

LFN @ LATR: NRA

Detecção de B em materiais tecnológicos por reacções nucleares

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DECN-IST, 06 Dez 2023

Detecção de Li em materiais tecnológicos por reacções nucleares

A fim de compreender e perspetivar de forma integradora e interligada a Física Nuclear e as suas potenciais aplicações tecnológicas, nas vertentes das reacções nucleares e detecção de elementos leves de grande importância tecnológica, como é o caso do boro, este projecto envolve...

Trabalho e objectivos:

- compreensão da física das dispersões elásticas e inelásticas (reacções nucleares): fundamentação, realização prática e resultados espectáveis – espectros
- separação das contribuições elástica, EBS, e inelástica, NRA
- aplicação à caracterização de materiais a nível microscópico: informação pertinente – composição elementar, quantificação, estrutura e espessura – e extracção da informação pertinente: análise dos espectros
- familiarização com a cadeia electrónica de detecção: fundamentação e realização prática – detectores de radiação, processadores de sinal e analisadores multicanal
- familiarização com o equipamento de produção e transporte de feixes de partículas: acelerador, campos deflectores e linhas de transporte
- montagem das amostras a utilizar com operação (limitada) dos sistemas de vácuo; estabelecimento de condições de operação, irradiação das amostras e recolha de dados

Análise de dados e resultados a atingir:

- análise (sumária) de espectros com calibração (conversão canal-energia) e identificação da composição elementar: identificação de elementos de $Z \geq 11$ por EBS, identificação de elementos de ^{11}B , $Z < 11$ (e.g. $^6,^7\text{Li}$ e $^{10,^{11}}\text{B}$) – por NRA
- quantificação integral de B detectado a partir de cálculo simples
- apresentação de resultados

Detecção de B em materiais tecnológicos por reacções nucleares

Justificação do Li:

o lítio – $\sim 2.5\%$ ${}^6\text{B}$ e 97.5% ${}^7\text{Li}$ - é um elemento com aplicações relevantes em áreas de grande importância e impacto tecnológico, nomeadamente:

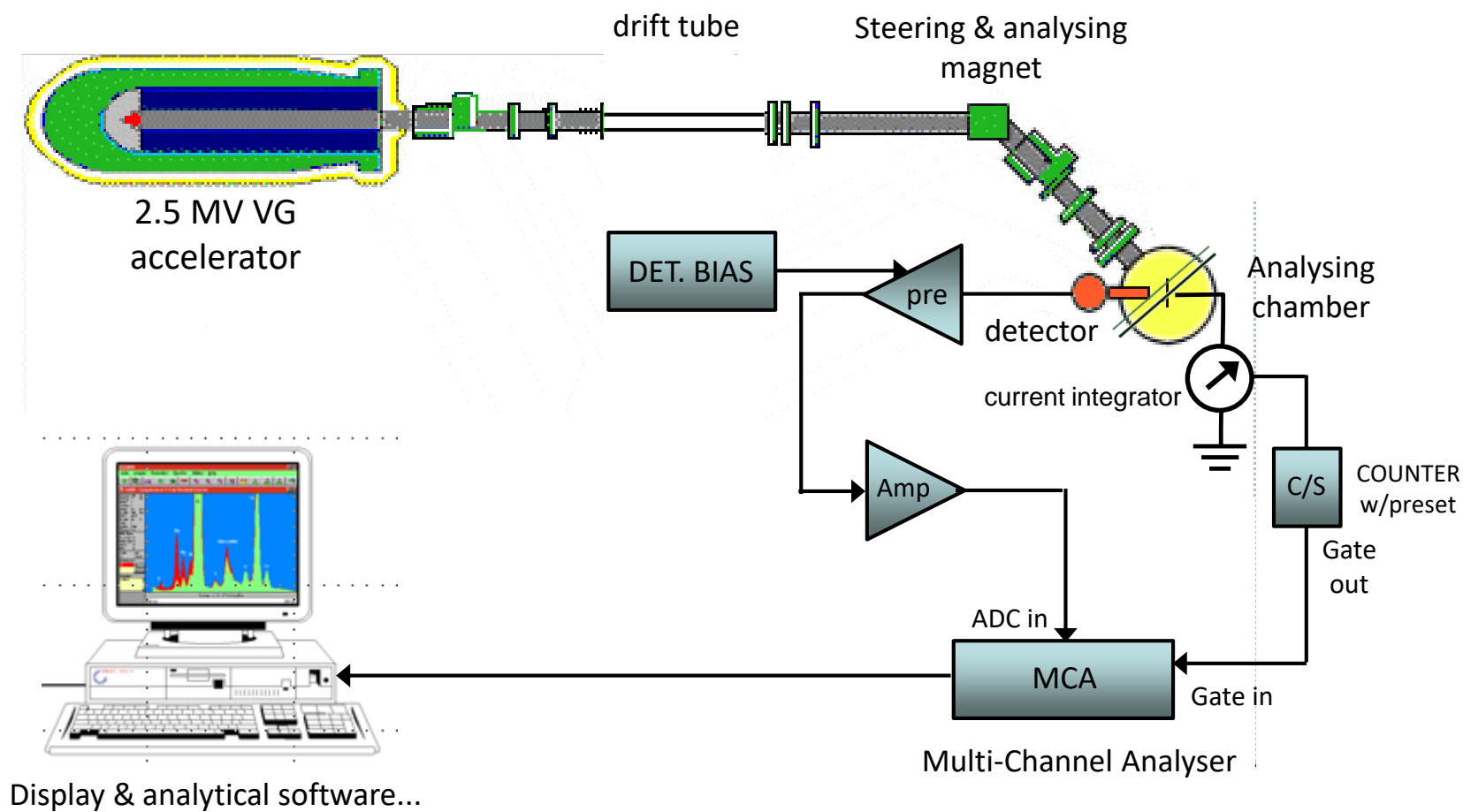
- farmácia: tratamento de transtorno bipolar, depressão nervosa ...
- energética: electrólitos sólidos para baterias;
- metalurgia: ligas leves para uso, por exemplo, em aeronáutica;
- óptica: diminuição de índice de refração
- vidros/cerâmicas: diminuição de ponto de fusão, coeficiente de expansão térmica ...
- purificação do ar: em ambientes reduzidos
- fusão nuclear: produção de trítio;
fontes de neutrões;

...

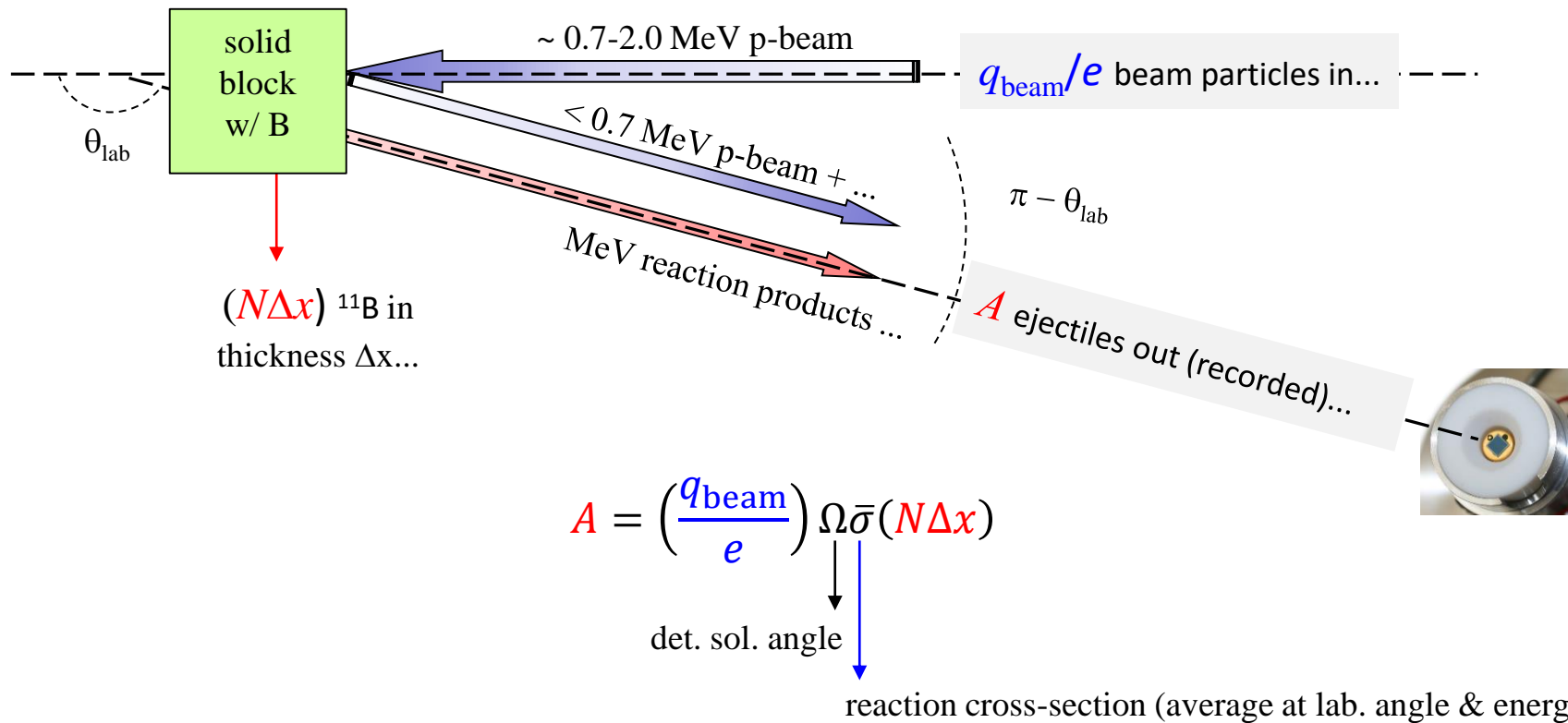
Justificação das reacções nucleares:

pela sua especificidade – ditada p/ estrutura nuclear dos isótopos envolvidos – são praticamente o único meio de detectar, de forma não destrutiva (preservando qto possível a amostra) isótopos leves ($Z < 12$) a energias baixas (e.g. $< 3\text{-}5$ MeV, disponíveis em "pequenos" aceleradores): em geral, a razão sinal-ruído é favorável (p/ ausência de fundo significativo) e, quando existem, as interferências de outras reacções (devidas a outros isótopos), são pouco significativas.

The 'production' chain...

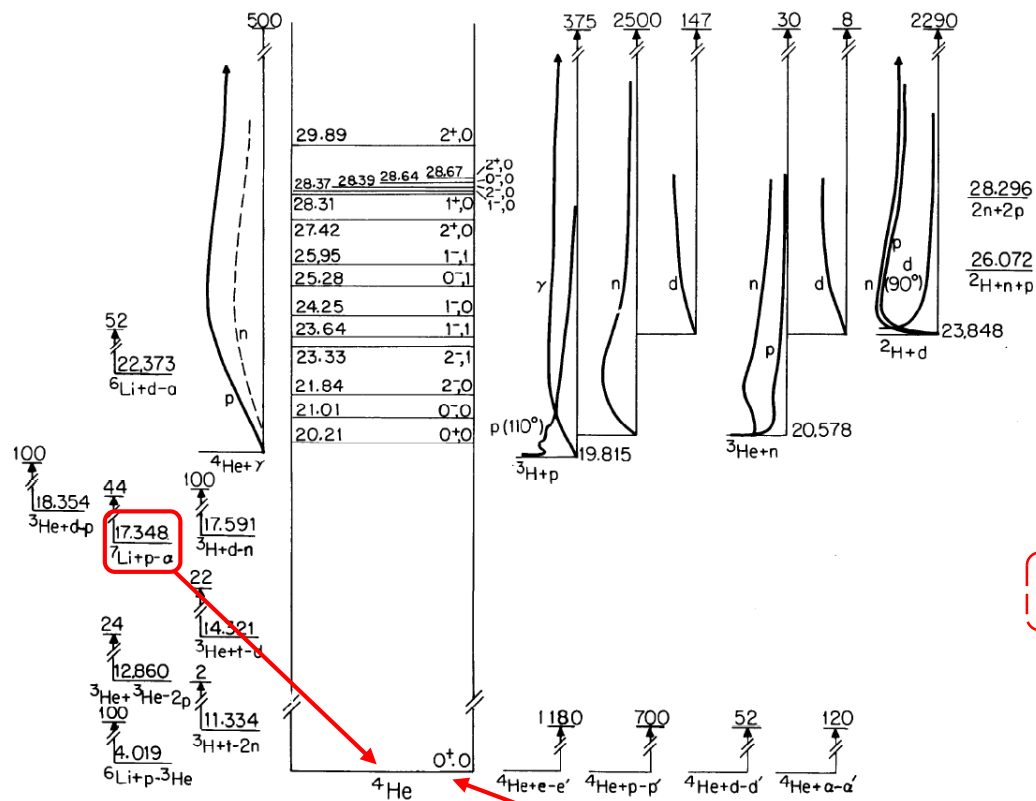


The experiment layout...



$N\Delta x$ "wanted" !

The reaction...



$I\pi = 0^+, \Gamma = 0.0000 \text{ eV}$

The reaction ...

NRA CALCulator

(C) R.C. da Silva (DECN/IST, 2019)

Type reaction as ${}^A\text{X}(a,b){}^A\text{Y}$:

EXAMPLES: type ${}^9\text{Be}(p,\alpha){}^6\text{Li}$ as ${}^9\text{Be}(p,a){}^6\text{Li}$ or ${}^9\text{Be}(p,4\text{He}){}^6\text{Li}$

(Target ${}^A\text{X}$ taken as stationary in laboratory frame)

type ${}^{241}\text{Am}(g,a)$ for α decay of ${}^{241}\text{Am}$

type ${}^{241}\text{Am}(g,p/n)$ for p/n separation energy

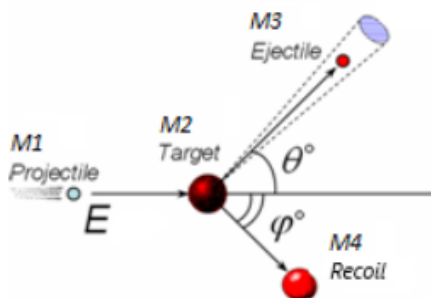
type ${}^{70}\text{Ga}(+e,g)$ for E.C. decay of ${}^{70}\text{Ga}$

type ${}^{70}\text{Ga}(g,e-/e+)$ for β^-/β^+ decay of ${}^{70}\text{Ga}$

PRIMARY ION energy E/MeV =

Recoil/Daughter EXCITED STATE energy/MeV =

SCATTERING ANGLE/ejectile angle θ /degrees =



CALC

LAB OUTPUTS: _____ ZMF OUTPUTS: _____

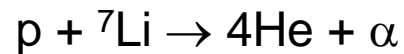
The reaction ...

NRA CALCulator

(C) R.C. da Silva (DECN/IST, 2019)

Type reaction as ${}^A\text{X}(a,b){}^A\text{Y}$

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type ${}^{241}\text{Am}(g,a)$ for α decay of ${}^{241}\text{Am}$

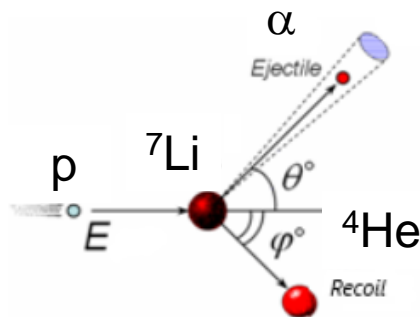
type ${}^{241}\text{Am}(g,p/n)$ for p/n separation energy

type ${}^{70}\text{Ga}(+e,g)$ for E.C. decay of ${}^{70}\text{Ga}$

type ${}^{70}\text{Ga}(g,e-/e+)$ for $\beta-/+$ decay of ${}^{70}\text{Ga}$

Recoil/Daughter EXCITED STATE energy/MeV =

SCATTERING ANGLE/ejectile angle $\theta/\text{degrees}$ =



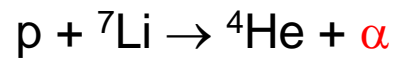
CALC

LAB OUTPUTS: _____ ZMF OUTPUTS: _____

?

The reaction ...

Só há um canal possível para a reacção:



$E_{\text{g.s.}} = 0 \text{ MeV}$

Calcule $Q = ?$

Calcule $T_{\alpha_0} (2 \text{ MeV} ; \theta_{\text{lab}} = 165^\circ) = ?$

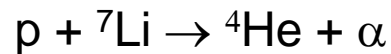
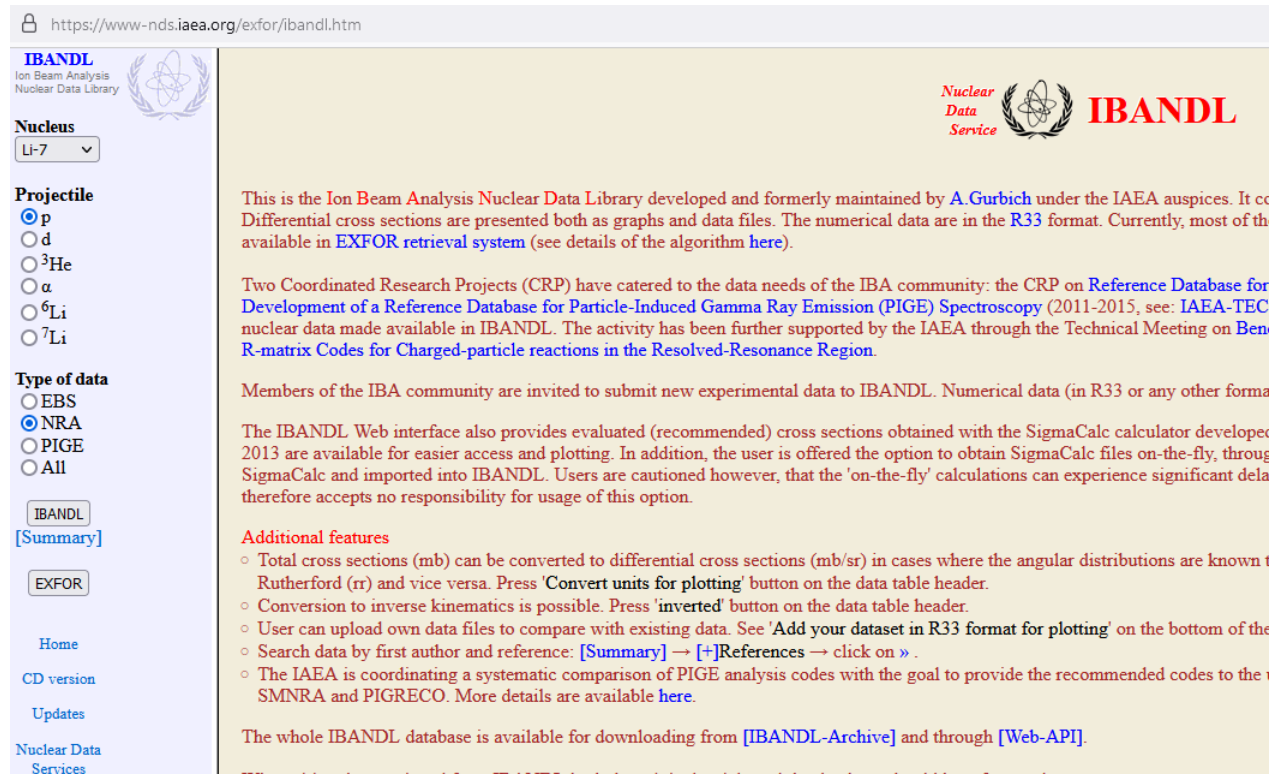
{cf. K. Krane, Ch.11 ("Nuclear Reactions")}

$Q = 17.346 \text{ MeV}$

$T_{\alpha} (2 \text{ MeV} ; \theta_{\text{lab}} = 165^\circ) = 7.539 \text{ MeV}$

The reaction ...

As secções eficazes: cf. <https://www-nds.iaea.org/exfor/ibandl.htm>

The screenshot shows the IBANDL (Ion Beam Analysis Nuclear Data Library) website. The left sidebar contains navigation links: Home, CD version, Updates, and Nuclear Data Services. The main content area includes a header with the IAEA logo and the text 'Nuclear Data Service IBANDL'. Below the header, there is a paragraph introducing the library, followed by a section on 'Additional features' listing various capabilities like unit conversion and data upload. At the bottom, there is a link to the IBANDL-Archive and a Web-API.

IBANDL
Ion Beam Analysis
Nuclear Data Library

Nucleus
Li-7

Projectile
☒ p
☐ d
☐ ${}^3\text{He}$
☐ α
☐ ${}^6\text{Li}$
☐ ${}^7\text{Li}$

Type of data
☐ EBS
☒ NRA
☐ PIGE
☐ All

IBANDL
[Summary]

EXFOR

Home
CD version
Updates
Nuclear Data Services

This is the **Ion Beam Analysis Nuclear Data Library** developed and formerly maintained by **A. Gurbich** under the IAEA auspices. It contains differential cross sections presented both as graphs and data files. The numerical data are in the **R33** format. Currently, most of the data are available in **EXFOR** retrieval system (see details of the algorithm [here](#)).

Two Coordinated Research Projects (CRP) have catered to the data needs of the IBA community: the CRP on **Reference Database for Development of a Reference Database for Particle-Induced Gamma Ray Emission (PIGE) Spectroscopy** (2011-2015, see: [IAEA-TEC](#) nuclear data made available in IBANDL. The activity has been further supported by the IAEA through the Technical Meeting on **Ben R-matrix Codes for Charged-particle reactions in the Resolved-Resonance Region**.

Members of the IBA community are invited to submit new experimental data to IBANDL. Numerical data (in R33 or any other format) can be converted to differential cross sections (mb/sr) in cases where the angular distributions are known in Rutherford (rr) and vice versa. Press 'Convert units for plotting' button on the data table header.

The IBANDL Web interface also provides evaluated (recommended) cross sections obtained with the SigmaCalc calculator developed in 2013 are available for easier access and plotting. In addition, the user is offered the option to obtain SigmaCalc files on-the-fly, through SigmaCalc and imported into IBANDL. Users are cautioned however, that the 'on-the-fly' calculations can experience significant delays and therefore accepts no responsibility for usage of this option.

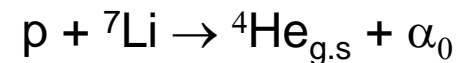
Additional features

- Total cross sections (mb) can be converted to differential cross sections (mb/sr) in cases where the angular distributions are known in Rutherford (rr) and vice versa. Press 'Convert units for plotting' button on the data table header.
- Conversion to inverse kinematics is possible. Press 'inverted' button on the data table header.
- User can upload own data files to compare with existing data. See 'Add your dataset in R33 format for plotting' on the bottom of the data table.
- Search data by first author and reference: [\[Summary\]](#) → [\[+\]References](#) → click on ».
- The IAEA is coordinating a systematic comparison of PIGE analysis codes with the goal to provide the recommended codes to the community. The SMNRA and PIGRECO. More details are available [here](#).

The whole IBANDL database is available for downloading from [\[IBANDL-Archive\]](#) and through [\[Web-API\]](#).

When citing data extracted from IBANDL, both the original article and the database should be referenced.

The reaction ...



As secções eficazes: cf. <https://www-nds.iaea.org/exfor/ibandl.htm>

https://www-nds.iaea.org/exfor/ibandl.htm

IBANDL
Ion Beam Analysis
Nuclear Data Library

Nucleus
Li-7

Projectile
☒ p
☐ d
☐ ${}^3\text{He}$
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Type of data
☐ EBS
☒ NRA
☐ PIGE
☐ All

IBANDL
[Summary]

EXFOR

Home
CD version
Updates
Nuclear Data
Services

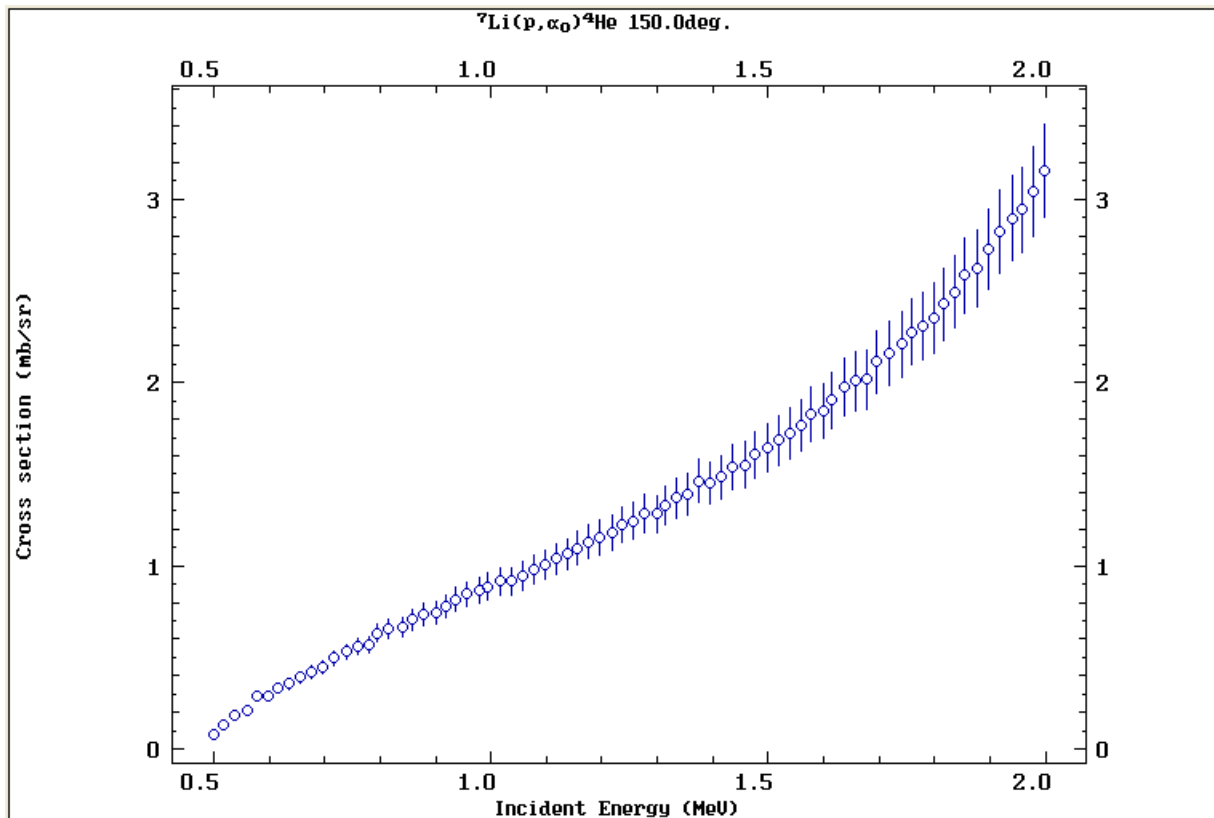
${}^7\text{Li} + p$

Type of data: NRA View: ☒ extended ☐ inverted Convert units for plotting: ☐ no ☒ mb/sr ☐ r Plots: [reset]

No.	Reaction	Angle	Energy(keV)	Pts	Update	X4	Reference	File	Plot
1	${}^7\text{Li}(p,p_1){}^7\text{Li}$	170°	1490-5900	43	2014-12-06	X4+	V.Paneta+(2012), Jour. Nucl. Instrum. Methods in Physics Res., Sect.B, Vol.288, p.53 »	View Save CSV	<input type="checkbox"/> mb
2	${}^7\text{Li}(p,p_1){}^7\text{Li}$	164°	2440-12050	64	2017-02-02	X4+	R.Gleyvod+(1965), Jour. Nuclear Physics, Vol.63, Issue.4, p.650 »	View Save CSV	<input type="checkbox"/> mb
3	${}^7\text{Li}(p,p_1){}^7\text{Li}$	160°	1490-5800	44	2014-12-06	X4+	V.Paneta+(2012), Jour. Nucl. Instrum. Methods in Physics Res., Sect.B, Vol.288, p.53 »	View Save CSV	<input type="checkbox"/> mb
4	${}^7\text{Li}(p,p_1){}^7\text{Li}$	155°	1730-10790	76	2017-02-02	X4+	M.Laurat(1969), Rept. Centre d'Etudes Nucleaires, Saclay Reports, No.3727 »	View Save CSV	<input type="checkbox"/> mb
5	${}^7\text{Li}(p,p_1){}^7\text{Li}$	150°	1490-6700	49	2014-12-06	X4+	V.Paneta+(2012), Jour. Nucl. Instrum. Methods in Physics Res., Sect.B, Vol.288, p.53 »	View Save CSV	<input type="checkbox"/> mb
6	${}^7\text{Li}(p,p_1){}^7\text{Li}$	145.7°	2530-12140	65	2017-02-02	X4+	R.Gleyvod+(1965), Jour. Nuclear Physics, Vol.63, Issue.4, p.650 »	View Save CSV	<input type="checkbox"/> mb
7	${}^7\text{Li}(p,p_1){}^7\text{Li}$	140°	2720-10600	31	2017-02-02	X4+	K.Kilian+(1969), Jour. Nuclear Physics, Section A, Vol.126, Issue.3, p.529 »	View Save CSV	<input type="checkbox"/> mb
8	${}^7\text{Li}(p,p_1){}^7\text{Li}$	140°	1490-6300	51	2014-12-06	X4+	V.Paneta+(2012), Jour. Nucl. Instrum. Methods in Physics Res., Sect.B, Vol.288, p.53 »	View Save CSV	<input type="checkbox"/> mb
9	${}^7\text{Li}(p,p_1){}^7\text{Li}$	123.1°	2370-11980	65	2017-02-02	X4+	R.Gleyvod+(1965), Jour. Nuclear Physics, Vol.63, Issue.4, p.650 »	View Save CSV	<input type="checkbox"/> mb
10	${}^7\text{Li}(p,p_1){}^7\text{Li}$	120°	2680-10610	32	2017-02-02	X4+	K.Kilian+(1969), Jour. Nuclear Physics, Section A, Vol.126, Issue.3, p.529 »	View Save CSV	<input type="checkbox"/> mb
11	${}^7\text{Li}(p,p_1){}^7\text{Li}$	90°	2680-10600	31	2017-02-02	X4+	K.Kilian+(1969), Jour. Nuclear Physics, Section A, Vol.126, Issue.3, p.529 »	View Save CSV	<input type="checkbox"/> mb
12	${}^7\text{Li}(p,\alpha_0){}^4\text{He}$	360°	600-2010	10	2022-09-13	-	S.Taskaev+(2021), Nucl., Instrum., Methods in Physics Res., Sect.B, Vol.525, p.55 »	View Save CSV	<input type="checkbox"/> tot
13	${}^7\text{Li}(p,\alpha_0){}^4\text{He}$	170°	1490-7000	65	2016-12-01	X4+	V.Paneta+(2012), Jour. Nucl. Instrum. Methods in Physics Res., Sect.B, Vol.288, p.53 »	View Save CSV	<input type="checkbox"/> mb
14	${}^7\text{Li}(p,\alpha_0){}^4\text{He}$	168°	600-2010	10	2022-09-05	-	S.Taskaev+(2021), Nucl., Instrum., Methods in Physics Res., Sect.B, Vol.525, p.55 »	View Save CSV	<input type="checkbox"/> mb
15	${}^7\text{Li}(p,\alpha_0){}^4\text{He}$	160°	1490-7000	66	2016-12-01	X4+	V.Paneta+(2012), Jour. Nucl. Instrum. Methods in Physics Res., Sect.B, Vol.288, p.53 »	View Save CSV	<input type="checkbox"/> mb
16	${}^7\text{Li}(p,\alpha_0){}^4\text{He}$	150°	130-1850	46	2012-01-20	X4+	I.Golicheff+(1974), Jour. Journal of Radioanalytical Chemistry, Vol.22, p.113 »	View Save CSV	<input type="checkbox"/> mb
17	${}^7\text{Li}(p,\alpha_0){}^4\text{He}$	150°	500-2000	76	2012-01-20	X4+	D.Dieumegard+(1980), Jour. Nuclear Instrum and Methods in Physics Res., Vol.168, p.93 »	View Save CSV	<input checked="" type="checkbox"/> mb
18	${}^7\text{Li}(p,\alpha_0){}^4\text{He}$	150°	4040-5290	22	2012-01-20	X4+	N.Sarma+(1963), Jour. Nuclear Physics, Vol.44, Issue.2, p.205 »	View Save CSV	<input type="checkbox"/> mb
19	${}^7\text{Li}(p,\alpha_0){}^4\text{He}$	150°	500-2000	76	2019-02-07	+	B.Maurel et al., in Ion Beam Handbook (s. 133), ed. J.W.Mayer & E.Rimini, (1977). »	View Save CSV	<input type="checkbox"/> mb
20	${}^7\text{Li}(p,\alpha_0){}^4\text{He}$	150°	1490-7000	65	2016-12-01	X4+	V.Paneta+(2012), Jour. Nucl. Instrum. Methods in Physics Res., Sect.B, Vol.288, p.53 »	View Save CSV	<input type="checkbox"/> mb
21	${}^7\text{Li}(p,\alpha_0){}^4\text{He}$	140°	1490-7000	65	2016-12-01	X4+	V.Paneta+(2012), Jour. Nucl. Instrum. Methods in Physics Res., Sect.B, Vol.288, p.53 »	View Save CSV	<input type="checkbox"/> mb
22	${}^7\text{Li}(p,\alpha_0){}^4\text{He}$	120°	440-2450	15	2022-09-11	X4+	W.E.Sweeney Jr+(1969), Jour. Physical Review, Vol.182, p.1007 »	View Save CSV	<input type="checkbox"/> mb

The reaction ...

As secções eficazes: cf. <https://www-nds.iaea.org/exfor/ibandl.htm>



The energy calibration...

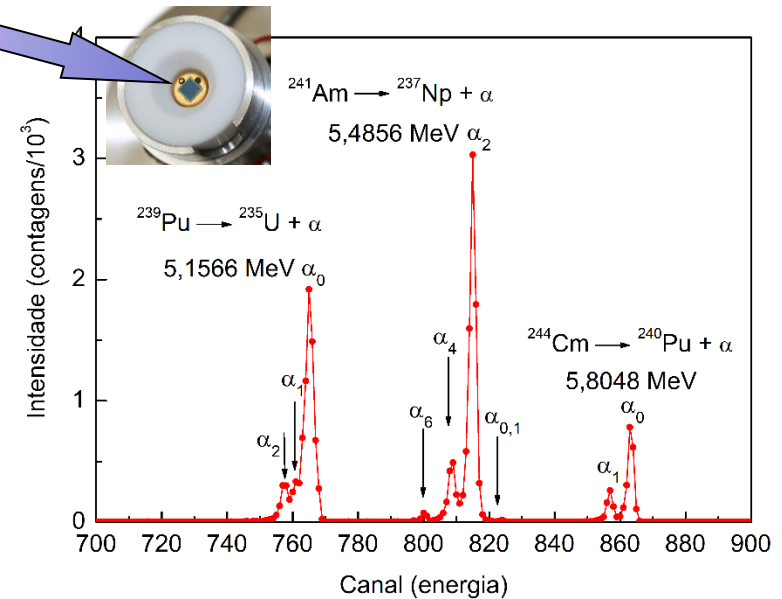
Establishing the channel-to-energy conversions

Exemplo



Triple
 α source

$\sim 5.5 \text{ MeV } \alpha$

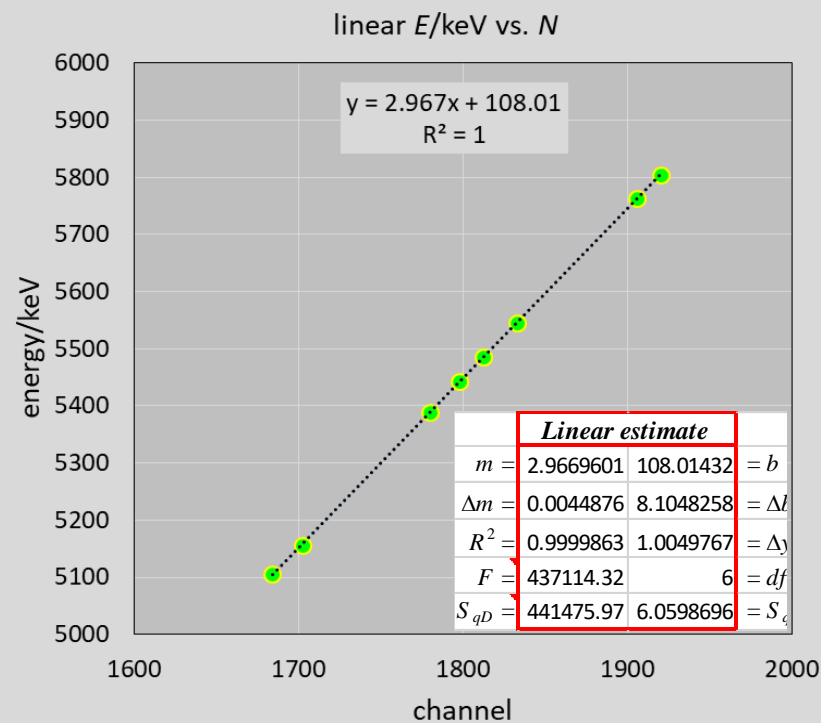


The energy calibration...

Establishing the channel-to-energy conversions

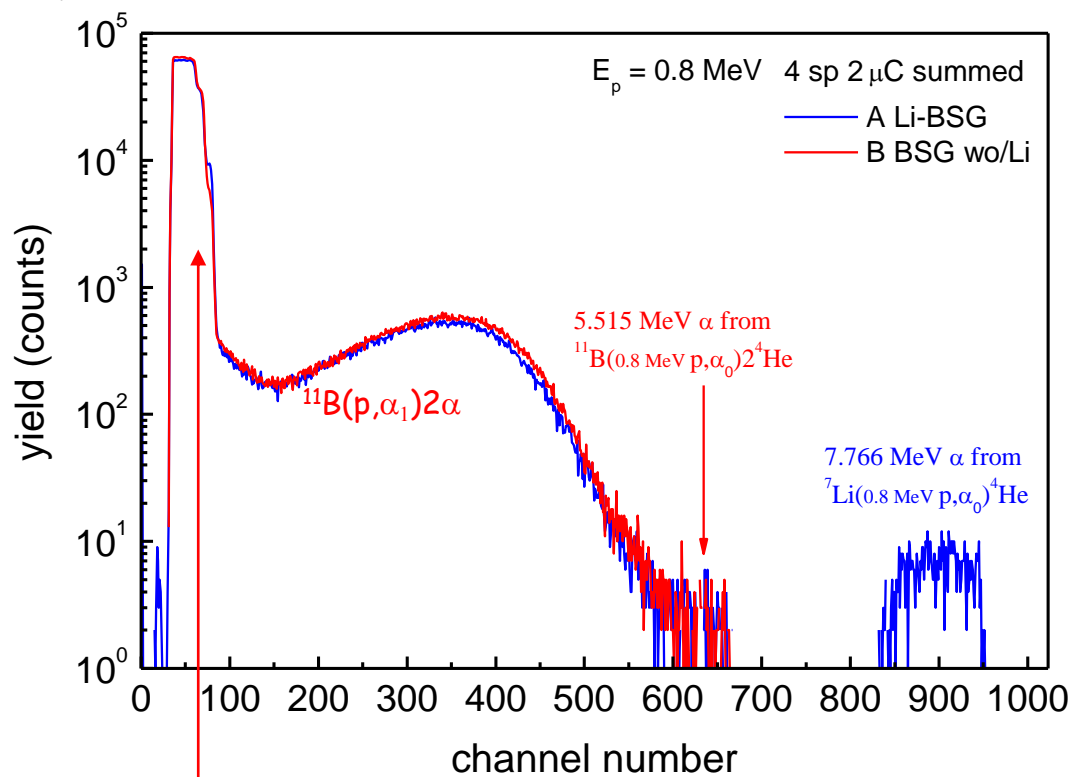
Exemplo

Fonte	Transição	I%	E_n/keV	E/keV
^{244}Cm (0+)	18,1 a			5901.61
	α_0	0+	76.4	0 5804.82
	α_1	2+	23.6	42.824 5762.70
	α_2	4+	0.022	141.690 5664
^{241}Am (5/2-)	432,2 a			5637.81
	α_0	5/2+	0.34	0 5544.5
	α_1	7/2+	0.20	33.192 5511.47
	α_2	5/2-	85.2	59.537 5485.56
	α_3	9/2+	0.04	75.89 5469.45
	α_4	7/2-	12.8	102.96 5442.80
	α_5	11/2+	0.01	130.00 5416.27
	α_6	9/2-	1.40	158.51 5388.23
	α_7	13/2+	-	191.5 5355.9
	α_8	11/2-	0.015	225.96 5321.9
^{239}Pu (1/2+)	24110 a			5244.50
	α_0	7/2-	0.03	0 5156.72
	α_1	1/2+	73.3	0.0768 5156.59
	α_2	3/2+	15.1	13.040 5144.3
	α_3	9/2-	0.03	46.204 5111.2
	α_4	5/2+	11.5	51.701 5105.5



The (kind of) primary 'deliverable'...

Exemplo I: espectros de vidros de borossilicato (BSG) não dopado e dopado c/ Li, obtidos no LATR/IST



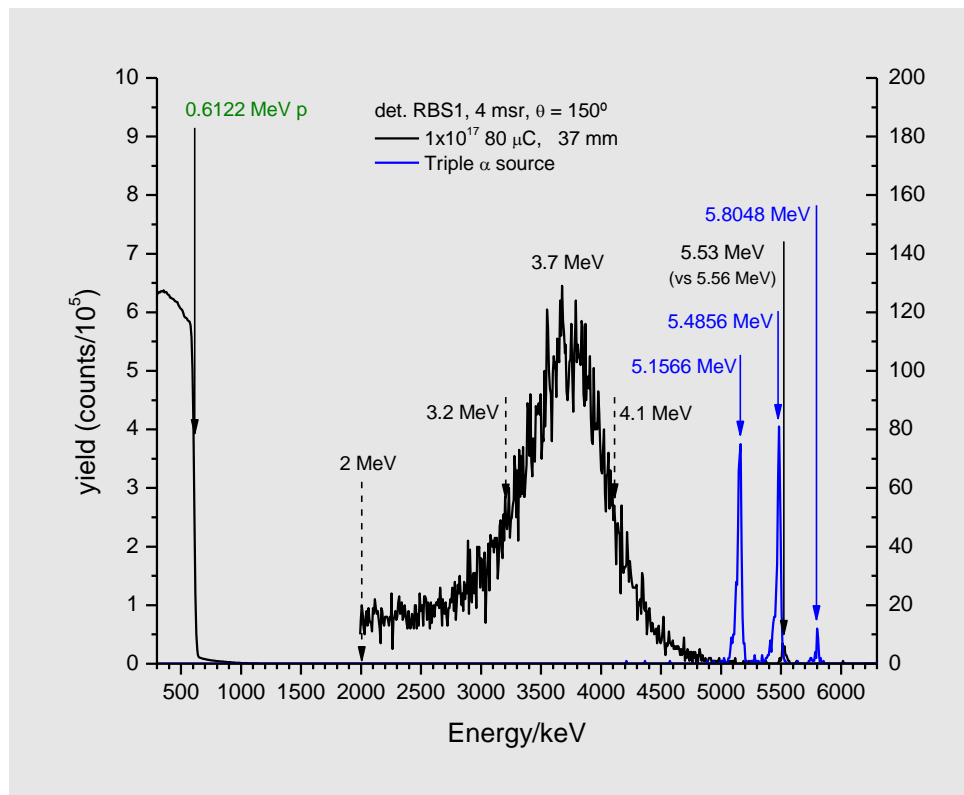
Q: o que é isto ?

Q: qual das amostras tem B ?

Qual das amostras tem Li ?

Exemplo II... Espectros NRA de Si implantado com B p/ $^{11}\text{B}(p,\alpha)$ c/ $E_p = 700$ keV, a 150°

Note-se a sobreposição dos espectros α da fonte radioactiva conhecida (a azul) usada p/ calibração



Q: conseguem justificar o espectro (distribuição em energia)?

Resultados...

Bibliografia:

- [1] Introductory nuclear physics (book), K.S. Krane, 2nd ed., Wiley, New York, 1988, USA.
- [2] Fundamentals of surface and thin film analysis, L.C. Feldman, JW. Mayer, North-Holland, New York, 1986, USA.
- [3] Ion beam analysis of Li-Sn alloys for fusion applications, R. Mateus et al., <https://doi.org/10.1016/j.nimb.2020.09.019>