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LITHIUM-INDUCED REACTIONS AND THE STRUCTURE OF LIGHT NUCLEI

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1. Introduction

Among reactions with complex nuclei lithium-induced reactions are of particular interest. As is well-known, the Li^6 and Li^7 nuclei have a marked cluster structure, $\alpha + d$ and $\alpha + t$, respectively. The binding energies of the clusters are low: 1.47 MeV and 2.47 MeV, respectively. Therefore, one has reason in many cases to consider the lithium nuclei as a more or less weak association of two clusters by analogy with a deuteron which frequently behaves as a weak association of $p + n$. According to this analogy one expects that the mechanism of reactions induced by Li^6 or Li^7 ions with one of the clusters outgoing is a stripping-like one, in the main:

$$(Li^6 = \alpha + d) + A \rightarrow \begin{cases} (A + \alpha = B) + d \\ (A + d = B') + \alpha \end{cases}$$

$$(Li^7 = \alpha + t) + A \rightarrow \begin{cases} (A + \alpha = B) + t \\ (A + t = B'') + \alpha \end{cases}$$

In the reaction either an α-particle or a deuteron or a triton will be exchanged. The final nucleus B is formed after the union of the exchanged particle with the target nucleus A.

If the reaction mechanism is a stripping-like one, in the main, the spectra of the deuterons and tritons produced in (Li^6, d) and (Li^7, t) reactions are given by the reduced α-widths of the various levels of the final nucleus B. Consequently, the spectra of deuterons and tritons from reactions on the same target nucleus must be similar. Morrison was the first to show that this is so, indeed[1]. In reactions on Li^6 and B^{10} targets[1,2,3] with Li ions of 2.1 MeV, 4.5 MeV, and 6 MeV energy no (or only very weak) transitions were found to the low-lying $T = 1$ levels of the final nuclei B^{10} and N^{14}, respectively. In the case of the (Li^6, d) reactions one can explain this fact by the isospin selection rule, but in the case of the (Li^7, t) reactions there is no such a forbiddenness. Therefore, it is reasonable to suppose that in both reactions the exchange of an α-particle takes place, i.e. a stripping-like mechanism. (The population of the $T = 1$ level at 9.17 MeV in the reaction $B^{10}(Li^6, d)N^{14}$ observed in[4] is surely caused by Coulomb mixing of the $T = 1$ level with the α-threshold levels lying near the $T = 1$ level[5]).

In this paper the simple Butler theory for (d, p) stripping reactions will be applied to lithium induced reactions. In Sec. 2 some characteristic differences between deuteron and lithium induced reactions are considered. In Sections 3 and

4 the angular distributions and the spectra of the light final products are discussed. It is shown that already the simple theory with plane waves (without account of Coulomb interactions) is able to explain some characteristic features of lithium induced reactions.

2. Stripping-like mechanism in lithium-induced reactions

Symbolically, one can write a stripping-like reaction in the following manner:

$$(A+B)+C \rightarrow A+(B+C).$$

With a certain probability the projectile will be in the cluster state $(A+B)$ we are interested in. The target nucleus will be C . The reaction mechanism consists in the union of the cluster B with the target nucleus C forming the final nucleus $(B+C)$. The angular distribution is given by /6,7,8/

$$\sigma(\theta) = \frac{K_f}{K_i}\,\frac{\mu_i}{\mu_f}\,\frac{1}{(2J_C+1)(2J_{AB}+1)} \sum_{\substack{M^J_{AB}\,M^J_C \\ M^J_{BC}\,M'^J_A}} |g(\theta)|^2$$

$$= 16\pi\,\mu_i\mu_f\,\frac{2J_{BC}+1}{(2J_C+1)(2S_B+1)}\,\frac{K_f}{K_i}\,(\Theta_0^{AB})^2(\Theta_0^{BC})^2(\Theta_{\ell_{AB}}^{AB})^2 \qquad (1)$$

$$\sum_{\ell_{BC}} (\Theta_{\ell_{BC}}^{BC})^2\, T^2\, R_i^2(q_A)\, R_f^2(q_C).$$

Here

$$\frac{K_f}{K_i} = \frac{K_A}{K_C} = \sqrt{\frac{A(B+C)}{(A+B)C}\left(1+\frac{Q}{E^L_{AB}}\right)} \sim \sqrt{1+\frac{Q}{E^L_{AB}}}$$

denotes the ratio of the momenta before and after the reaction, A is the mass of the particle A ; $\mu_i = \frac{(A+B)C}{A+B+C}$, $\mu_f = \frac{A(B+C)}{A+B+C}$, $\mu_{AB} = \frac{AB}{A+B}$ ... are reduced masses; J_x , M^J_x is the angular momentum of the particle x ; $q_A^2 = |\vec{K}_f + \frac{A}{A+B}\vec{K}_i|^2$, $q_C^2 = |\vec{K}_i + \frac{C}{B+C}\vec{K}_f|^2$ are the momentum transfers without account of inner momenta; $(\Theta_0^{AB})^2(\Theta_{\ell_{AB}}^{AB})^2$ is the reduced width for the channel $(A+B)$. $(\Theta_{\ell_{AB}}^{AB})^2$ is that part of the reduced width which depends only on the symmetry properties of the level /9/,

$$\Theta^2_{\ell_{AB}} = \left(\frac{A}{A-n_B}\right)^N \binom{n_{AB}}{n_B} K^2_{n_B}(N\ell_{AB},\ell_{AB}) \langle T_A\, m^T_A, T_B\, m^T_B \mid T_{AB}\, m^T_{AB}\rangle^2 \times$$

$$\times \sum_{\lambda_{AB}} \{ \langle \ell^{n_{AB}}[f_{AB}]\, L_{AB} S_{AB} T_{AB} \| \} \ell^{n_A}[f_A] L_A S_A T_A , \ell^{n_B}[f_B]\, \ell_{AB} S_B T_B \rangle \times \qquad (2)$$

$$\times U(S_{AB} J_{AB} L_A \ell_{AB} ; L_{AB} \lambda_{AB})\, U(L_A S_A \lambda_{AB} S_B ; J_A S_{AB}) (-)^{L_{AB}+L_A} \}^2 ,$$

while the radial depending parts and the change of the total cross section due to the Coulomb interaction are implied in $(\Theta_0^{AB})^2$. In the following calculations it will be assumed that $(\Theta_0^{AB})^2$ depends neither on the level nor on the momentum with which the cluster is captured into a certain orbit.

Further

$$T = \epsilon_{AB} + \frac{q_A^2}{2\mu_{AB}} = \epsilon_{BC} + \frac{q_C^2}{2\mu_{BC}} = \epsilon_{AB} - \tfrac{1}{2}\left\{ \frac{K_o^2}{\mu_1} - \frac{K_A^2}{\mu_{AB}} - \frac{K_C^2}{\mu_{BC}} - \frac{2K_A K_C}{M_B}\cos\theta \right\}$$

$$= \epsilon_{BC} - \tfrac{1}{2}\left\{ \frac{K_A^2}{\mu_f} - \frac{K_C^2}{\mu_{BC}} - \frac{K_A^2}{\mu_{AB}} - \frac{2K_A K_C}{M_B}\cos\theta \right\} \qquad (3)$$

is the transferred energy, and

$$R^2(q) \sim \frac{1}{T^2} W^2(\ell, \Lambda, R, q) \sim \frac{1}{T^2}\left\{ qR\, j_{\ell-1}(qR) - (\ell+1+\Lambda) j_\ell(qR) \right\}^2 \qquad (4)$$

where ϵ_{AB}, ϵ_{BC} are the binding energies of the clusters (A+B) and (B+C), respectively, ℓ is the orbital momentum, R – the cut-off radius, j_ℓ – the spherical Bessel function, $\Lambda = R\left[\frac{d}{dr} \ln \mu(r)\right]_{r=R}$ (The notations are the same as in /6/).

In the (Li^6, d), (Li^6, α), (Li^7, t), (Li^7, α) reactions the orbital momentum ℓ_{AB} is given by

$$\vec{\ell}_{AB} = \vec{L}_{AB} - \vec{L}_A - \vec{L}_B = \vec{L}_{AB},$$

where $L_A = L_B = 0$ are the orbital momenta of the clusters, L_{AB} is that of the lithium ion. The nuclei Li^6 and Li^7 are with more than 95% in the states $[2]\,^{13}S$, and $[3]\,^{22}P$, respectively. Therefore, L_{AB} is a good quantum number and ℓ_{AB} takes on only one value.

Analogously, it is

$$\vec{\ell}_{BC} = \vec{L}_{BC} - \vec{L}_B - \vec{L}_C = \vec{L}_{BC} - \vec{L}_C .$$

One has

$$\ell_{BC} = \begin{cases} 0,2 \\ 1,3 \\ 0,2,4 \end{cases}$$

for the capture of a deuteron, triton, and α -particle, respectively, in the 1p -orbit. In principle, the capture of a cluster is more complicated than that of only one nucleon, because in general a cluster can be captured into a certain orbit with, at least, two different orbital momenta. Interference terms do not appear in reactions with an exchange of a deuteron or an α -particle because of $S_B = 0$ and $J_A = 0$ respectively, and $L_B = 0$.

Another difference between lithium and deuteron induced reactions is connected with the size of the projectile. In the (d, p) stripping theory the deuteron is small as compared with the target nucleus, what leads to the known fact that the angular distribution is given nearly perfectly by the properties of the target nucleus. The deuteron influences the angular distribution as a form factor, only. For lithium induced reactions on light nuclei this assumption does not hold, projectile and target nucleus are of a comparable size. Therefore, $R_1^2(q_A)$ in formula (1) must also be expressed in the form (4). The angular distribution is

$$\sigma(\theta) \sim (2J_{BC}+1)\,(\Theta^{AB}_{\ell_{AB}})^2 \sum_{\ell_{BC}} (\Theta^{BC}_{\ell_{BC}})^2\, F_{\ell_{AB}\ell_{BC}}$$

with

$$F_{\ell_{AB}\ell_{BC}} = \frac{1}{T^2}\, W^2(\ell_{AB}, \Lambda, R_A, q_A)\, W^2(\ell_{BC}, \Lambda, R_C, q_C) \qquad (5)\ .$$

In a (d, p) reaction there is $F \sim W^2(\ell_{BC}, \Lambda, R_C, q_C)$ what means that the angular distribution is given mainly by only one spherical Bessel function.

Thus, the angular dependence is more complicated in lithium-induced reactions as compared to a (d, p) reaction even when the cluster is captured with only one ℓ_{BC}.

3. Angular distribution

As an example of an angular distribution let us consider the $Li^7(Li^6, d)B^{11}$ reaction leading to B^{11} in its ground and first excited state. As to the ratio between the stripping part

$$(Li^6 = He^4 + d) + Li^7 \rightarrow (Li^7 + He^4 = B^{11}) + d$$

and the heavy particle stripping part

$$(Li^7 = He^5 + d) + Li^6 \rightarrow (Li^6 + He^5 = B^{11}) + d$$

only a little is known. The reduced widths for $Li^6 \rightarrow He^4 + d$ and $Li^7 \rightarrow He^5 + d$ are large but the binding energy of the $He^4 + d$ clusters in Li^6 is less than that of the $He^5 + d$ clusters in Li^7 (1.5 MeV and 9.7 MeV, respectively). Therefore, one can assume the stripping part in this reaction to be the dominant one.

The angular distribution following from the Butler theory (without account of heavy particle stripping) for the $Li^7(Li^6, d)B^{11}$ reaction with lithium ions of 2 MeV is shown in Fig. 1. The reduced α-widths $B^{11} \rightarrow Li^7 + \alpha$ are given in Table 1. Both angular distributions are determined by α-particles with $L = 2$, in the main. The angular distribution of $L = 2$ α-particles has no maximum in the forward direction in the case of the transition to the first excited level, but has a forward maximum in the case of the transition to the ground state. The difference between the two theoretical angular distributions is in a qualitative agreement with that in the experimental ones[10]. Here, it is not tried to find the best agreement with the experimental curves because only the difference between similar transitions will be discussed, which must be involved already in the theory with plane waves.

One of the most discussed angular distributions[8,11] is that of the $C^{12}(Li^6, \alpha)N^{14}$ reaction leading to N^{14} in its ground and second excited state both having $J=1$. The wave functions for these two $J=1$ levels are different from each other[12]:

$$\psi_{(\text{ground state})} = 0.950\ [442]\ ^{13}D - 0.247\ [442]^{13}S - 0.259\ [433]\ ^{11}P$$

$$\psi_{(\text{sec. exc. state})} = 0.954\ [442]\ ^{13}S + 0.243\ [442]\ ^{13}D + 0.173\ [433]\ ^{11}P \ .$$

In the first case deuterons with $L=2$ and in the second case deuterons with $L=0$ give the main contribution to the reduced deuteron width (see Table 2). In both cases the $L=0$ deuterons have a maximum in the forward direction, the $L=2$ deuterons have no such a maximum (see Fig. 2). Therefore, the observed difference[13] between the two angular distributions may be understood already in a theory with plane waves as it must be, though both reactions lead to levels of N^{14} having $J=1$.

Differences between the angular distributions of deuterons and tritons originating from the (Li^6, d) and (Li^7, t) reactions on the target nucleus B^{10} are to be expected from the fact that $\ell_{AB}=0$ for (Li^6, d) reactions

$$\sigma(\theta) \sim \frac{1}{T^2}\{q_A R_A j_{-1}(q_A R_A) + \beta_{AB} R_A j_0(q_A R_A)\}^2 \times$$

$$\times \{q_C R_C j_{\ell_{BC}-1}(q_C R_C) - (\ell_{BC} + 1 + \Lambda_{BC}) j_{\ell_{BC}}(q_C R_C)\}^2$$

$$\equiv F_{0\ell_{BC}}(\theta)$$

and $\ell_{AB}=1$ for (Li^7, t) reactions

$$\sigma(\theta) \sim \frac{1}{T^2}\{q_A R_A j_0(q_A R_A) + \frac{(\beta_{AB} R_A)^2}{\beta_{AB} R_A + 1} j_1(q_A R_A)\}^2 \times$$

$$\times \{q_C R_C j_{\ell_{BC}-1}(q_C R_C) - (\ell_{BC} + 1 + \Lambda_{BC}) j_{\ell_{BC}}(q_o R_o)\}^2$$

$$\equiv F_{1\ell_{BC}}(\theta)$$

Thus, the observed differences[2] between the angular distributions of deuterons and tritons are not in contradiction with a stripping-like mechanism of these reactions. They are connected with the fact that $R_i^2(q_A)$ is an expression of the form (4), also, in contrast to (d, p) reactions.

The deuterons and tritons from the (Li^6, d) and (Li^7, t) reactions on Li^6 and Li^7 have different angular distributions/10/, too. In these cases one can assume the differences to follow, in the main, from a different heavy particle stripping part in the two reactions. For $Li^6 + Li^6$ and $Li^7 + Li^7$ the ratio between stripping and "heavy particle stripping" part is known, and the angular distribution of these reactions regarding Coulomb interaction will be considered in a next paper.

4. Spectra

If the reaction mechanism is in the main a stripping-like one, then the spectrum of the light final product is proportional to the spectrum of the reduced widths. One has for the relative population of a level

$$\sigma \sim (2J_{BC} + 1) \sum_{\ell_{BC}} (\Theta^{BC}_{\ell_{BC}})^2 \qquad (6)$$

neglecting energy depending factors. This formula is a rough one, so for a comparison with experimental results spectra are suitable with a pronounced maximum. Spectra of such a kind have been discussed frequently in the last time. Pronounced maxima were found in the spectrum of α-particles produced in(Li^d, α) reactions on Li^6, Li^7, Be^9 targets/15,16,17/. It could be shown that in these reactions the final nucleus is formed in a relative high excited state, in the main, the energy of which is listed in Table 3.

For comparison, the spectrum of reduced deuteron widths of the Be^9 nucleus is calculated in the framework of the shell model and shown in Fig. 3. For those of the nuclei Be^8 and B^{11} see paper/18/. As can be seen, the maximum in the theoretical spectra is at the same energy as the maximum in the experimental ones. The maximum in the spectrum of reduced deuteron widths arises because some levels lie very close to one another the reduced width of each of them is not (or only a little) larger than the reduced width of the other levels in the lower energy region. A level with a marked target nucleus + deuteron structure doesn't exist. In the case of Be^8 and B^{11} the maxima are near the deuteron threshold, what was discussed earlier/18/. But in the case of Be^9 there is no correlation between threshold and maximum (Table 3). It would be very interesting to look for a second maximum near the deuteron threshold in Be^9 what could give valuable conclusions about the existence or nonexistence of threshold levels additionally to the well-known levels of the 1p-shell. ("Deuteron threshold levels" are levels with large reduced deuteron widths lying near the threshold for deuteron decay/19/.

Either there is only one level with a marked target nucleus + deuteron structure or there are some levels without a marked two particle structure but lying near one another).

Surely, in all the three considered reactions one cannot neglect heavy particle stripping. In the case of the $Li^6(Li^6, \alpha)Be^8$ reaction both the stripping and the "heavy particle stripping" parts are equal. In the other reactions the two mechanisms are different and the spectrum of α – particles depends on the relative contribution of the two mechanisms.

Stripping: $Li^7 + (Li^6 = \alpha + d) \rightarrow \alpha + (Li^7 + d = Be^9)$

$$Be^9 + (Li^6 = \alpha + d) \rightarrow \alpha + (Be^9 + d = B^{11})$$

Heavy particle stripping:

$$(Li^7 = \alpha + t) + Li^6 \rightarrow \alpha + (Li^6 + t = Be^9)$$

$$(Be^9 = \alpha + He^5) + Li^6 \rightarrow \alpha + (Li^6 + He^5 = B^{11})$$

One expects a smaller contribution of the heavy particle stripping part as compared to the stripping one, because the binding energies of the clusters in Li^7 and Be^9 are larger than those of the clusters in Li^6 (2.47 MeV and 2.53 MeV, respectively, as compared to 1.47 MeV).

For the Be^9 nucleus the spectrum of reduced triton widths corresponding to the heavy particle stripping mechanism in the $Li^7(Li^6, \alpha)Be^9$ reaction is shown in Fig. 4. The spectrum of reduced triton widths has a weaker maximum in the region of 10 to 12 MeV than the spectrum of the reduced deuteron widths. But the overall picture of the reduced widths remains the same also if both mechanisms contribute to the reaction. Especially, it remains the maximum near 12 MeV which is far from the deuteron threshold and far from the triton threshold (the difference in energy is equal to the difference in the binding energies of the corresponding clusters in Li^6 and Li^7).

A quantitative comparison of the theoretical spectra with the experimental ones shows not only whether the reaction mechanism is a stripping one but also whether the shell model gives the right reduced widths for the emission of clusters x). As is well known, the reduced cluster widths calculated in the framework of the shell model generally agree with the experimental ones. There were some difficulties only in calculating small reduced α – widths /21/ where admixtures to the pure shell model levels can give a nonnegligible contribution to the reduced widths. Because levels with not too small reduced widths are of interest in strip-

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x) There is no other method to calculate reduced cluster widths than that developed in the framework of the shell model /20,9/.

ping reactions, one may hope that the calculated reduced widths for these reactions are correct. But this assumption must be proved experimentally what has not been done, so far.

Only a little is known about the contribution of heavy particle stripping to σ_{tot} excluding the cases $Li^6 + Li^6$ and $Li^7 + Li^7$. In principle, in the $Li^6(Li^7, t)B^{10}$ reaction one could estimate the contribution of heavy particle stripping from the population of the first $T=1$ level, because this level can be populated in heavy particle stripping

$$(Li^6 = He^3 + t) + Li^7 \rightarrow t + (Li^7 + He^3 = B^{10}).$$

The $(2J+1)\Theta^2$ values for the first four levels are given in Table 4. The probability for population of the $T=1$ level is less than that for the other three levels. Therefore, one can give no more than an upper limit for heavy particle stripping (The $T=1$ level can be populated also by Coulomb mixing of the $T=0$ and $T=1$ shell model levels).

5. Conclusions

As is seen from the foregoing, the statements done in the framework of the Butler theory for lithium induced reactions are not in disagreement with the experimental data. One must not expect the theory neglecting Coulomb interactions to be in a full agreement with all experimental results. Especially, the differences between the maxima and the minima in the experimental angular distributions are less than those in the Butler theory with plane waves what is caused by Coulomb interactions, obviously.

But the theory with plane waves must explain the differences between angular distributions of similar reactions which have been observed experimentally and which do not depend on Coulomb interactions. As is shown in Sec. 3, the Butler theory with plane waves can explain such differences in a qualitative manner.

The relative excitation of the various levels of the final nucleus (or the spectrum of the light outgoing particle) is very characteristic of the reaction mechanism. It is proportional to the corresponding reduced widths, if the reaction mechanism is a stripping-like one. In Sect. 4 for some (Li^6, α) reactions the theoretical spectra of reduced deuteron widths and the experimental spectra of α-particles are compared and found to agree.

Thus, it seems justified to make the two assumptions: 1. In reactions of the type (Li^6, d), (Li^6, α), (Li^7, t), (Li^7, α) the preponderant reaction mechanism is the stripping-like one; 2. The reduced cluster widths follow from the shell model. For a more detailed discussion further experimental data are necessary.

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Table 1

Reduced α-widths for $B^{11} \to Li^{7} + \alpha$ calculated with the shell model wave functions of ref./12/

States of B^{11} JT, E [MeV]	Θ_L^2 L=0	L=2	L=4	$(2J+1)\sum_L \Theta_L^2$ (relative units)	σ_{exp} (relative units)
3/2 1/2, 0 MeV	0.17	0.39	-	1	1
1/2 1/2, 2.13 MeV	-	0.32	-	0.27	{0.68 a); 0.13 b)}

a) in $Li^{7}(Li^{6}, d)B^{11}$, E=2.1 MeV, ref./10/

b) in $Li^{7}(Li^{7}, t)B^{11}$, E= 2.1 MeV, ref./10/

Table 2

Reduced deuteron widths for $N^{14} \to C^{12} + d$ calculated with the shell model wave functions of ref./12/

States of N^{14} JT, E [MeV]		Θ_L^2 L=0	L=2	$(2J+1)\sum_L \Theta_L^2$ (relative units)	σ_{exp} (relative units)
1,0	0 MeV	0,02	0,22	1	1
1,0	3,9 MeV	0,31	(0,01	1.3	{1.1 a); 2,2 b); 1.8 c); 1.3 d)}

a) E = 1.7 MeV, ref./13/

b) E = 3.2 MeV, ref./14/

c) E = 3.6 MeV, ref./14/

d) E = 4.0 MeV, ref./14/

Table 3

The position of the maximum in the spectra of α-particles from the (Li^6, α) reactions on Li^6, Li^7, Be^9 and in the corresponding spectra of reduced deuteron widths for Be^8, Be^9, B^{11}.

Reaction	Position of the maximum (exp) [MeV]		Position of the maximum (theor.) [MeV]	Threshold for deuteron decay [MeV]
$Li^6(Li^6, \alpha)Be^{8*}$	20.7	a)	20 - 21	22.3
$Li^7(Li^6, \alpha)Be^{9*}$	11.9	b)	11	16.7
$Be^9(Li^6, \alpha)B^{11*}$	13.2	c)	12 - 13	15.8

a) ref./15/, b) ref./16/, c) ref. /17/

Table 4

$(2J+1)\sum_L \Theta_L^2$ for $B^{10} \to Li^7 + He^3$ and for $B^{10} \to Li^6 + He^4$ calculated with the shell model wave functions of ref./12/

States of B^{10} JT, E [MeV]	$(2J+1)\sum \Theta_L^2$ for $B^{10} \to Li^7 + He^3$ (relative units)	$(2J+1)\sum \Theta_L^2$ for $B^{10} \to Li^6 + \alpha$ (relative units)	σ_{exp} (relative units) $Li^6(Li^7, t)B^{10}$	$Li^6(Li^6, d)B^{10}$
3; 0; 0 MeV	1	1	1	1
1; 0; 0.72MeV	0.32	15.55	5.9 a)	5.0 a)
0; 1; 1.74 MeV	0.08	-	$\leq$ 0.12 b)	< 0.1 b)
1; 0; 2.15 MeV	0.36	18.05	14.2 b)	6.8 b) 8.1 c)

a) E = 2.1 MeV, ref. /10/

b) E = 2.6 to 3.6 MeV, ref./22/, in relation to σ_{exp} of the first (1,0) level of ref./10/.

c) E = 1,2 to 2.8 MeV, ref./23/, in relation to σ_{exp} of the first (1,0) level of ref./10/

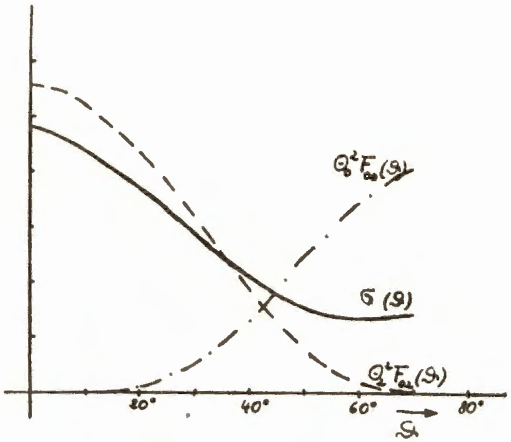

Fig. 1a. $\Theta_L^2 F_{0L}$ and $\sigma = \sum_L \Theta_L^2 F_{0L}$ for L=0 and L=2 deuterons from the $Li^7(Li^6,d)B^{11}$ reaction leading to B^{11} in its ground state (E=2 MeV, $R_A = R_C = 4$ fm shell model wave functions from ref/12/).

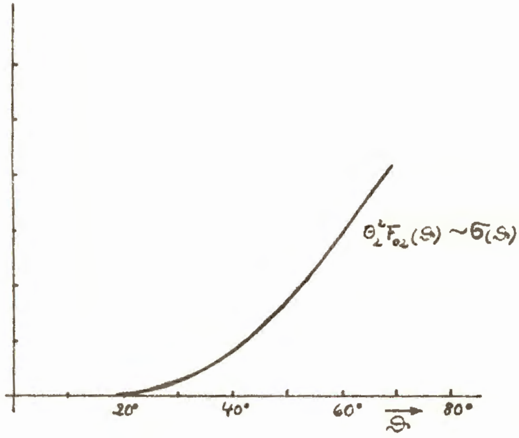

Fig. 1b. $\Theta_L^2 F_{0L}$ for L=2 deuterons from the $Li^7(Li^6,d)B^{11}$ reaction leading to B^{11} in its first excited state (E=2 MeV, $R_A = R_C = 4$ fm , shell model wave functions from ref./12/).

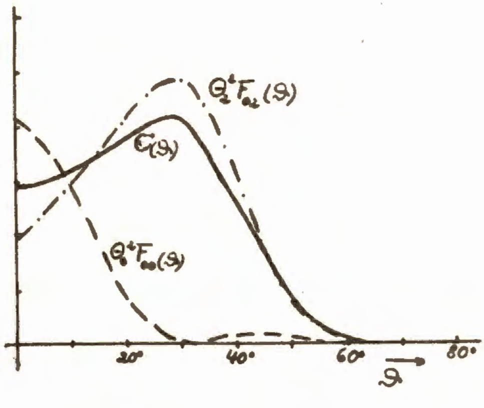

Fig. 2a. $\Theta_L^2 F_{0L}$ and $\sigma = \sum_L \Theta_L^2 F_{0L}$ for L = 0 and L = 2 α-particles from the $C^{12}(Li^6,\alpha)N^{14}$ reaction leading to N^{14} in its ground state (E = 3.5 MeV, $R_A = R_C = 4$ fm , shell model wave functions from ref./12/).

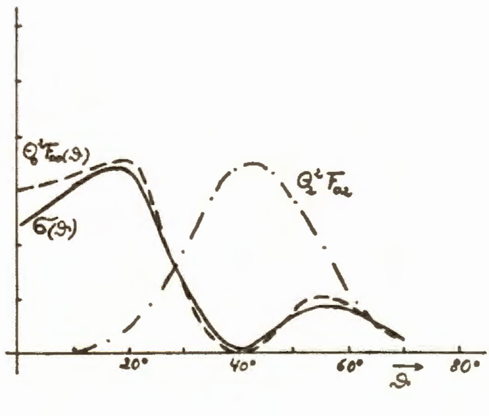

Fig. 2b. $\Theta_L^2 F_{0L}$ and $\sigma = \sum_L \Theta_L^2 F_{0L}$ for l = 0 a nd L = 2 α-particles from the $C^{12}(Li^6,\alpha)N^{14}$ reaction leading to N^{14} in its second excited state (E = 3.5 MeV, $R_A = R_C = 4$ fm , shell model wave functions from ref./12/).

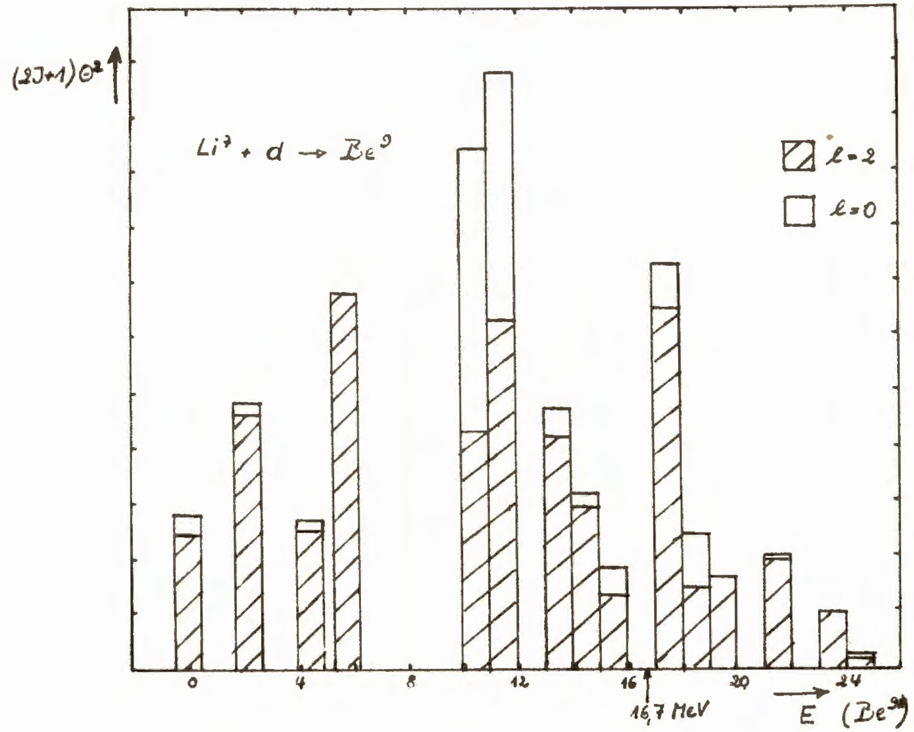

Fig. 3. The spectrum of reduced deuteron widths $Be^{9} \rightarrow Li^{7} + d$ calculated with the shell model wave functions from ref./12/.

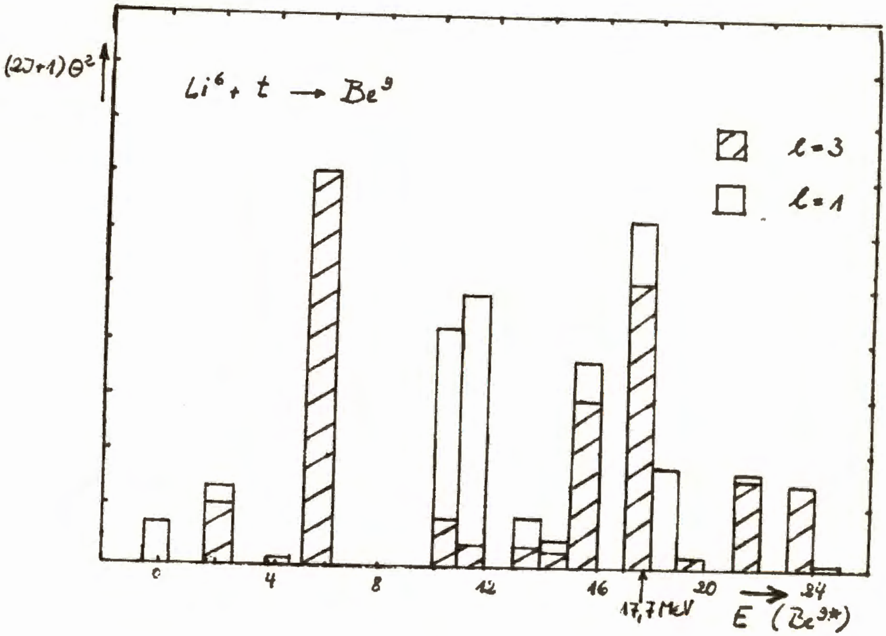

Fig. 4. The spectrum of reduced triton widths $Be^9 \to Li^6 + t$ calculated with the shell model wave functions from ref. /12/;