New broad ^{8}Be resonances from S-matrix poles

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R-matrix fit to experimental data

Thanks to G.M. Hale

- Most comprehensive
- ^{4}He α, ^{7}Li p, ^{7}Be n, ^{6}Li d $\rightarrow$ ^{4}He α, ^{7}Li p, ^{7}Be n, ^{6}Li d Data:11
- Cross-sections:
  - Total (plotted)
  - Differential
  - Polarization Data
- > 4700 data points
- 69 references
- ~100 parameter fit
- χ^2 / d.o.f. = 7.4
- Up to E_X = 25-26 MeV

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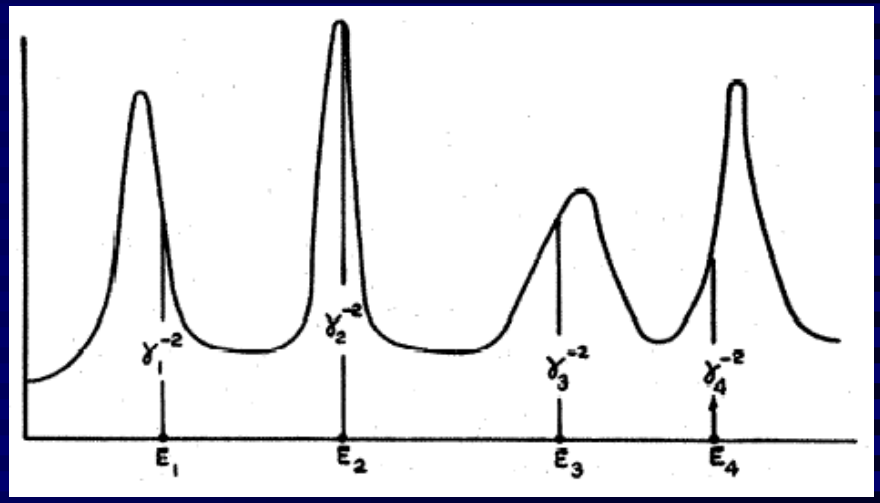
Features of R-matrix theory



Restrictions

- Non-relativistic
- Two initial & two final particles

Inclusions

- Rigorous
- Multichannel & Unitary
- Smooth "background" processes $\Leftrightarrow$ infinite # resonances

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S-matrix poles

R real, S complex

$$S_{c'c} = \frac{I_c(a_c, k_c)}{O_c(a_c, k_c)}\delta_{c'c} + i\sum_{\mu}\frac{g_{\mu c'}\,g_{\mu c}}{\mathcal{E}_{\mu}(E) - E}$$

$$g_{\mu c} = \frac{\sqrt{2k_c a_c}\mathcal{G}_{\mu c}(E)}{O_c(a_c, k_c)}$$

$$E_x \equiv Re[\mathcal{E}_{\mu}(E^*)] \qquad \Gamma \equiv 2\,Im[\mathcal{E}_{\mu}(E^*)]$$

$$\Gamma_c \equiv |g_{\mu c}|^2 = 2\,|k_c^*|\,a_c\,|\mathcal{G}_{\lambda c}(E^*)/O_c(a_c, k_c^*)|^2$$

$$\gamma_c \equiv |\mathcal{G}_{\lambda c}(E^*)|$$

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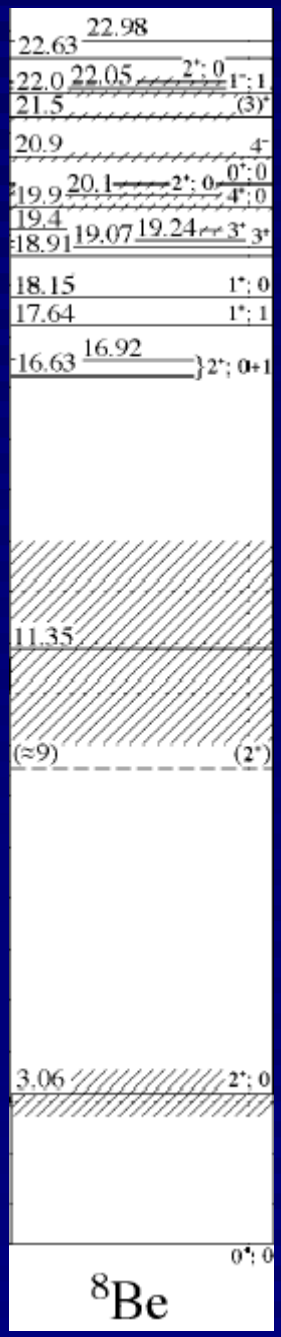

4+0

2+0

2+0

0+0

6Li d

7Be n

7Li p

αα

8Be resonances

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All J^{π}

T=0,1

Agree √

R-m. > Exp.

Thanks G.M.Hale

$J^{\pi}T$	E_x (MeV)		Γ (keV)		i	
	R-m.	Exp.	R-m.	Exp.	%	
0^+0	[0.01]	0	[0.01]	0.00557(25)	[0]	†‡
	20.13	20.2	750	720(20)	0	†‡
1^+0	18.17	18.150(4)	140	138(6)	1	†‡
1^+1	17.66	17.640(1)	10	10.7(5)	0	†‡
1^+1	20.45	-	690	-	0	†
2^+0	2.77	3.03(1)	1200	1513(15)	[0]	†‡
	16.40	-	19200	-	0	†II
	20.10	20.1	680	880(20)	4	†‡
	22.09	22.2	590	≈ 800	0	†‡
	22.78		1670		0	¶
	23.25	25.2	2000	-	0	†
3^+0	19.24	19.24	170	227(16)	29	†‡
3^+1	19.02	19.07	270	270(20)	30	†‡
4^+0	11.57	11.35(15)	4400	≈ 3500	0	†‡
	17.59	-	7900	-	0	†II
	24.35	25.5	4600	broad	0	†
1^-0	19.33	19.4	650	≈ 645	13	
2^-1	18.92	18.91	120	122	2	
3^-0	21.35	21.5	950	1000	0	
4^-0	21.50	20.9	1060	1600(200)	0	

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Partial width

Reduced width ampl.

$J^\pi T(E_x)$	Γ_c (keV)	$g_c \times 100$ ($\sqrt{\text{MeV}}$)
0^+	$\alpha\,1s$ $p\,3p$ $n\,3p$ $d\,5d$ $d\,1s$	
$0^+0(0)$	[0.010]	[82]
$0^+0(20)$	550 40 120	24 25 53 86 61
1^+	$p\,5p$ $p\,5f$ $p\,3p$ $n\,5p$ $n\,5f$ $n\,3p$ $d\,5d$ $d\,3s$ $d\,3d$	
$1^+0(18)$	81 0.00008 60	91 4 78
$1^+1(18)$	5 0.00008 6	65 27 69
$1^+1(20)$	220 23 160 170 4 80	51 182 44 55 181 38 5 1 4
2^+	$\alpha\,1d$ $p\,5p$ $p\,5f$ $p\,3p$ $p\,3f$ $n\,5p$ $n\,5f$ $n\,3p$ $n\,3f$ $d\,5s$ $d\,5d$ $d\,3d$ $d\,1d$	
$2^+0(3)$	910	100
$2^+0(16)$	1930	170 17 13 54 13 17 14 54 13 10 65 31 11
$2^+0(20)$	170 130 20 130 0.06 140 2 100 0.02	14 43 213 43 11 59 180 50 21 21 25 45 25
$2^+0(22)$	110 240 9 10 7 280 5 10 4	11 42 55 9 46 49 61 10 52 36 68 49 14
$2^+0(23)$	40 290 2 20 0.8 260 2 20 0.3 230 70 30 4	7 45 17 11 13 46 29 13 10 69 35 24 8
$2^+0(25)$	70 930 20 20 4 880 20 30 2 50 40 30 2	9 79 61 10 25 80 79 14 24 29 22 18 5
3^+	$p\,5p$ $p\,5f$ $p\,3f$ $n\,5p$ $n\,5f$ $n\,3f$ $d\,5d$ $d\,3d$	
$3^+0(19)$	130 0.07 0.4 7 0.001 0.009	56 24 57 98 43 131
$3^+1(19)$	320 0.3 2 3 0.0001 0.0004	96 60 157 30 43 82
4^+	$\alpha\,1g$ $p\,5f$ $p\,3f$ $n\,5f$ $n\,3f$ $d\,5d$	
$4^+0(11)$	4000	135 17 28 17 27 0.6
$4^+0(18)$	5300 2 4	135 33 50 33 50 3
$4^+0(24)$	50 40 70 30 60 800	9 60 77 59 77 107
1^-	$p\,5d$ $p\,3s$ $p\,3d$ $n\,5d$ $n\,3s$ $n\,3d$ $d\,5p$ $d\,3p$ $d\,1p$	
$1^-(19)$	44 230 110 4 280 9	101 45 158 101 65 156
2^-	$p\,5s$ $p\,5d$ $p\,3d$ $n\,5s$ $n\,5d$ $n\,3d$ $d\,5p$ $d\,3p$	
$2^-(19)$	3 0.4 73 80 0.03 0.08	5 14 178 58 127 208
3^-	$p\,5d$ $p\,3d$ $n\,5d$ $n\,3d$ $d\,5p$	
$3^-0(21)$	220 340 120 190	96 119 95 120 4
4^-	$p\,5d$ $n\,5d$	
$4^-0(21)$	610 350	153 153

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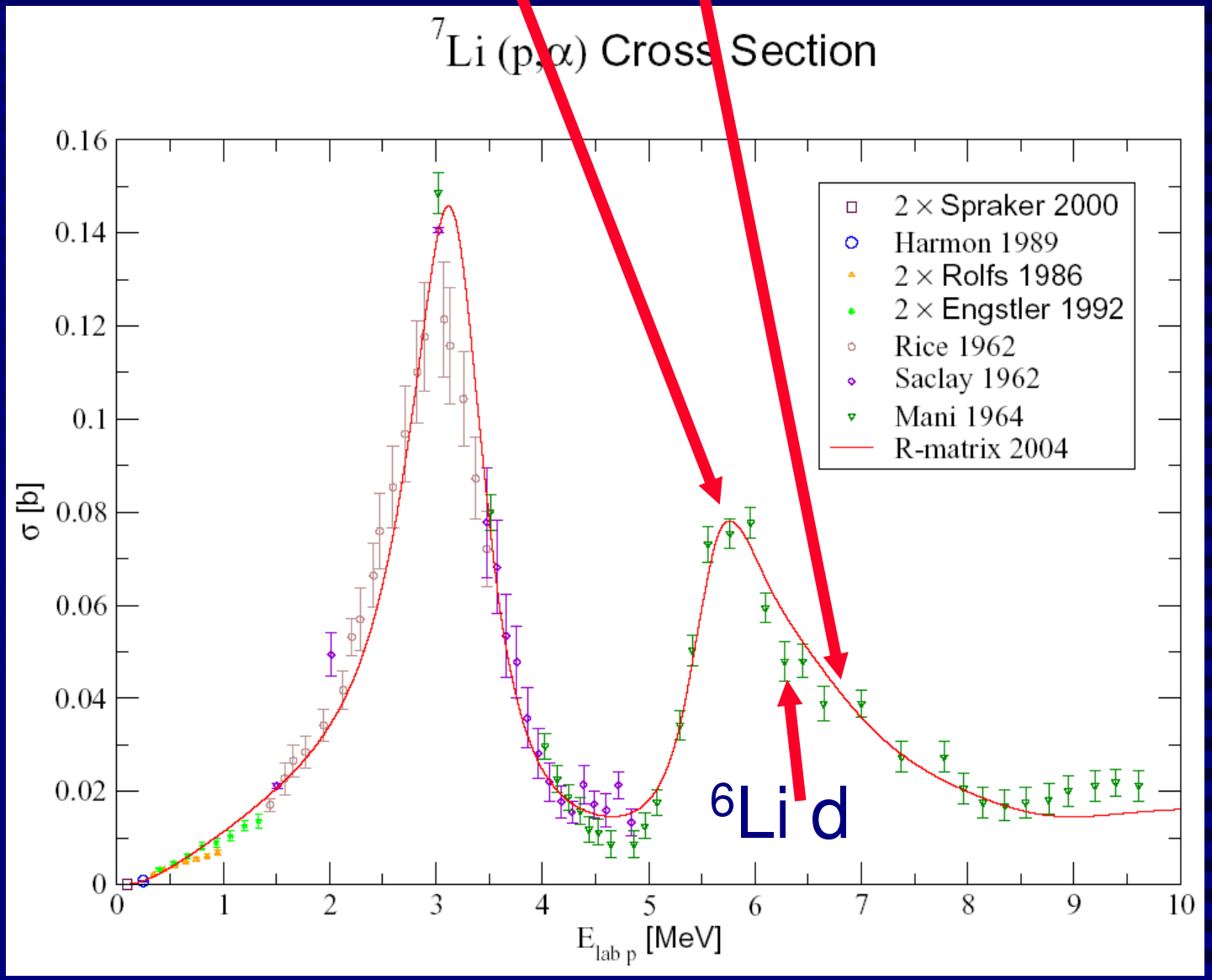
2^+ 0(22) & 2^+ 0(23)



2^+ 0(22) known

Also: Inverse

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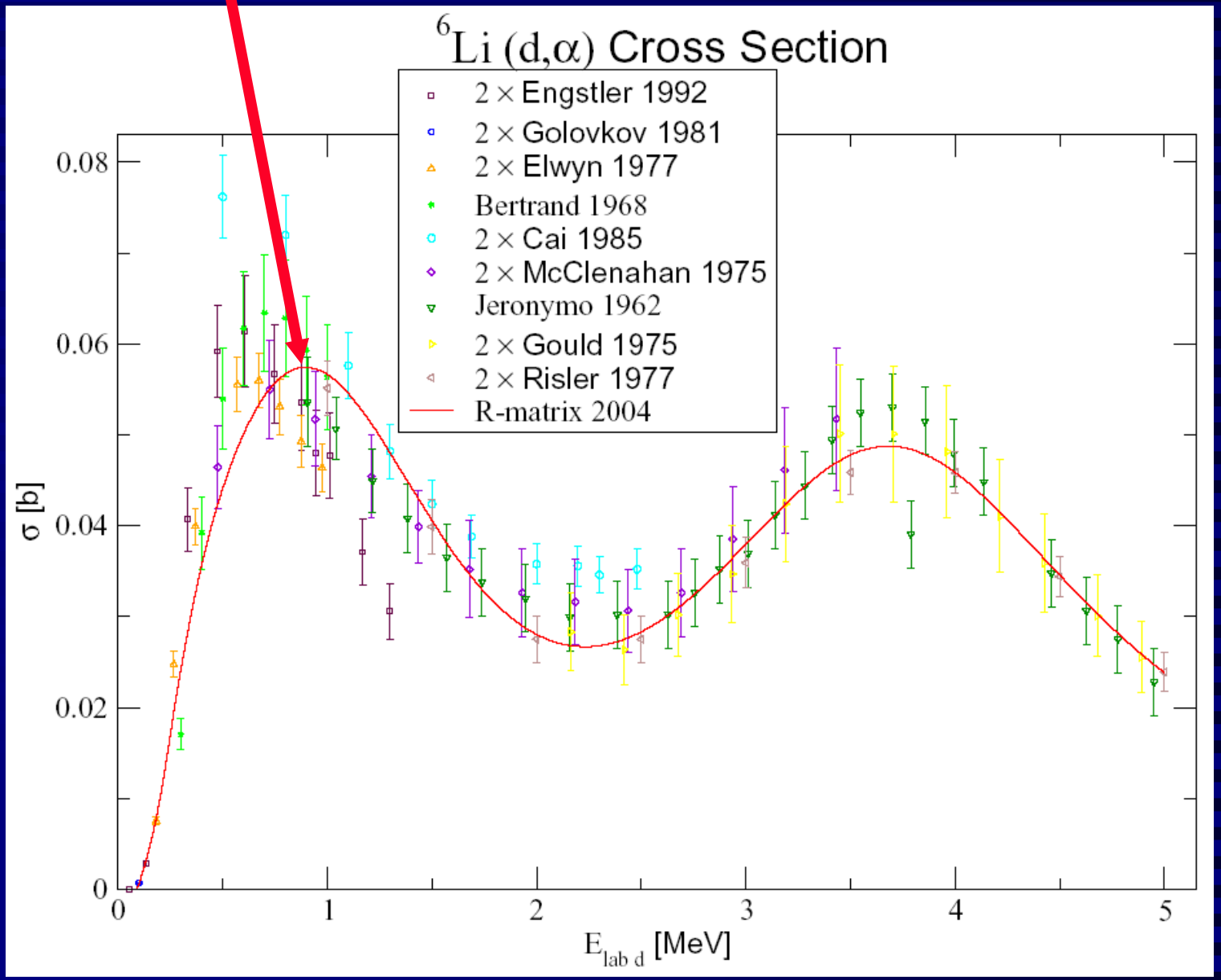
2^+ 0(23)



Also:

^{6}Li (d,p)

^{6}Li (d,n)

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Conclusions

- ^{8}Be resonance parameters to 26 MeV
- π T = - 0 of J=3 21 MeV determined
- T of 4^- & 1^- (19) determined
- Previous 22 MeV 2^+ 0 is two
- Extremely *broad* 2^+ 0(16) confirmed
- Very broad 4^+ 0(18) discovered
- 1^+ 1(20) discovered

END

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Resonances not found

- Narrow $2^+(16.6; 16.9),\ 1^+1(17)$ and $2^-(19)$
- Broad $4^+0(20),\ 1^-?(19),\ 1^-1(22),\ (1,2)^-1(24)$

three resonances in the region $22 - 23$ MeV with unknown $J^\pi T$

^{4}He (α,α) data not available

Should be found

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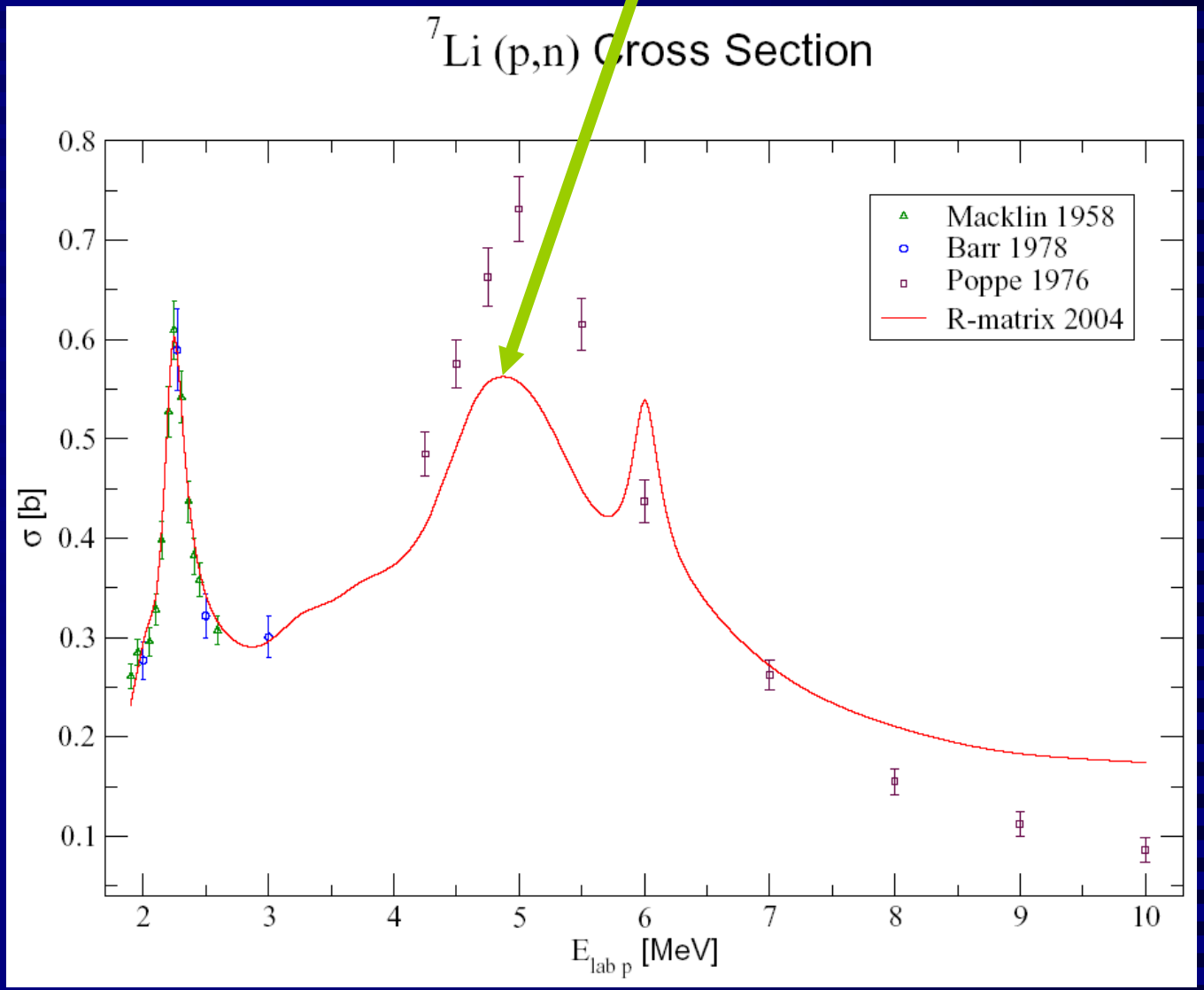
π T of J=3 21 MeV determined



Exp: $3^{(+)}$

R-m: 3^{-} 0

Old data

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Is extra 2^+ state consistent?

- √ ^{6}Li (d,α) analysis below 1 MeV only found 2^+ 0(22) *Czerski et al.1997*
- √ Two 2^+ resonances at 21.5 & 22.5 MeV in ^{7}Li (p,p_1) & ^{7}Li (p,n_1)

  Presser, Bass 1972
- ✗ Not in NCSM

  Caurier, Navratil, Ormand, Vary 2001

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Extremely broad 2^+ 0(16) confirmed

- √ R-matrix: ^{4}He (α,α), ^{9}Be (p,d), ^{8}Li, ^{8}B @ 9 MeV *Barker et al. 1968,69,88,89,2000* ?
- √ R-matrix: ^{4}He (α,α), ^{8}Li, ^{8}B. Not up to 26 MeV *Warburton 1986*

Energy varies as new data included ?

- √ NCSM: 14-21 MeV
- ✗ GFMC: Not up to 22 MeV ?

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Very broad 4^+0(18) discovered

- E_x=17.59 MeV
- Γ =7.9 MeV

√ NCSM: 20-26 MeV

✗ GFMC: Not up to 19 MeV

Pieper, Wiringa, Carlson 2004

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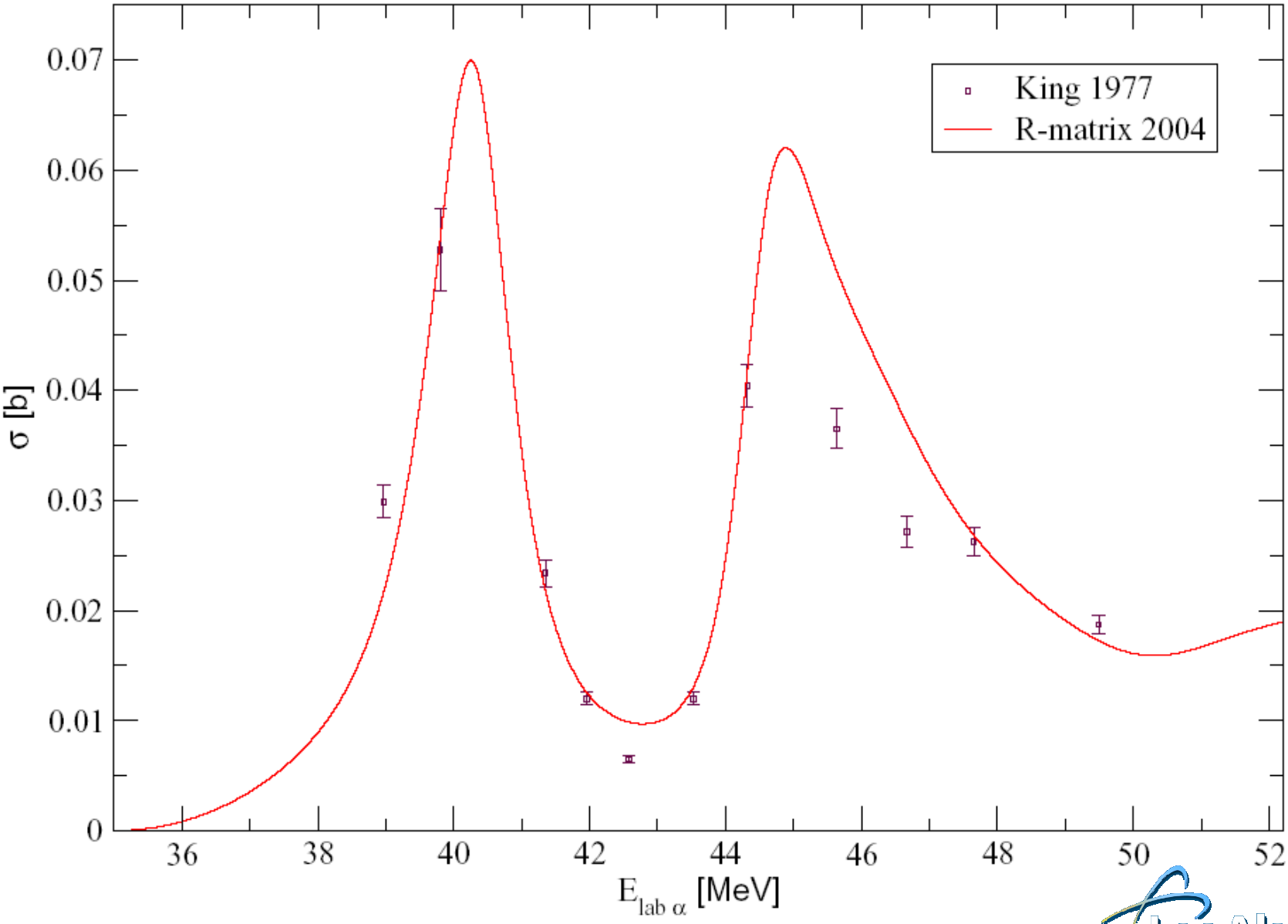
^{4}He (α,p) Cross Section



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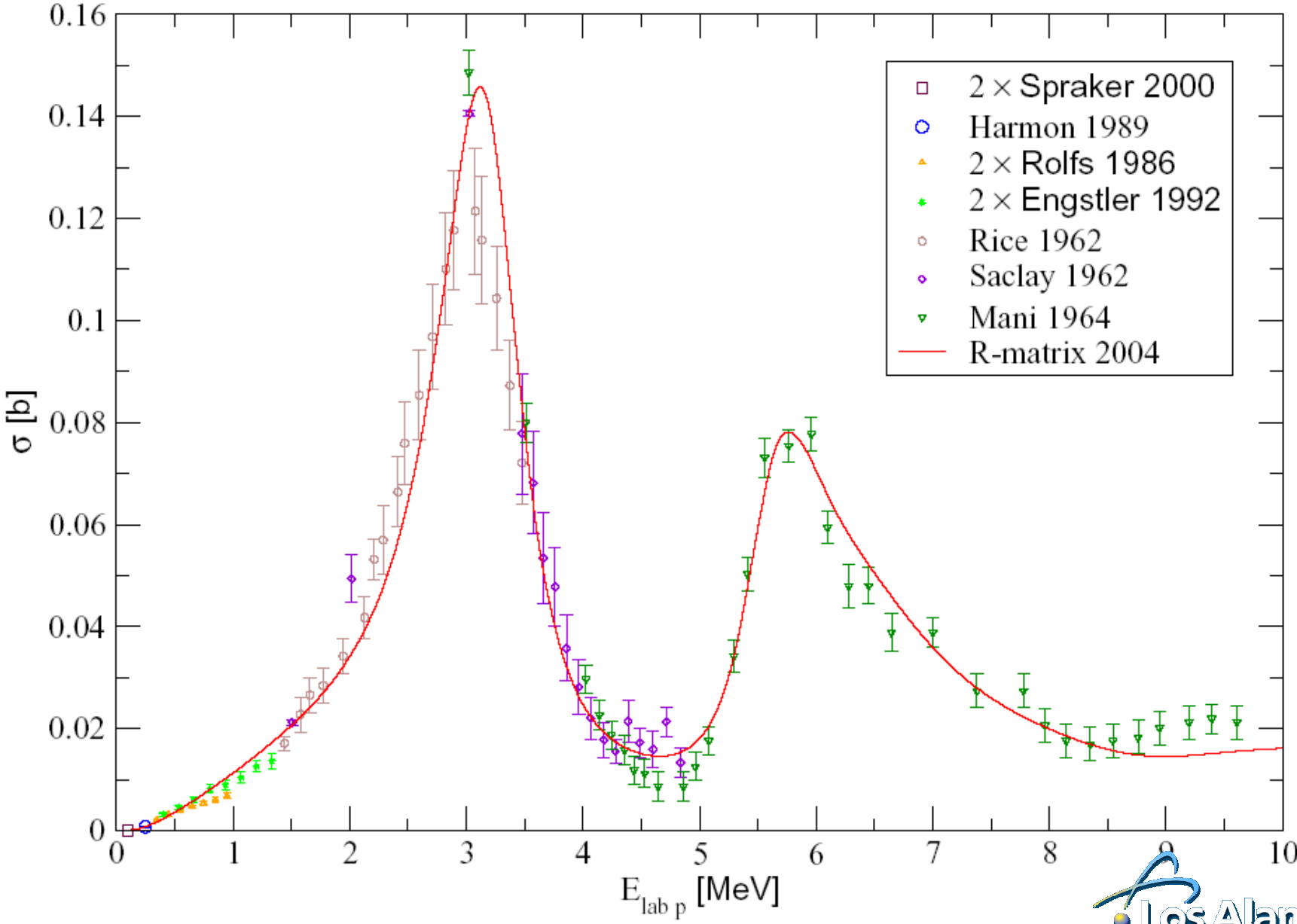
^{7}Li (p,α) Cross Section



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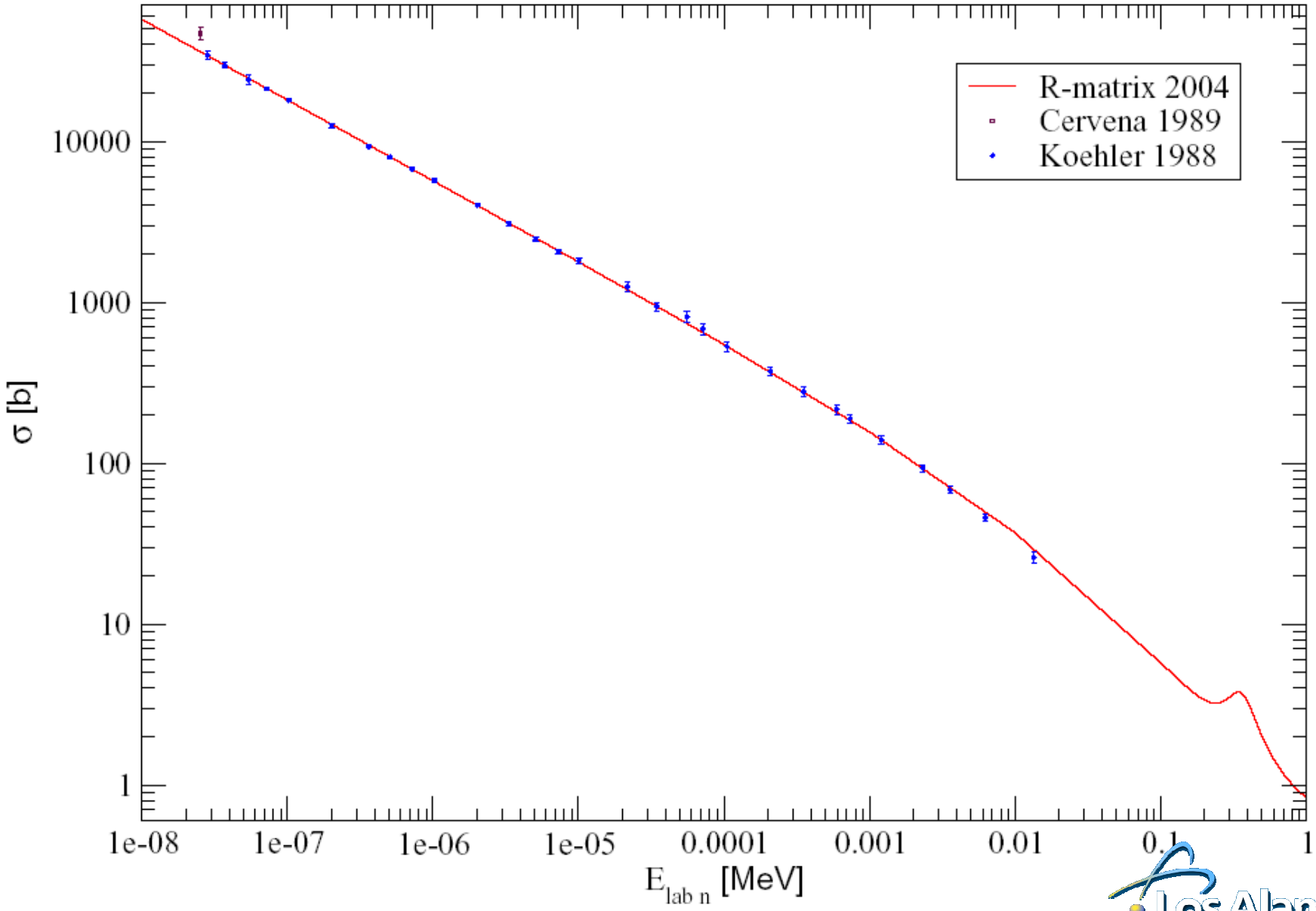
^{7}Be (n,p) Cross Section



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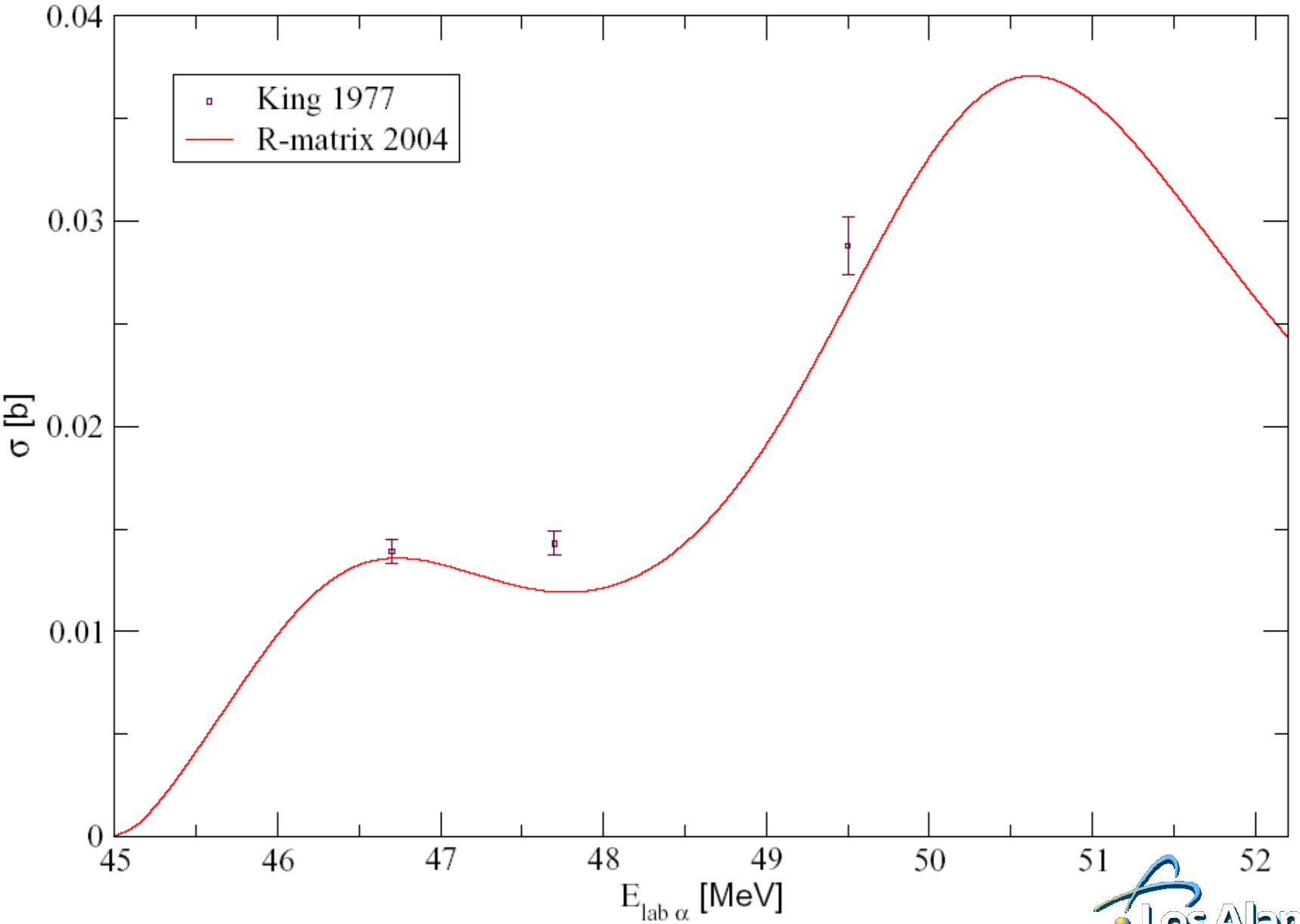
^{4}He (α,d) Cross Section



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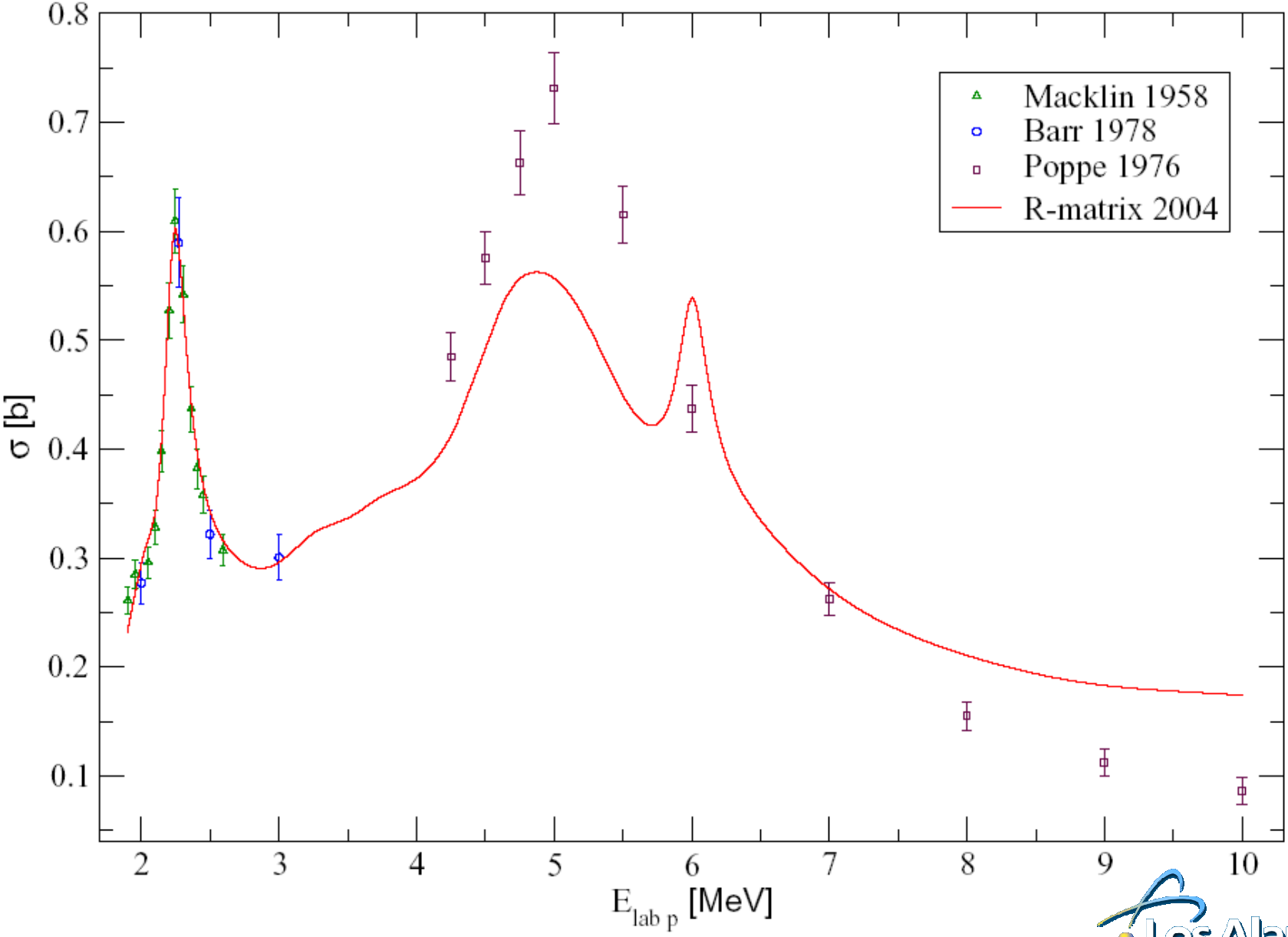
^{7}Li (p,n) Cross Section



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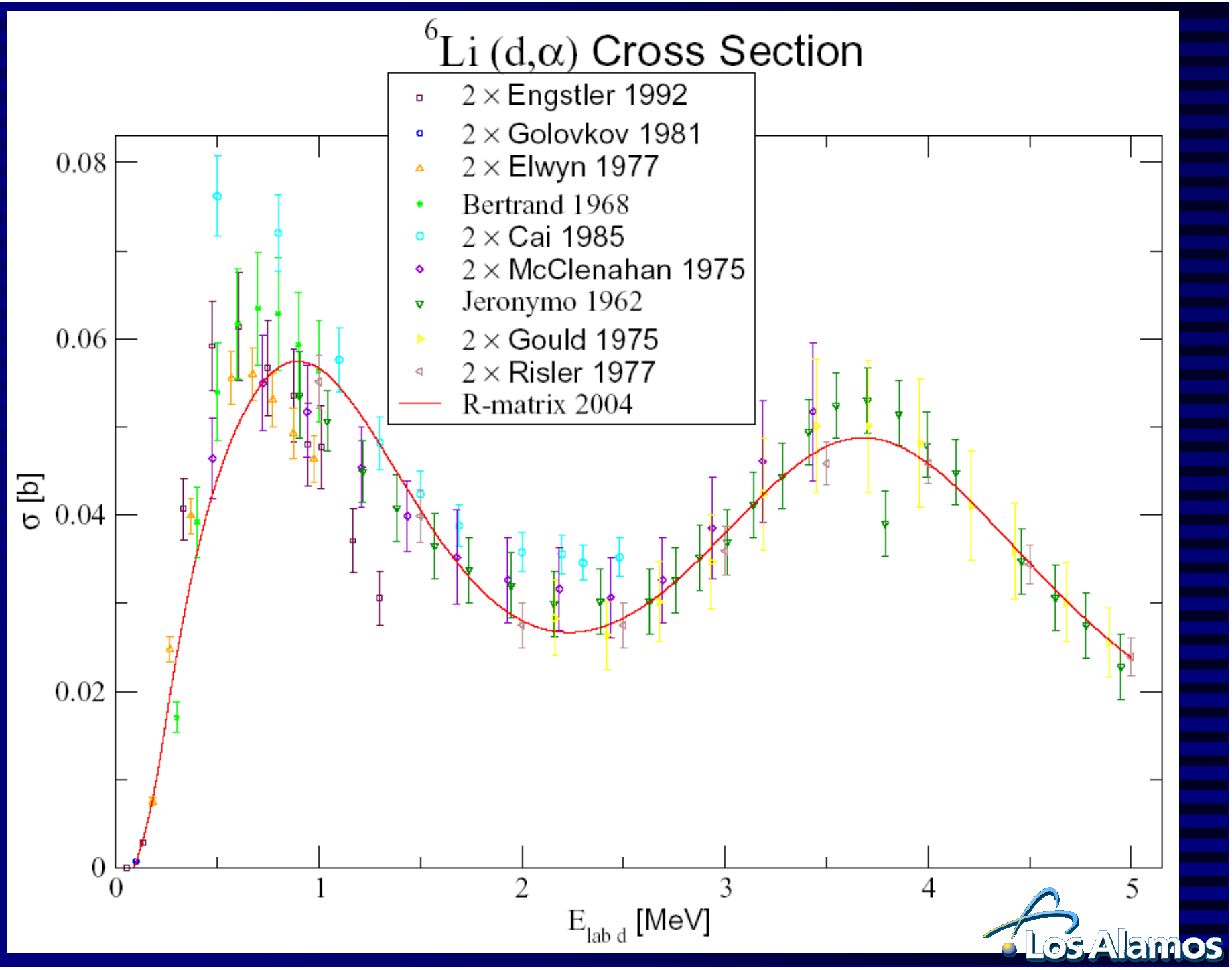
^{6}Li (d,α) Cross Section
2 × Engstler 1992
2 × Golovkov 1981
2 × Elwyn 1977
Bertrand 1968
2 × Cai 1985
2 × McClenahan 1975
Jeronymo 1962
2 × Gould 1975
2 × Risler 1977
R-matrix 2004
σ [b]
0.08
0.06
0.04
0.02
0
0
1
2
3
4
5
$E_{lab\ d}$ [MeV]
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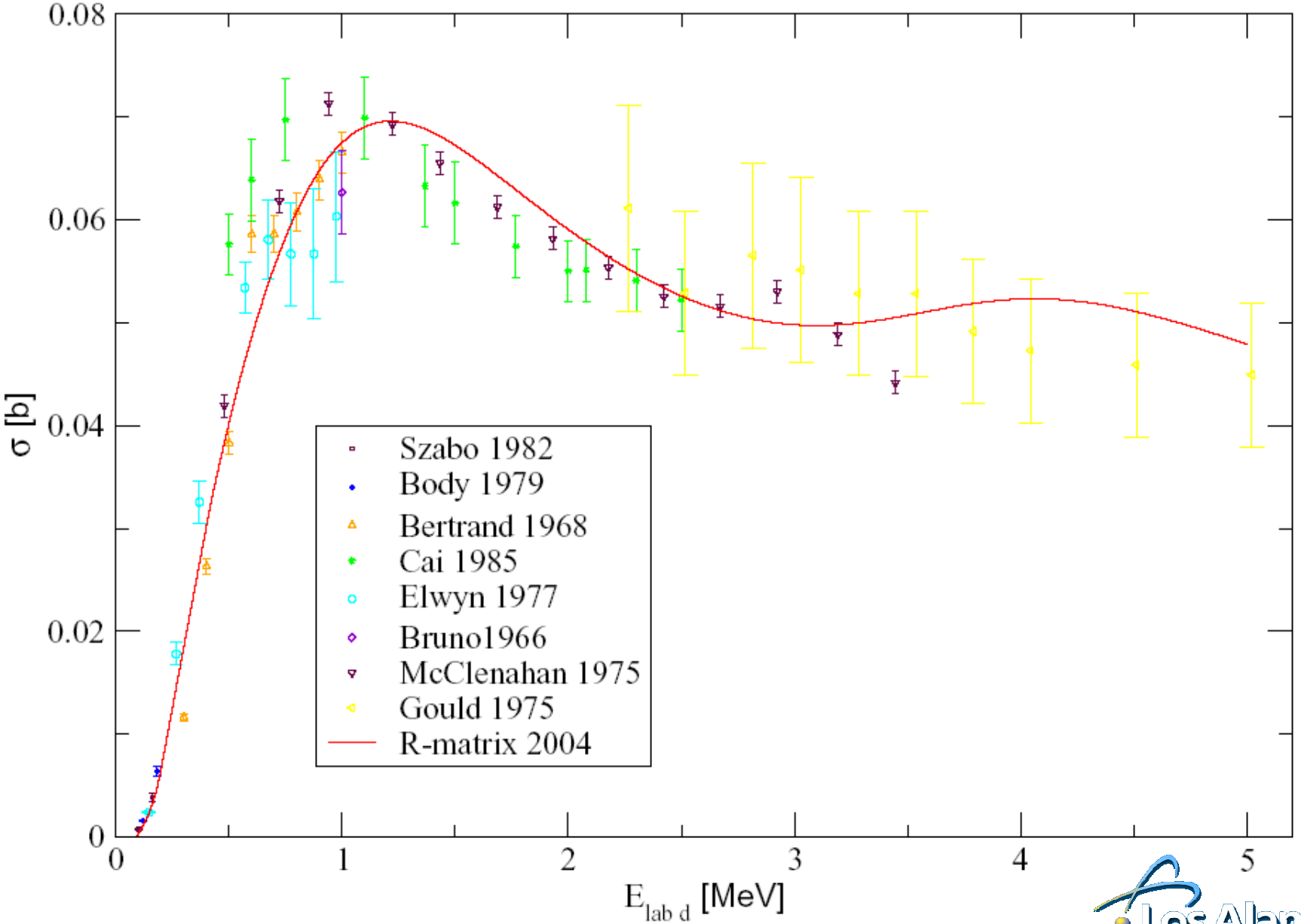
^{6}Li (d,p) Cross Section



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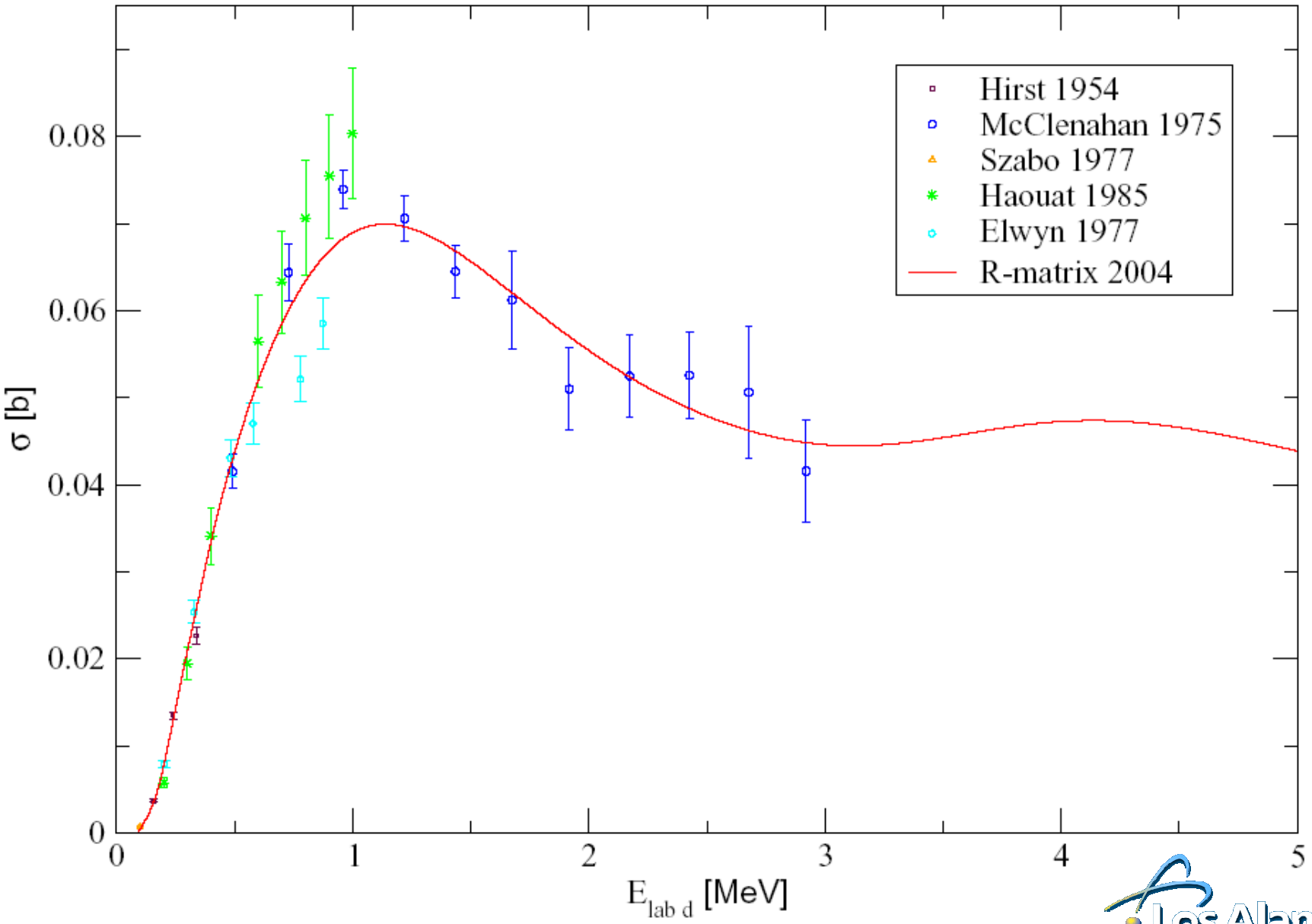
^{6}Li (d,n) Cross Section



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