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EVALUATION OF A TRITIUM BREEDING LAYER IN A FUSION-FISSION HYBRID SYSTEM

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ABSTRACT

A transmutation layer in a Tokamak system was designed with a spent nuclear fuel matrix composed by transuranic nuclides spiked with thorium. A previous study evaluated the transmutation layer localization in a fusion-fission hybrid system and results showed among all liquid metal coolants studied, the lead (Pb) and the lead-bismuth (LBE) coolants presented the higher transmutation rates. However, by not using lithium-based coolants, the tritium production is substantially decreased and it is required to maintain the D-T fusion reactions. So, the aim of this work is to analyze and compare what material could be used as a tritium breeder layer and how its insertion and localization could affect the system. The neutron flux and reaction rates were analyzed to evidence the best tritium breeder material at the breeder layer localization. The first results have shown that pure lithium at the chose tritium breeder layer location is more effective regarding the tritium production and also maintaining a harder neutron spectrum in transmutation layer.

1. INTRODUCTION

Previous studies performed at Nuclear Engineering Department - UFMG shows the most appropriate place for the transmutation layer in a Fusion-Fission Hybrid System (FFS) - a nuclear fusion reactor coupled to a fission blanket - based on Tokamak [1]. The chosen place is characterized by a hardened neutron spectrum with high neutron flux capable to achieve actinide transmutation over transmutation layer. These two features allow to increase the fission probability of the actinides.

In order to continue this study different coolant materials were tested with the purpose to enhance the fission probability over the radiative capture for transmutation. Therefore, the coolants studied have low ratio of moderation and high thermal mechanical properties that allow a better heat transfer. The coolants proposed are lead, sodium and lead-bismuth, sodium-potassium, lithium-lead, magnesium-lead eutectic alloys. Between them the best choices for higher actinides transmutation are lead (Pb) and lead-bismuth eutectic (LBE) liquid metals [2].

Tritium and deuterium are two isotopes of hydrogen that will be used as fuel to the fusion reaction in International Thermonuclear Experimental Reactor (ITER). While deuterium can be extracted from seawater in virtually boundless quantities, the supply of available tritium is limited. Tritium can be produced within the Tokamak when neutrons escaping the plasma interact with a specific material contained in the blanket.

Considering these two coolants option Lead and LBE instead of LiPb, there is a low tritium production for Lead and LBE compared to LiPb. Therefore, these coolant choices do not produce a significant amount of tritium to self-sustain the nuclear reactions.

Hence, the main purpose of this work is considered the insertion of a tritium breeder layer, placed before the transmutation layer. The goal of this work is to find the most suitable material for self sustain tritium production considering the different material options such as lithium, lithium-lead, lithium-magnesium, lithium-tin and pure lithium as well.

1.1. Tritium Breeders

The concept of 'breeding' tritium during the fusion reaction is important for the future needs of a large-scale fusion power plant [3]. All the candidates to tritium production have lithium in their composition because it is the most promising source of tritium due to its microscopic tritium production cross sections, mainly in lithium-6 (^{6}Li) [4]. Tab.1 shows some attributes of the analyzed tritium breeders. All the tritium breeders were chosen due to their liquid state at work temperature around 671.15 K, which is the temperature reference on the layer place. Fig.1 presents the microscopic tritium production cross sections for the different lithium materials evaluated. It shows that the cross sections had the same behavior through the energy spectrum analyzed. The highest probability for Li-6 to produce tritium is for thermal neutrons; in contrast, the Li-7 is for fast neutrons (~12 MeV). The Fig.1 presents two peaks of 0.5 MeV and 12MeV, which represents the highest probability for tritium production considering the range between 0.1 to 20 MeV.

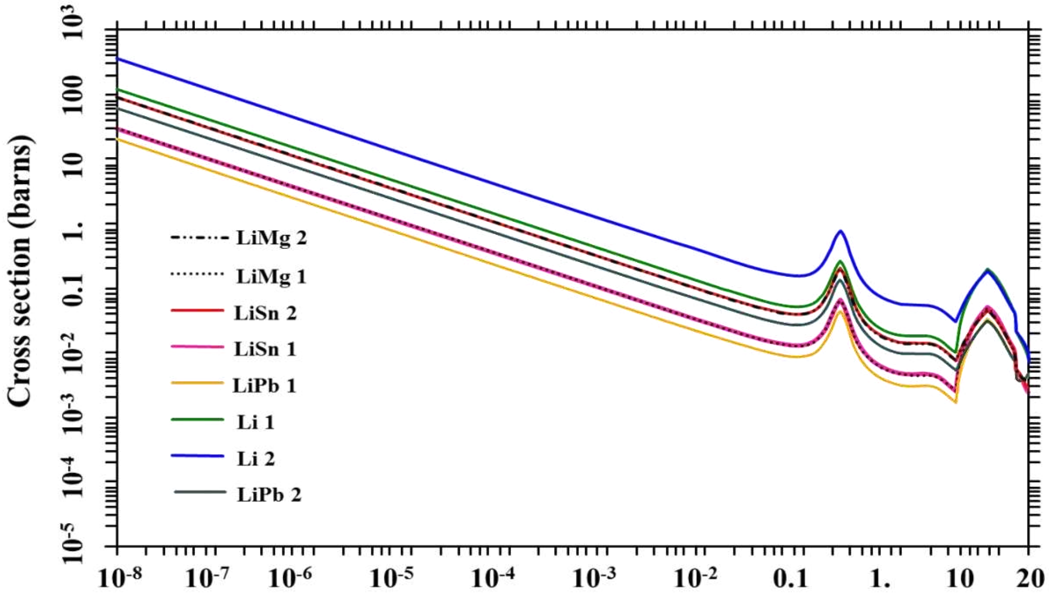

Fig.1. Tritium breeders cross sections for tritium production.

1.1.1. Li

Overall elements, lithium has the highest specific heat and electrochemical potential. It also has excellent thermal and electrical conductivity; similarly, it has shown to exhibit superconductivity below 400 K and ferromagnetism properties as a gas. The element is considered both toxic and corrosive and must be handled with extreme care.

Natural lithium is composed of two stable isotopes, lithium-6 (^{6}Li - 6.5wt%) and lithium-7 (^{7}Li - 93.5wt%) with extremely low binding energies. The tritium (^{3}H) production from the natural lithium is $^{6}Li(n, {}^{3}H)\alpha$ mainly for thermal neutrons, and $^{7}Li(n, {}^{3}H)n'\alpha$, which needs a neutron energy higher than 2.5 MeV to reaction happens. Further, ^{6}Li neutron reaction is an exothermic reaction, releasing 4.8 MeV. The considered lithium ratios were natural lithium (Li 1) and lithium enriched in 20% ^{6}Li (Li 2) [5 – 9].

1.1.2. LiPb

Lithium-Lead ($Li_{17}Pb_{83}$) is an eutectic alloy proposed as a coolant for fusion systems due to the tritium generation for neutron-lithium reaction. LiPb eutectic allows the use of enriched or natural Li and has a relatively low cost in comparison with other tritium generation. LiPb toxicity varies with the lead concentration (being higher with greater lead amount). The most suitable clad considered for this alloy was stainless steel with aluminum coating to avoid tritium and lithium leakage. The considered lithium-lead ratio was 0.7wt% Li – 99.3wt% Pb, where LiPb 1 has natural lithium and LiPb 2 has 20% ^{6}Li enrichment, which *LiPb 2* is the coolant material used in Ref.1 [1, 7, 8].

1.1.3. LiMg

The lithium-magnesium alloy is an extremely light and strong alloy with one of the lowest metallic materials densities. This alloy has high electrical and thermal conductivities. However, its poor resistance to corrosion and low creep strength has slowed down its development and industrial use. The considered lithium-magnesium ratio was 8.7wt% Li – 91.3wt% Mg, where LiMg 1 has natural lithium and LiMg 2 has 20% ^{6}Li enrichment to increasing the tritium production [10, 11].

1.1.4. LiSn

Lithium-Tin alloy is a potential tritium breeder in a fusion reactor. Li–Sn alloy has a relatively low vapor pressure, a reasonably melting point, good thermal physical properties (thermal conductivity and heat capacity). However, there are a lot of basic properties not available such as boiling point. The considered lithium-tin ratio was 2wt% Li – 98wt% Sn, where LiSn 1 has natural lithium and LiSn 2 has 20% ^{6}Li enrichment [12, 13].

Tab.1. Features of tritium breeders [5 - 13].

Tritium Breeder	Density at ~ 400°C (g/cm^3)	Melting Point (°C)	Boiling Point (°C)
LiMg 1	1.51	210	N/A
LiMg 2	1.496	210.7	N/A
Li 1	0.495	180.54	1347
Li 2	0.486	183.8	1350.3
LiPb 1	9.33	235	1665
LiPb 2	9.33	235	1665
LiSn 1	6.28	320	N/A
LiSn 2	6.274	320	N/A

N/A: not available.

2. METHODOLOGY

The FFS system design based on a Tokamak is shown in Fig.2 [1]. First of all the tritium breeder layer was placed between the heat sink and the transmutation layer. The breeder layer was modeled with 2 cm thickness. This is due to the limitation of the MCNP to track the particles simulated on the system, thus the breeder layer volume is 5.13389 m^3. In addition, the tritium breeder layer insertion in FFS causes an increase of 2 cm proportional for the external layers geometry dimensions. The materials used were the same, according to the ITER guidelines [14] and the article of Fusion Engineering and Design [15].

The Tokamak simulations were performed by MCNP5 code [16] using 10^8 particles (nps). This amount of particles was suitable to obtain properly neutron flux and reaction rate calculation. The simulation uses different materials for the tritium breeder layer (Li, LiMg, LiSn, and LiPb) comparing the reaction rate for tritium production using two coolant materials (Pb, LBE). Moreover, the analysis focuses on how the insertion of the tritium breeder layer affects the neutron spectrum profile.

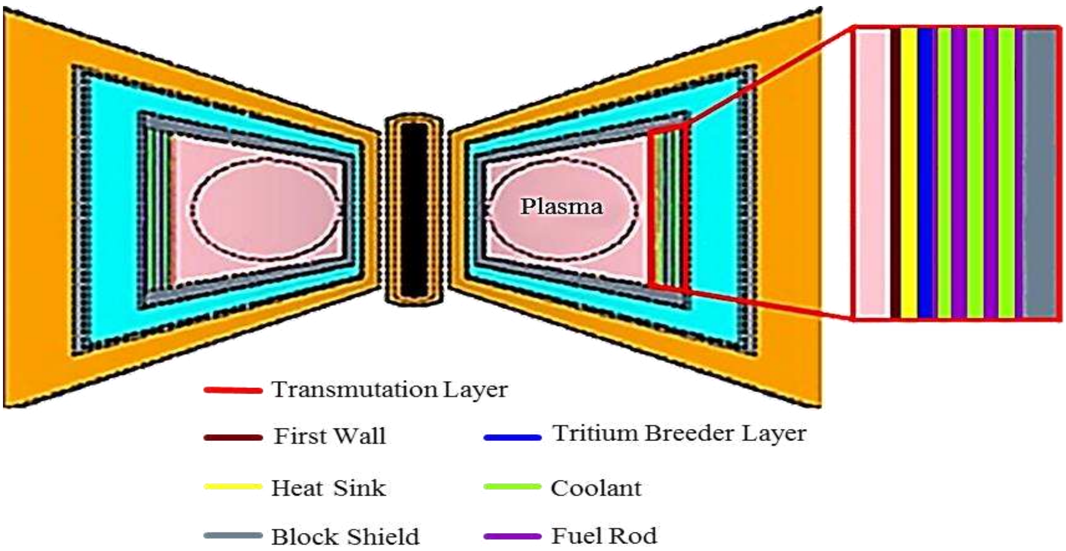

Fig.2. Tritium Breeder Layer in a FFS based on Tokamak.

3. RESULTS AND DISCUSSION

The reaction rate for tritium production considering both reactions (n, ^{3}H) and (n, n' ^{3}H) over the tritium breeder layer is shown in Fig.3. The analyses consider both coolants Pb and LBE proposed previously on the transmutation layer. First, the tritium breeders with 20% ^{6}Li enrichment present higher tritium production values than their respective correlatives without ^{6}Li enrichment. The Li 2 tritium breeder material presented the highest reaction rate value for tritium production, which is almost double of Li 1 production value. Among them, LiPb1 presents the lowest reaction rate value for tritium production, which already was studied as a coolant candidate for the transmutation layer on the FFS [2]. Further, the Tritium breeders produced a slightly larger amount of tritium with the use of LBE coolant than the use of Pb coolant due to the higher neutron scattering cross sections at the resonance region for LBE [2].

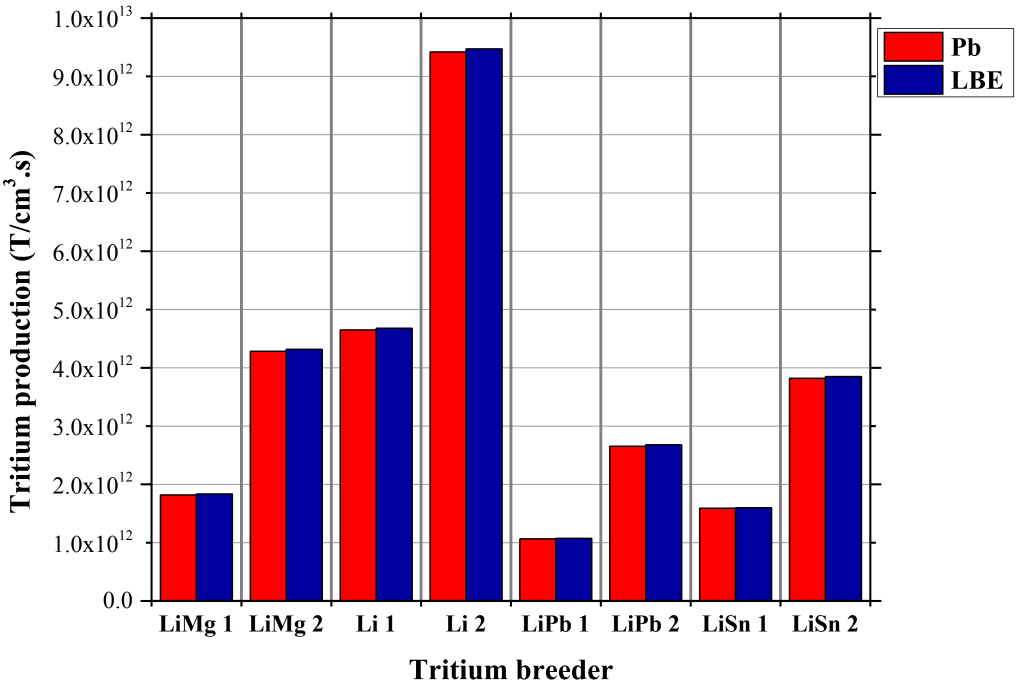

Fig.3. Reaction rate for tritium production.

It is possible to verify in Fig.4 the reaction rate percentage for each tritium breeder considering elastic scattering, tritium production, and other reactions. The elastic scattering is the predominant reaction for all materials in the breeder layer inducing changes in neutron flux, especially on the hardened neutron spectrum.

On the one hand, others reactions for lithium-tin alloys show larger percentage values, which is not interesting from the point of view in tritium production purpose. On the other hand, pure lithium Li 1 and Li 2 presented larger percentage values for tritium production, mainly for Li 2.

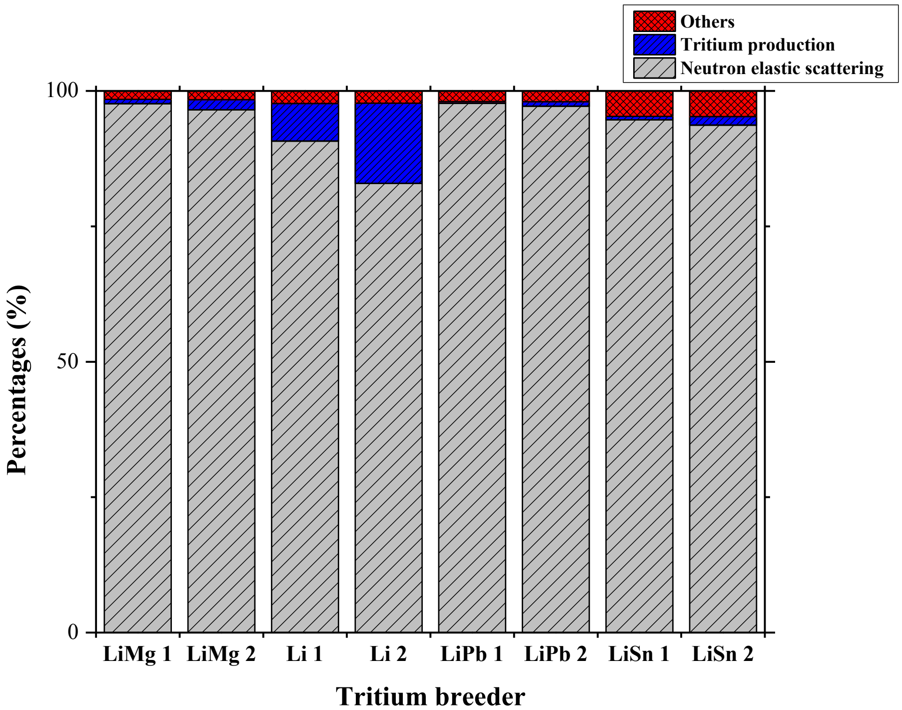

Fig.4. Total neutron reactions for tritium breeders.

In the Fig.5 is shown the neutron spectrum before the transmutation layer in Tokamak system. The study took into consideration the neutron flux without the tritium breeder layer in the system for comparison purpose. Unlike, the tritium breeder layer placed on the system modifies the neutron spectrum, even more, varying the different tritium breeders used.

When the tritium breeder layer is placed at the system, the neutrons with 14.1 MeV are moderated due to elastic scattering reactions. This modifies the neutron spectrum from 14.1 MeV to an energy range between 0.01 and 1 MeV. The transmutation probability increases for the neutrons with high energy (>5 MeV), this can be seen in the fission-to-total absorption probability ($\sigma_f/(\sigma_f+\sigma_\gamma)$) for each transuranic nuclide [17].

The tritium breeders that use natural lithium present a greater neutron flux than those with ^{6}Li enrichment due to neutron elastic scattering for ^{7}Li. Although, Li 2 presented a smaller neutron spectrum in the mentioned energy range, which means that occurs less elastic scattering reactions. It contributes to a hardened neutron spectrum reaching the transmutation layer. Moreover, the thermal neutrons flux is smaller at Li 2 due to the higher reaction rate for tritium production in this energy range.

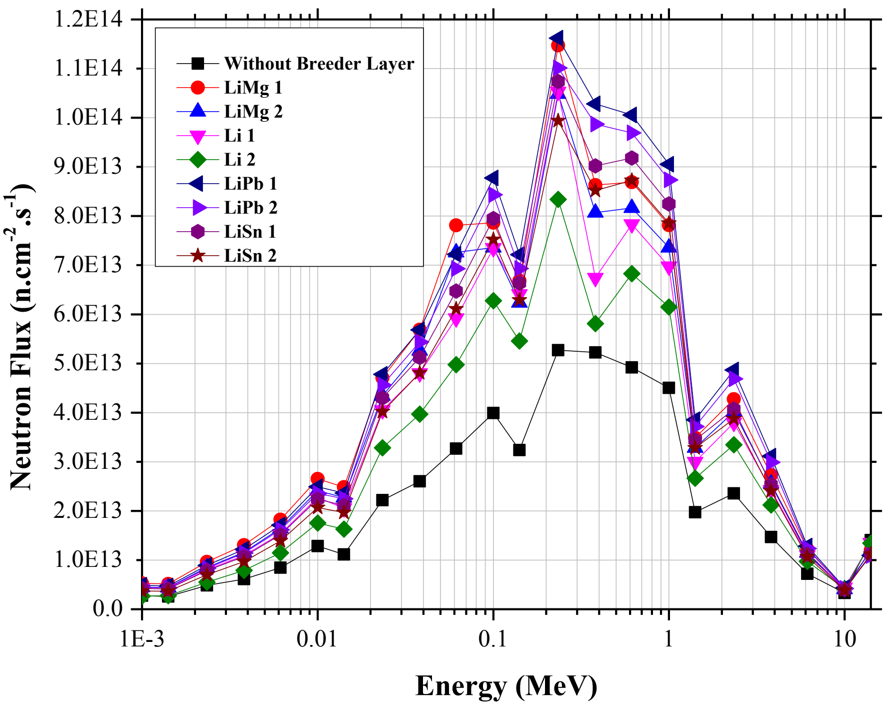

Fig.5. Neutron spectra before the transmutation layer.

4. CONCLUSION

The tritium production is studied with the purpose to have an acceptable amount of tritium production as a fuel for fusion reactions on the Tokamak. The Li 2 tritium breeder material presents the highest reaction rates for tritium production. It also showed a slightly greater tritium production considering the use of LBE coolant. The neutron flux analysis showed the influence of tritium breeders on the Tokamak system due to the moderation of 14.1 MeV energy neutrons. Despite, Li 2 had less influence in the hardened neutron spectrum due to the low neutron moderation. Furthermore, it presents a higher absorption of thermal neutrons for tritium production. To sum up, the best choice between the coolants are the LBE, and for the tritium breeder, is the Li 2.

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REFERENCES

[1] C.E. Velasquez *et al.*, "Fusion–Fission Hybrid Systems for Transmutation", Journal of Fusion Energy, **Volume 35 – Number 1**, pg 1-134 (2016).

[2] R.V. A. Marques *et al.*, “Liquid Metal Coolants for Fusion-Fission Hybrid System – A Neutronic Analysis”. No prelo.

[3] International Thermonuclear Experimental Reactor (ITER) Organization – Tritium Breeding (2018), retrieved from https://www.iter.org/mach/TritiumBreeding.

[4] HyperPhysics - © 2016 C.R. Nave, Georgia State University, Nuclear Fusion (2018), retrieved from http://hyperphysics.phy-astr.gsu.edu/hbase/NucEne/fusion.html.

[5] American Elements – The Advanced Materials Manufacturer ®, Lithium (2018), retrieved from https://www.americanelements.com/li.html.

[6] Nuclear Data Center at KAERI (Korea Atomic Energy Research Institute), Nuclide Table – Lithium (2018), retrieved from http://atom.kaeri.re.kr:8080/ton/index.html.

[7] E. Mas de les Valls *et al.*, “Lead–lithium eutectic material database for nuclear fusion technology”, Journal of Nuclear Materials, **Vol. 376**, 3rd edition, pp. 353-357 (2008).

[8] Y. Wu, F.D.S. Team, “Conceptual design and testing strategy of a dual functional lithium–lead test blanket module in ITER and EAST”, IOP Publishing and International Atomic Energy Agency, **Nucl. Fusion 47**, pp. 1533–1539 (2007).

[9] K.Lackner, EFDA-Garching , “ITER and the Fusion Reactor: Status and Challenge to Technology”, European Fusion Development Agreement – 15ª Plansee Seminar, Vol.4 (2001).

[10] A. Sanschagrin *et al.*, “Mechanical properties and microstructure of new magnesium-lithium base alloys”, Materials Science and Engineering, ELSEVIER (1996).

[11] American Elements – The Advanced Materials Manufacturer ®, Lithium-Magnesium Alloy (2018), retrieved from https://www.americanelements.com/lithium-magnesium-alloy.

[12] Yi Kang, Takayuki Terai, “Moderate tritium properties in lithium–tin alloy as a liquid breeder/coolant”, ELSEVIER, *Fusion Engineering and Design*, Volume 81, Issues 1–7, February 2006, Pages 519-523.

[13] K. Natesan, W. E. Ruther, “Fabrication and properties of a tin–lithium alloy”, ELSEVIER, Journal of Nuclear Materials, Volumes 307–311, Part 1, December 2002, Pages 743-748.

[14] International Thermonuclear Experimental Reactor (ITER) - Final Design Report (2001), retrieved from http://www.naka.jaea.go.jp/ ITER/FDR/.

[15] Y. Wu, F.D.S. Team, “CAD-based interface programs for fusion neutron transport simulation.” **Fusion Eng. Des. 84**, 1987–1992 (2009).

[16] X-5 Monte Carlo Team, MCNP, A General Monte Carlo N-Particle Transport Code, Version 5, vol. II. User’s Guide University of California, Los Alamos National Laboratory (2003).

[17] C.E. Velasquez *et al.*, "Axial Neutron Flux Evaluation in a Tokamak System: a Possible Transmutation Blanket Position for a Fusion Transmutation System", Nuclear Physics 42:237–247, Sociedade Brasileira de Física (2012).