the Coulomb scattering amplitude.
- If necessary, experimental data can be corrected in the analysis. For examples, the re-normalization and some sources of the resolution are considered as the experimental parameters (those options are not used in this analysis).
- The R-matrix (and the experimental) parameters are deduced through the simultaneous fit to measured cross-sections for the different reactions. We use the generalized least-square method which is equivalent with the approach in the KALMAN/SOK code [14].
- An object-oriented programming technique is used so as to make it easier for us to continue further development/management of the code.

## 3 R-matrix analysis for the $^8\text{Be}$ system

### 3.1 Energy eigenvalues for the compound system

Through the R-matrix analysis, in principle, it is possible to deduce the energy eigenvalue  $E_\lambda$  and the corresponding  $J^\pi$  for the compound system from experimental cross-sections. However, we found it is not so easy to do this essentially because of the reasons as follows.

- A number of broad resonances overlap/interfere in the relevant energy range, which makes it difficult to identify the each position explicitly.
- Since experimental cross-sections are limited, we may fall into mis-assignments of  $J^\pi$  even for the major levels.
- The analysis is very time consuming since number of channels is significant due to different combination of the partitions, angular momentum and channel spins. For instance, more than 20 channels could be involved only in just the  $J^\pi = 2^+$  state in the relevant energy range.

Therefore, in this analysis, we take the energy eigenvalues and the corresponding  $J^\pi$  of  $^8\text{Be}$  from the latest version of ENSDF [8, 9]. Indeed, the level information given in such a database had been evaluated based on a number of measurements for the nuclear structure. In this sense, present analysis inherits the knowledge from a long-standing accumulation of such studies.

### 3.2 Channels considered

In the present analysis, we tried to include all the explicit channels as much as possible except for the  $\gamma$ -ray channels. For examples, the channels considered are listed in Table 1 for  $J^\pi = 2^-$  and  $2^+$  where the channels with high angular momentums ( $l = 3, 4$ ) were preliminary neglected as we found they were less important in the relevant energy range.

**Table 1.** Possible and considered channels for  $J^\pi = 2^\pm$ .

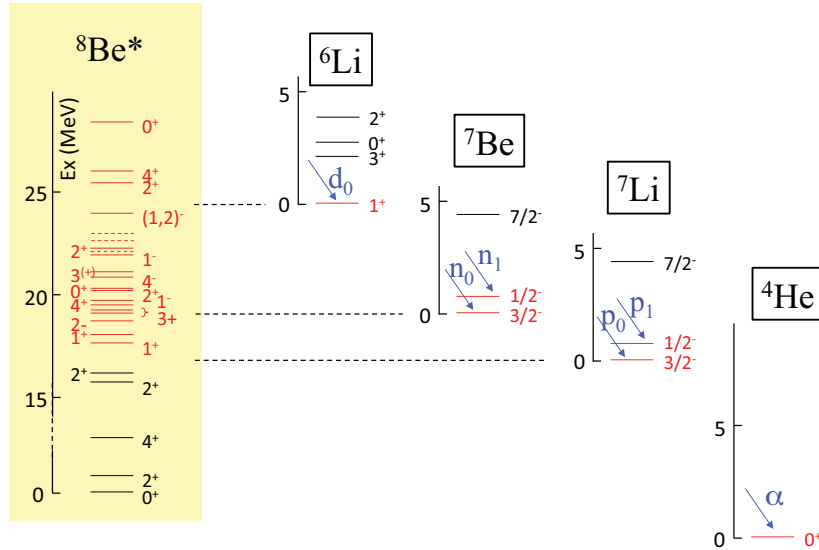
$J^\pi$	Partition	$l$	$s$	considered ?
$2^-$	$n+{}^7\text{Be}_{\text{g.s.}}$	0	2	yes
		2	1, 2	yes
		4	2	no
	$n+{}^7\text{Be}_{1\text{st}}^*$	2	0, 1	yes
		$p+{}^7\text{Li}_{\text{g.s.}}$	0	2
	$p+{}^7\text{Li}_{\text{g.s.}}$	2	1, 2	yes
		4	2	no
		$p+{}^7\text{Li}_{1\text{st}}^*$	2	0, 1
	$d+{}^6\text{Li}_{\text{g.s.}}$	1	1, 2	yes
		3	1, 2	no
$2^+$	$n+{}^7\text{Be}_{\text{g.s.}}$	1	1, 2	yes
		3	1, 2	no
	$n+{}^7\text{Be}_{1\text{st}}^*$	1	1	yes
		3	1	no
	$p+{}^7\text{Li}_{\text{g.s.}}$	1	1, 2	yes
		3	1, 2	no
	$p+{}^7\text{Li}_{1\text{st}}^*$	1	1	yes
		3	1	no
	$d+{}^6\text{Li}_{\text{g.s.}}$	0	2	yes
		2	0, 1, 2	no
4		2	no	
$\alpha+{}^4\text{He}_{\text{g.s.}}$	2	0	yes	

Figure 1 illustrates the excited levels of  ${}^8\text{Be}$  together with the final states in the residual nuclei for the  $p+{}^7\text{Li}$  reaction. We include both the ground and the first excited states for the residuals  ${}^7\text{Be}$  and  ${}^7\text{Li}$  whereas only the ground state is considered for  ${}^6\text{Li}$  and  ${}^4\text{He}$ . The other levels, such as the second excited level in  ${}^7\text{Be}$  and  ${}^7\text{Li}$  ( $J^\pi = 7/2^-$ ) could also be populated in the relevant energy range. Unfortunately, we did not include such states in the present analysis, since corresponding measured cross-sections, such as for  ${}^7\text{Li}(p, p_2){}^7\text{Li}^*$  and  ${}^7\text{Li}(p, n_2){}^7\text{Be}^*$ , have not been reported. Therefore, we need to admit the present analysis could have some incompletenesses due to the lack of the coupling effects from those neglected channels.

### 3.3 Parameters to be searched for

In most cases, the boundary condition parameters are fixed to some plausible values (e.g.,  $R_c \sim 1.2A^{1/3} + 0.8$  (fm) and  $B_c \sim l$  for the neutron reaction), then all the other R-matrix parameters  $E_\lambda$  and  $\gamma_{\lambda c}$  are searched for. Such an approach could be reasonable for the neutron reaction as a number of successful analyses had been reported. However, it is not clear to be reasonable also for the charged-particle reactions. In this analysis, we decided to fix the  $E_\lambda$  value to the level energy taken from ENSDF, instead the boundary condition parameters are treated as free parameters to be searched for as well as the  $\gamma_{\lambda c}$  values.

Since the energy range of the analysis is limited while there should be interferences from a number of levels which exist below the reaction threshold and above the upper-energy end of the analysis. Furthermore, there must be the direct-reactions which may go through the collective excitation of the



**Figure 1.** Excited levels of  ${}^8\text{Be}$  and final states of the residual nuclei considered in this analysis. Note the level energies and corresponding  $J^\pi$  are taken from ENSDF.

target, the isobaric analog state, the breakup of the residual nuclei and so on. In this study (although we are still looking for more reasonable solutions), we tried to supplement such contributions by putting pseudo levels far above the relevant energy range, in which the reduced-width amplitudes for those distant levels are fitting parameters.

### 3.4 Experimental cross-sections to be fitted

Experimental data preliminary used are listed in Table 2 and 3 for the cross-sections and differential cross-sections, respectively. Those data were collected from the EXFOR database [15]. We fitted cross-sections for the different reactions which share the same compound nucleus  ${}^8\text{Be}^*$  simultaneously, viz., for the  $n+{}^7\text{Be}$ ,  $p+{}^7\text{Li}$ ,  $d+{}^6\text{Li}$  and  $\alpha+{}^4\text{He}$  reactions.

## 4 Results and discussion

### 4.1 Fitted results

Figure 2 shows example results of the cross-sections obtained by the R-matrix fits together with typical experimental data up to  $E_p = 10$  MeV. Although the present results are still preliminary, reasonable fits had been achieved not only for the major reaction  ${}^7\text{Li}(p, n_0){}^7\text{Be}$  but also for the other reactions. It is also true for the differential cross-sections as example results are illustrated in Figs 3 and 4 for the  ${}^7\text{Li}(p, n_0){}^7\text{Be}$ ,  ${}^7\text{Li}(p, p_0){}^7\text{Li}$  and  ${}^7\text{Li}(p, p_1){}^7\text{Li}^*$  reactions. However, more reasonable fits are expected

**Table 2.** Experimental cross-sections preliminary used in this work

Reaction	Author	(Year)	$E_{inc.}$ (MeV)
${}^7\text{Li}(p, p_1){}^7\text{Li}$	Presser <i>et al.</i> [16]	(1972)	1.7 – 6.0
	Mateus <i>et al.</i> [17]	(2002)	0.7 – 2.4
${}^7\text{Li}(p, n_0){}^7\text{Be}$	Burke <i>et al.</i> [18]	(1974)	2.1 – 3.8
	Sekharan <i>et al.</i> [19]	(1976)	1.9 – 4.2
	Poppe <i>et al.</i> [20]	(1976)	4.0 – 26.0
${}^7\text{Li}(p, n_1){}^7\text{Be}$	Presser <i>et al.</i> [16]	(1972)	2.4 – 6.0
	Poppe <i>et al.</i> [20]	(1976)	4.5 – 26.0
${}^7\text{Li}(p, \alpha){}^4\text{He}$	Cassagnou <i>et al.</i> [21]	(1962)	1.4 – 4.8
	Mani <i>et al.</i> [22]	(1964)	3.0 – 11.9
	Spraker <i>et al.</i> [23]	(2000)	0.04 – 0.1
${}^6\text{Li}(d, p_0){}^7\text{Li}$	Mcclenahan <i>et al.</i> [24]	(1975)	0.5 – 3.5
	Dunjiu <i>et al.</i> [25]	(1985)	0.5 – 2.5
${}^6\text{Li}(d, p_1){}^7\text{Li}$	Mcclenahan <i>et al.</i> [24]	(1975)	0.4 – 3.4
	Dunjiu <i>et al.</i> [25]	(1985)	1.0 – 2.5
${}^6\text{Li}(d, \alpha){}^4\text{He}$	Mcclenahan <i>et al.</i> [24]	(1975)	0.5 – 3.4
	Gould <i>et al.</i> [26]	(1985)	2.2 – 5.9
	Dunjiu <i>et al.</i> [25]	(1985)	0.5 – 2.5
${}^4\text{He}(\alpha, p_0){}^7\text{Li}$	King <i>et al.</i> [27]	(1977)	38 – 50
${}^4\text{He}(\alpha, p_1){}^7\text{Li}$	King <i>et al.</i> [27]	(1977)	38 – 50
${}^4\text{He}(\alpha, n){}^7\text{Li}$	King <i>et al.</i> [27]	(1977)	38 – 50
${}^7\text{Be}(n, p){}^7\text{Li}$	Gledenov <i>et al.</i> [28]	(1987)	thermal – 416 eV
${}^7\text{Be}(n, p_0){}^7\text{Li}$	Koehler <i>et al.</i> [29]	(1988)	thermal – 13.5 keV

to be obtained since we have not yet investigated the sign of the reduced-width amplitude for all the levels and channels.

#### 4.2 Features in the ${}^7\text{Li}(p, n_0){}^7\text{Be}$ reaction

Figure 5 plots the calculated  ${}^7\text{Li}(p, n_0){}^7\text{Be}$  cross-sections and those from  $J^\pi = 1^\pm, 2^\pm$  and  $3^\pm$  which are found to be major contributors on this reaction. The source of the largest peak observed around  $E_p = 2$  MeV is quite simple as we confirmed it comes from the  $3^+$  level at  $E_x = 19.235$  MeV of  ${}^8\text{Be}^*$ . On the other hand, the situation seems to be rather complicated for the second largest peak around  $E_p = 5$  MeV where a number of different  $J^\pi$  contribute to the resonant cross-section. Looking at ENSDF,  $J^\pi = 3^{(+)}$  at  $E_x = 21.5$  MeV is suggested for the main source of the resonance where the positive parity is assigned preliminary. In this analysis, let us suggest that both the  $J^\pi = 3^+$  (p-wave) and  $3^-$  (d-wave) levels are necessary to reproduce the experimental cross-sections. This is highly possible since the results obtained are also consistent with the measured differential cross-sections as illustrated in Fig 6. It is noticeable that the background from  $J^\pi = 2^-$  is so huge that extends over a very wide energy range. This is a tail from the  $J^\pi = 2^-$  (s-wave) at  $E_x = 18.91$  MeV exists below the reaction threshold, which suggests it is important to analyze cross-section in a wide energy range as much as possible to determine the background contributions with a reasonable accuracy.

**Table 3.** Experimental differential cross-sections preliminary used in this work

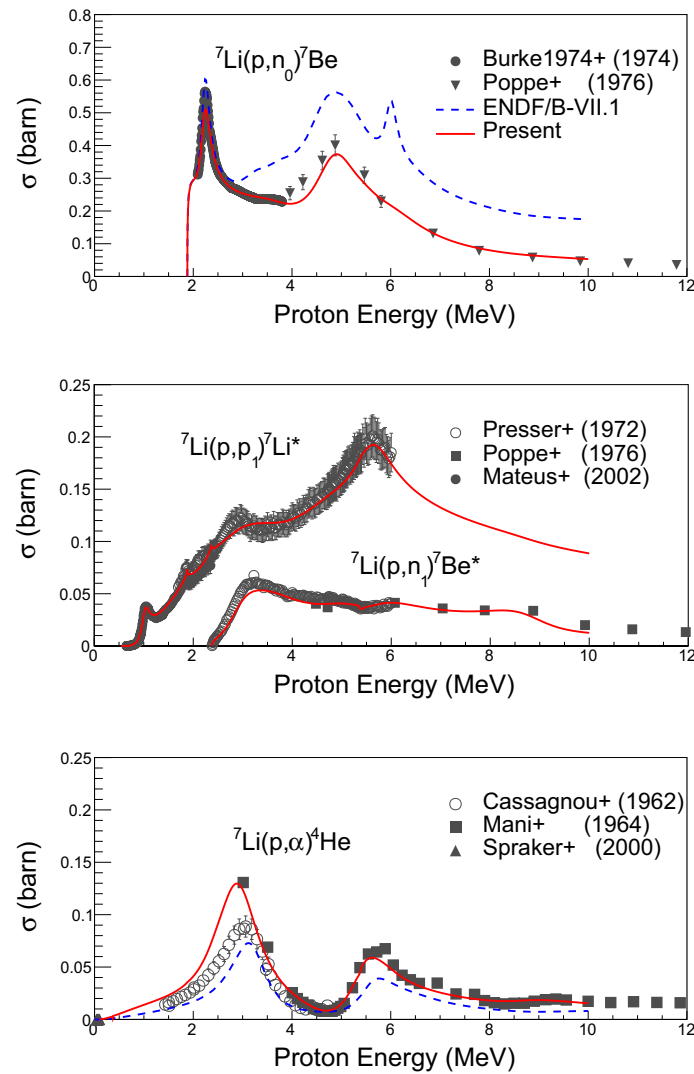
Reaction	Author	(Year)	$E_{inc.}$ (MeV)	$\theta$ (degree)
${}^7\text{Li}(p, p_0){}^7\text{Li}$	Bashkin <i>et al.</i> [30]	(1951)	0.9 – 3.7	164 [I]
	Warters <i>et al.</i> [31]	(1953)	0.4 – 1.4	50, 70, 89.2, 110, 130, 143.4, 160 [c]
	Fasoli <i>et al.</i> [32]	(1964)	3.0 – 5.5	65.8, 70.1, 90.0, 97.4, 109.9, 125.3, 140.7, 149.5, 168.3 [c]
	Gleyvod <i>et al.</i> [33]	(1965)	2.5 – 12.1	70, 90, 130, 150, 166 [c]
	Kilian <i>et al.</i> [34]	(1969)	2.7 – 10.6	60, 90, 120, 140 [I]
	Peneta <i>et al.</i> [35]	(2012)	1.5 – 7.0	140, 150, 160, 170 [I]
${}^7\text{Li}(p, p_1){}^7\text{Li}^*$	Bashkin <i>et al.</i> [30]	(1951)	0.9 – 3.7	164 [I]
	Fasoli <i>et al.</i> [32]	(1964)	3.0 – 5.5	65.8, 70.1, 90.0, 97.4, 109.9, 125.3, 140.7, 149.5, 168.3 [c]
	Gleyvod <i>et al.</i> [33]	(1965)	2.5 – 12.1	70, 90, 130, 150, 166 [c]
	Kilian <i>et al.</i> [34]	(1969)	2.7 – 10.6	60, 90, 120, 140 [I]
	Guzhovskij <i>et al.</i> [36]	(1984)	3.0 – 8.0	55 [I]
	Peneta <i>et al.</i> [35]	(2012)	1.5 – 7.0	140, 150, 160, 170 [I]
${}^7\text{Li}(p, n_0){}^7\text{Be}$	Austin <i>et al.</i> [37]	(1962)	2.0 – 3.5	0 [I]
	Burke <i>et al.</i> [18]	(1974)	1.9 – 3.8	0 – 160 [I]
	Borchers <i>et al.</i> [38]	(1963)	3.2 – 10.0	0 [I]
	Elbakr <i>et al.</i> [39]	(1972)	2.2 – 5.5	0 [I]
	( $p, n_0 + n_1$ ) Meadows [40]	(1972)	3.4 – 7.0	3, 15, 50 [I]
${}^7\text{Li}(p, n_1){}^7\text{Be}^*$	Guzhovskij <i>et al.</i> [36]	(1984)	3.0 – 8.0	55 [I]
	Elbakr <i>et al.</i> [39]	(1972)	2.5 – 5.5	0 [I]
${}^7\text{Li}(p, \alpha){}^4\text{He}$	Peneta <i>et al.</i> [35]	(2012)	1.5 – 7.0	140, 150, 160, 170 [I]
${}^6\text{Li}(d, p_0){}^7\text{Li}$	Elywn <i>et al.</i> [41]	(1977)	1.0 – 1.0	15 – 165 [I]
${}^6\text{Li}(d, p_1){}^7\text{Li}$	Elywn <i>et al.</i> [41]	(1977)	1.0 – 1.0	15 – 165 [I]
${}^6\text{Li}(d, n_0){}^7\text{Be}$	Elywn <i>et al.</i> [41]	(1977)	0.2 – 0.9	0 – 148.5 [I]
${}^6\text{Li}(d, n_1){}^7\text{Be}$	Elywn <i>et al.</i> [41]	(1977)	0.2 – 0.9	0 – 148.5 [I]
${}^6\text{Li}(d, \alpha){}^4\text{He}$	Elywn <i>et al.</i> [41]	(1977)	0.1 – 1.0	15 – 165 [I]

**Table 4.** Channel radii preliminary obtained for each partition

particle	$r_{exp}$ (fm)	nuc.	$r_{exp}$ (fm)	$r_c$ (fm)
n	-	${}^7\text{Be}$	-	3.32
p	0.80	${}^7\text{Li}$	2.43	3.68
d	2.00	${}^6\text{Li}$	2.54	6.08
$\alpha$	1.68	${}^4\text{He}$	1.68	2.84

### 4.3 Channel radii obtained

Since we fixed the energy eigenvalues of the compound to the level energies of  ${}^8\text{Be}^*$  given in ENSDF, the boundary condition parameters could be searched for in the fitting procedure. Table 4 lists the channel radii obtained, in which we preliminary assumed the value is different for each particle-nucleus pair in this analysis. We found that the values obtained are somewhat larger than the experi-

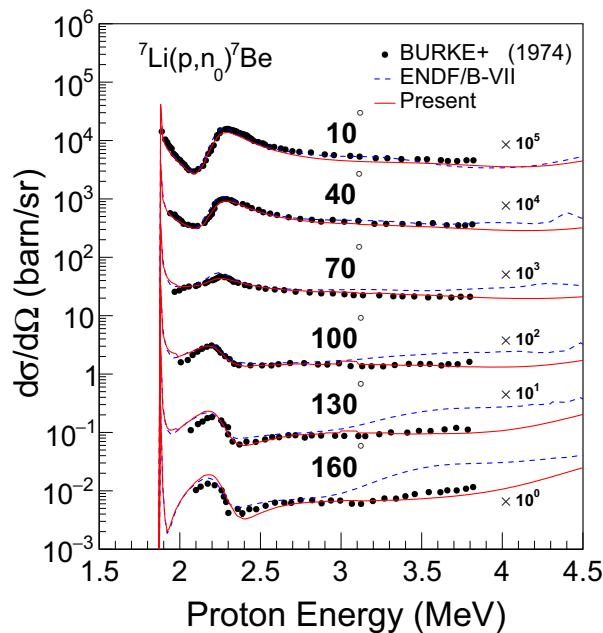


**Figure 2.** Example results of the cross-sections obtained by the R-matrix fits together with typical experimental data up to  $E_p = 10$  MeV.

mental r.m.s charge radii [42] for the nuclei. Imagine that the nucleus has a certain diffuseness at the surface, and the particle itself is not the point-particle. Therefore, the present values may be consistent with well-known physical pictures of the atomic nucleus.

#### 4.4 Correlation matrices of the cross-sections

Figure 7 illustrates the correlation matrices obtained in the present R-matrix fit for  ${}^7\text{Li}(p,n){}^7\text{Be}$  and  ${}^7\text{Li}(p,\alpha){}^4\text{He}$  cross-sections. Since the R-matrix theory is straightforward to the quantum mechanics,



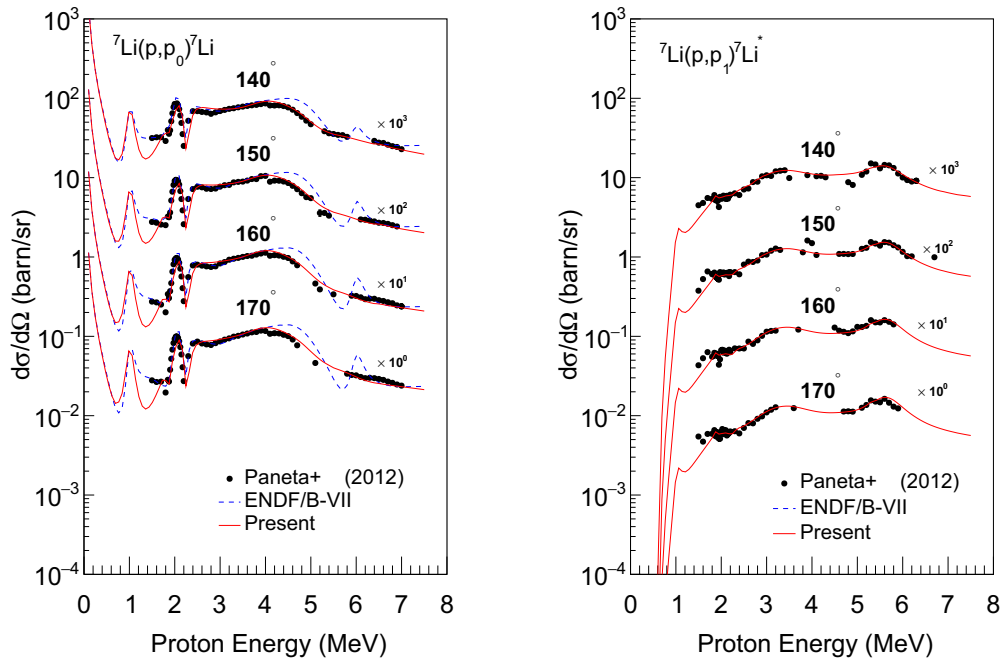
**Figure 3.** Example results of the R-matrix fit for  ${}^7\text{Li}(p,n){}^7\text{Be}$  differential cross-sections together with the experimental data of Burke *et al.* [18]

the correlation matrices obtained visualize some features in the reactions. For example, correlation becomes local at around the resonance peaks both in the reactions. This is a consequence of the physical constraint from the theory in which the collision matrix (S-matrix) is always unitary. Another noticeable feature is a very strong correlation observed above  $\sim 7$  MeV both in the reactions. The main source of such a strong correlation is the background for which we gave the pseudo levels to supplement the contributions from the bound/distant levels and direct reactions.

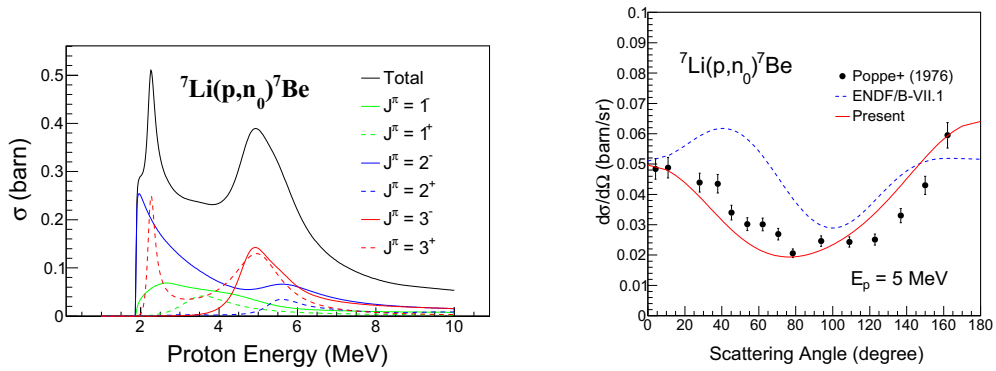
## 5 Summary

A comprehensive R-matrix analysis is currently underway for the  ${}^8\text{Be}$  compound system toward a consistent evaluation of the  $p+{}^7\text{Li}$  cross-sections over the resonance energy region. In this analysis, the energy eigenvalues were fixed to the level energies given in ENSDF, instead we tried to search for values of the boundary condition parameters as well as the reduced-width amplitudes for each channel. Reasonable fits were obtained simultaneously for all the measured cross-sections we analyzed, where the agreements appeared to be better than the existing evaluations up to  $E_p = 10$  MeV. It should be noted that we included first excited state of  ${}^7\text{Li}$  and  ${}^7\text{Be}$  for the final states while such a detailed analysis have not been reported.

In the course of the analysis, it was found that some additional levels were necessary to achieve a reasonable fit to the resonant shape of experimental cross-sections. Besides, the channel radii obtained

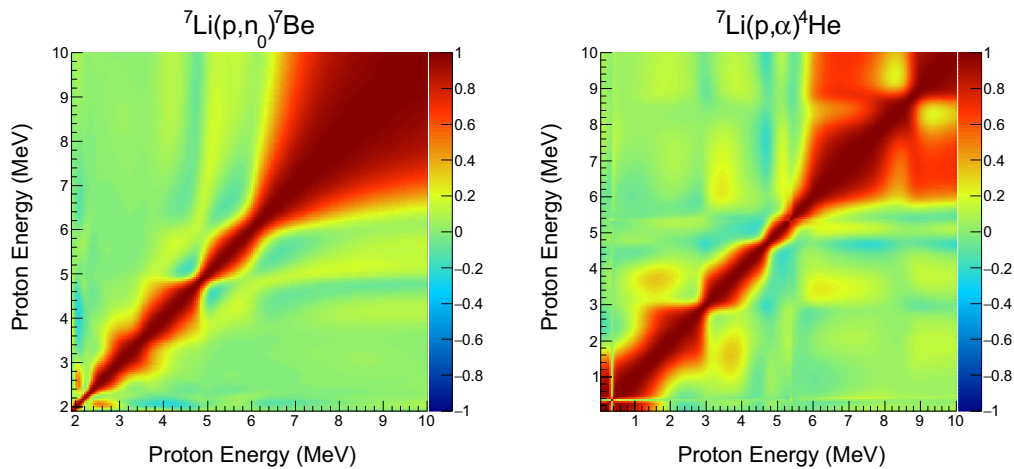


**Figure 4.** Example results of the R-matrix fit for  ${}^7\text{Li}(p, p_0){}^7\text{Li}$  and  ${}^7\text{Li}(p, p_1){}^7\text{Li}$  differential cross-sections together with the experimental data of Peneta *et al.* [35]



**Figure 5.** Contributions from the different  $J^\pi$  for the  ${}^7\text{Li}(p, n_0){}^7\text{Be}$  cross-section.

**Figure 6.** Calculated and experimental [20] differential cross-sections for the  ${}^7\text{Li}(p, n_0){}^7\text{Be}$  reaction at  $E_p = 5$  MeV.



**Figure 7.** Correlation matrices obtained in the R-matrix fit for  ${}^7\text{Li}(p, n_0){}^7\text{Be}$  (left) and  ${}^7\text{Li}(p, \alpha){}^4\text{He}$  (right) cross-sections.

may be consistent with well-known physical pictures of the atomic nucleus. However, at the same time, the present analysis left worrisome points,

- We neglected channels for the reactions such as  ${}^7\text{Li}(p, p_2){}^7\text{Li}^*$  and  ${}^7\text{Li}(p, n_2){}^7\text{Be}^*$ .
- The direct (including breakup) reactions were supposed to be supplemented by the tails from the distant levels.
- The hard-sphere well was assumed to calculate the potential scattering phase-shifts.

Although we have not yet understood if such approximations are acceptable, present knowledge obtained could be a useful guide toward a consistent evaluation of the  $p+{}^7\text{Li}$  cross-section in the resonance energy range. To understand more detailed natures in the reactions, measured differential cross-sections are needed for the second excitation state of  ${}^7\text{Li}$  and  ${}^7\text{Be}$ . Also, the optical model may give some interpretations for those approximations.

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