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# $^8$HE $\beta$-DECAY TO THE $^6$LI+N+N CHANNEL

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**Abstract**

Up to now only a small fraction of the Gamow-Teller (GT) sum rule is known to be exhausted in the spectrum of $^8$Li. $^8$He $\beta$-decay to the $^6$Li+n+n channel is studied as a process which may indicate the concentration of GT strength at high excitation energies (near 9 MeV) in the spectrum of $^8$Li. An estimate of the branching ratio is obtained with a COSMA $^8$He wave function and a three-body $^6$Li+n+n continuum.

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## 1 Introduction

$^8$He $\beta$-decay to different channels in the $^8$Li nucleus is relatively well studied experimentally [?, ?]. These decays are interesting because of the serious impact of this process on our understanding of the nuclear structure both of $^8$He and $^8$Li [?]. $^8$He is characterized by the largest neutron-to-proton ratio among all known bound nuclei and was found to have an extended neutron halo. The only available experimental data on $^8$He, namely the matter radius [?] and fragmentation [?] are not very sensitive to the internal structure, so the simple cluster-orbital shell model of $^8$He, developed in [?] is sufficient to describe them. Based on our experience concerning $\beta$-decay of another halo nucleus $^6$He to the $\alpha$-d continuum [?] we can expect high sensitivity of the $\beta$-decay transition probability to the $^8$He halo structure. As for $^8$Li, a lot of theoretical and experimental efforts were made to describe the nuclear structure and reactions, particularly due to important astrophysical applications. So, the most reliable information is obtained for particle stable and low lying continuum states (see e.g. [?, ?, ?, ?, ?, ?] and references therein).The main part of the Gamow-Teller strength should be concentrated, however, far in the continuum. Therefore, despite a significant amount of theoretical papers [?, ?, ?, and references therein], dealing with $^8$He $\beta$ -decay or touching it somehow, the understanding of the process is rather poor. The reasons for that are: 1) the complexity of the problem, namely different clusterization of $^8$He ( presumably $\alpha$+4n ) and $^8$Li (mainly $\alpha$+$^3$H+n in the low lying states) and 2) the numerous open channels of the decay (discrete spectrum $1^+$ , 0.98 MeV; two-body continuum $^7$Li+n, $^6$He+d, three-body continuum $\alpha$+$^3$H+n, $^6$Li+n+n.

This work may be considered as a kind of post script to the article [?], where among other processes $^8$He $\beta$-decay to $\alpha$+$^3$H+n continuum is studied to extract the properties of the hypothetical [1] Gamow-Teller (GT) resonance (or Halo Analog state, see [?]). The properties of the state are quite uncertain within the approach used in [?] $E_R$=8.5–8.8 MeV, $\Gamma$=0.5–1.3 MeV, $B_{GT}$=2.7–4.2 and rather different from results of analysis in R-matrix "sequential decay" formalism [?]: $E_R$=9.3 MeV, $\Gamma$=1.0 MeV, $B_{GT}$= 5.18. Anyway those approaches show that this state, being observed in the $\alpha$+ $^3$H+n channel, exhausts a part (22–43%) only, of the GT sum rule in $^8$He. For comparison, in $^6$He the fraction of the GT sum rule exhausted in the GT resonance (here $^6$Li ground state) is about 82%. So we would expect a much greater GT strength to appear in the region of the GT resonance in $^8$He. Available theoretical shell model calculations [?, ?] also mainly give around 80% in the $\beta$ - decay window. Our present aim is to show, whether the GT strength can be observed in $^8$He $\beta$ -decay to the other channel, here $^6$Li+n+n, or it can be seen only in nuclear reactions. The threshold of this

[1] This state is hypothetical in the sense that it has never been observed in "ordinary" nuclear reactions, but only in $\beta$-decays, where its properties are not so evidently manifested.

decay is situated at 9.2 MeV , so the branching ratio is strongly suppressed by a phase space factor, but nevertheless could be accessible for modern experiments ($\beta$ - delayed two neutron emission) if, of course, the GT strength in this energy interval were high enough. The impact of this channel on the triton $\beta$-delayed spectrum - the only observable indicating the high-lying state in $^8$Li with relatively large $B_{GT}$ value - is expected to be insignificant. This follows from the comparison of the reduced widths for triton ($\theta_t$=0.012) and neutron ($\theta_n$= 0.26) in $^6$Li(n,$\alpha$)$^3$H and $^6$Li(n,n)$^6$Li reactions,respectively [?]. At the same time the $\beta$ - delayed neutron spectrum could be enhanced at low energies supporting the experimental data [?, ?]. The $^6$He+d channel with threshold energy of 9.783 MeV [?] is also open for the $\beta$-decay and contributes to the GT strength at the same level as $^6$Li+n+n but is beyond the reach of present experimental facilities.

## 2 $^6$Li+n+n continuum

For three body continuum calculations we need NN and $^6$Li-N potentials reproducing experimental scattering phases.The neutron-neutron interaction in our calculations was taken as the Gogny-Pires-De Tourreil potential [?], including repulsion at small distances, spin-orbit and tensor forces. This potential was tried successfully in calculations of A=6 nuclei [?]. The $^8$Li-N interaction used in our calculations is based, mainly on the theoretical paper [?], where theoretical phase-shifts were derived and experimental cross-sections were reproduced well. In our paper we investigate the responses in the continuum to various choices of this interaction. We tried the following $^6$Li-n potentials:
i) A Wood-Saxon potential, including central, spin-orbit and spin-spin interactions of the form $\mathbf{I}_{6Li} \cdot \mathbf{s}_n$. The potential parameters are listed in Table 1. ii) The same as i), but with a more hard repulsive core at small distances and a shallow attractive potential in S-wave
The potentials in all partial waves are the same excluding the s-wave, where a repulsive core was used to take the Pauli principle into account approximately. We should note here that a d-wave potential is very important for the $^6$Li+n+n continuum as we show below. Another important point, noticed in [?] is the odd-even l-dependent and spin-dependent behavior of phase shifts, which was simulated a by spin-spin interaction of the form $(-1)^l\mathbf{I}\mathbf{s}$, where $\mathbf{I}$ is the spin of $^6$Li (I=1) and s - the neutron spin.

A $^8$Li continuum wave function (WF) $^6$Li+n+n was constructed in the following way:

$$\Psi_{^8Li} = \Psi_{^6Li} \cdot \Psi_{^6Li+n+n} \qquad (1)$$

where $\Psi_{^6Li}$ is the $^6$Li ground state WF in a three-cluster $\alpha + n + p$ representation, obtained in [?] and $\Psi_{^6Li+n+n}$ is a three-body continuum WF (see [?]). The main advantage of this function is that it takes final state interaction into account properly, which means that the shape of spectra and shape of the energy distribution of the GT strength in the $^6$Li+n+n continuum can be obtained correctly. A serious disadvantage of this function is that it does not involve the "polarization terms" responsible for dissolving of the $^6$Li cluster when valence neutrons are approaching the core. Those terms according to our expectations would be extremely important between the $^6$Li+n+n and $^6$He+d thresholds. In more details this question is discussed in the end of the next section.

The exact expression for the WF (??) is

$$\Psi_{^8Li}^{JM_J}(E) = \sqrt{\frac{2}{\pi}}\frac{(2\pi)^3}{(æ\rho)^{5/2}} \sum_{K\,S\,S_{2n}\gamma;K'S'S'_{2n}\gamma'} C^{JM_J}_{LM_LSM_S}\, \mathcal{J}_{K,\gamma}(\Omega_æ) \times$$
$$\times\, i^K\, \chi^{K'S'S'_{2n}\gamma'}_{K\,S\,S_{2n}\gamma}(æ\rho) \left[\mathcal{J}_{K',\gamma'}(\Omega_\rho) \otimes \left[\Psi^{J_{Li}T_{Li}}_{^6Li} \otimes \Phi^{S_{2n}T_{2n}}_{2n}\right]_{S'T}\right]_{JM_J}$$

The function $\Phi^{S_{2n}T_{2n}}_{2n}$ is a spin-isospin function of the two valence nucleons, $\gamma = \{L, l_x, l_y\}$ is a multyindex replacing the set of quantum numbers, and standard hyperspherical harmonics are written as

$$\mathcal{J}_{K,\gamma}(\Omega_5) = \mathcal{J}^{l_xl_y}_{KL}(\Omega_5) = \psi^{l_xl_y}_K(\theta)\ \left[Y_{l_xm_x}(\Omega_x) \otimes Y_{l_ym_y}(\Omega_y)\right]_{LM_L}$$

The hyperangular functions $\psi^{l_xl_y}_K(\theta)$ are expressed in terms of Jacobi polynomials $P^{\alpha,\beta}_n$ by

$$\psi^{l_xl_y}_K(\theta) = N^{l_xl_y}_K(\sin\theta)^{l_x}(\cos\theta)^{l_y}\, P^{l_x+1/2,\,l_y+1/2}_{\frac{K-l_x-l_y}{2}}(\cos 2\theta)$$

where the quantum number $K = l_x + l_y + 2n$ $(n = 0, 1, 2\ldots)$ corresponds to a three-body hypermoment. The standard sets of Jacobi variables in the coordinate and momentum spaces and their connection with hyperspherical variables can be found elsewhere [?]

The functions $\chi^{K'S'S'_{2n}\gamma'}_{K\,S\,S_{2n}\gamma}(æ\rho)$ are obtained as solutions of a set of hyperradial equations for the three-body continuum [?] with cluster-cluster interactions described in the previous section.

The results of our calculations show two sharp resonances in the $\beta$-decay energy window, first (more strong) at 0.5 MeV above three-body threshold and another one (much weaker) at 0.7 MeV. The former looks presumably as a dineutron in a d-wave relative to $^6$Li and closely connected with the d-wave behavior of the $^6$Li-n potential: if the potential in d-wave is switched off the resonance completely disappears. The latter looks as two neutrons in a relative p-wave and a p-wave relatively to $^6$Li. We have also obtained a state in a vicinity of 8 MeV $^8$Li excitation energy with the structure of a dineutron in s-wave relative to $^6$Li. This state is bound in our case, but in reality it is situated above the $^7$Li+n and $\alpha$+t+n threshold.

## 3 $\beta$-decay calculations

The $^8$He WF in our calculation is taken in a simple analytical form

$$\Psi_{^8He} = \Psi_\alpha \cdot \Psi_{4n} \tag{2}$$

where four valence neutrons are assumed to occupy $0p_{3/2}$ states relative to the $\alpha$ -core. The motivation for this choice of the WF can be found in papers [?]. A Slater determinant of the active part $\Psi_{4n}$ of the $^8$He WF can be rewritten:

$$\Psi_{4n} = \Phi^{T=2}_{T_3=2} \cdot \sum_{J=0,2} A_J \left[ \left[ \Psi_{3/2}(1) \otimes \Psi_{3/2}(2) \right]_J \otimes \left[ \Psi_{3/2}(3) \otimes \Psi_{3/2}(4) \right]_J \right]_{00}$$

$$\Psi_{3/2}(i) = C^{3/2 M_i}_{1 m_i 1/2 \nu_i} \varphi(r_i) Y_{1 m_i}(\hat{r}_i) \chi_{\nu_i} \quad ; \qquad \varphi(r) = \sqrt{\tfrac{8}{3\sqrt{\pi}}} \tfrac{r}{r_0^{5/2}} exp\left(-\tfrac{r^2}{2r_0^2}\right)$$

$$A_0 = -1/\sqrt{6} \qquad A_2 = \sqrt{5/6}.$$

To calculate the GT matrix elements we have to change coupling scheme and coordinates in the WF (??). The transformation from individual coordinates of valence nucleons accounted from the $\alpha$ -particle center of mass to a Jacobi scheme of WF (??) is simplified by the analytical character of the WF (??). The GT strength function in the momentum (energy) space is given by the expression:

$$B_{GT}(E_x, E_y) = B_{GT}(E, \theta_{æ}) = \frac{2J'+1}{2J+1} \sum_{S\, S_{2n}\, L\, l_x\, l_y} \left| \sum_K M_{K, S\, S_{2n}\, L\, l_x\, l_y}(E)\, \psi_K^{l_x l_y}(\theta_{æ}) \right|^2$$

The expression for the spectrum of the particle number 3 (number in the definition of Jacobi coordinate) in units of the branching ratio is given by:

$$\frac{dBr(E_y)}{dE_y} = \frac{\lambda^2 t_{1/2}(^8He)}{2\ ft(0^+ \to 0^+)} \cdot \frac{\sqrt{2M}}{2\pi} \int_0^{Q-E_y} B_{GT}(E_x, E_y)\, f\,(A, Z, Q - E_x - E_y)\, \frac{\sqrt{E_x E_y}}{E^{5/2}}\, dE_x$$

$Q$ is the maximum energy of the $\beta$-decay; $Q$ =1.37 MeV for the $^6$Li+n+n channel. To obtain the spectra of the other particle(s) we should calculate $B_{GT}(E_x, E_y)$ using matrix elements $M^i_{K, S\, S_{2n}\, L\, l_x\, l_y}(E)$ transformed to the Jacobi system, where the particle of interest is the third. It is done by means of Raynal-Revai coefficients [?]:

$$M^i_{K, S\, S_{2n}\, L\, l_x\, l_y}(E) = \sum_{l'_x l'_y} R^{l'_x l'_y}_{l_x l_y}(j \to i; KL)\, M^j_{K, S\, S_{2n}\, L\, l'_x\, l'_y}(E)$$

The results of these calculations are shown in Figures 1–3. The GT strength function depending only on the total energy is shown in Fig.1. The total GT strength in the $\beta$-decay window is given by the expression



$$\begin{aligned} B_{GT}(int) &= \frac{\sqrt{2M}}{2\pi} \int_0^{E_x+E_y<Q} B_{GT}(E_x, E_y)\, \frac{\sqrt{E_x E_y} dE_x dE_y}{E^{5/2}} \\ &= \frac{\sqrt{2M}}{\pi} \sum_{K, S\, S_{2n}\, L\, l_x\, l_y} \int_0^Q \left| M_{K, S\, S_{2n}\, L\, l_x\, l_y}(E) \right|^2 \frac{dE}{\sqrt{E}} \end{aligned}$$

This gives $B_{GT}(int)$=0.312 for "Potential i)", $B_{GT}(int)$=0.15 for "Potential ii)" and $B_{GT}(int)=2.\times10^{-4}$ for the plane wave case (no final state interaction). From these resultes we see that a final state interaction is very important and essentially influences the $B_{GT}$ values for $\beta$ - decay to continuum states. Still the values for "potential i) and ii)" are rather small. What is the reason for such low values? Let us make a rough estimate based only at the percentage of the main components in $^8$He and $^6$Li+n+n. $^8$He in COSMA (2) looks like $^6$He($2^+$) plus two neutrons with J=2 ( the weight of this configuration being 5/6) and $^6$He($0^+$) plus two neutrons with J=0 (the weight of this configuration is 1/6). It is clear that the whole $^6$Li+n+n WF (taking into account the inner structure of the $^6$Li core) (1) is unfavorable for the $^8$He $\beta$-decay, because the $^8$He components overlapping well with $^6$Li itself do not overlap well with the WF of the two neutron relative motion and vice versa. Here we come to the conclusion that if the situation with concentration of the GT strength near 9 MeV in the $^8$Li spectrum is realized in nature, it can occur due to polarization of the $^6$Li cluster by the two outer neutrons. The $^8$He nuclear structure (2) implies that the polarization term should have a form $^6$Li($3^+$)+2n, which provides much greater overlap of the initial and final states. Therefore the spectra of $^6$Li and neutrons, shown in figures 2 and 3 respectively, are reliable in the sense of their shape but give only low limits for the total intensity. Values obtained for the branching ratii [2] are: Br=$1.01\times10^{-5}$ for "Potential i)", Br=$3.89\times10^{-6}$ for "Potential ii)", Br=$4.5\times10^{-10}$ for the three-body plane wave case. The first two values can be considered as an estimate of the lower limit for the branching ratio, connected purely with assymptotics of the exit channel. Anb upper limit can be estimated based on the low energy enhancement of the experimental neutron spectrum [?, ?]. If the enhancement is attributed to the $^6$Li +2n channel, $B_{GT}$ has to be $\approx 3$ in (9.3-9.7 MeV) energy region, and the branching values given above should be multiplied by a factor 10. So, in this case the branching ratio for neutrons would be $4.\times10^{-4}$–$8.\times10^{-5}$. These are also rather small values, but nevertheless accessible in modern experiments.

[2] As the two neutrons are coming from a single decay event, listed branching ratii should be doubled for neutrons.

## 4 Conclusion

The direct $\beta$-decay of $^8$He to the three-body continuum $^6$Li+n+n is calculated, and spectra of $^6$Li and neutrons are obtained. The branching ratio for neutrons is found on the level $2.\times10^{-5}$–$7.8\times10^{-6}$. It is argued that this value could increase to $4.\times10^{-4}$ –$8.\times10^{-5}$ in the case of GT strength concentration in the spectrum of $^8$Li at 9.3–9.8 MeV due to core polarization. If two neutron emission from $^8$He $\beta$-decay were discovered experimentally it could indicate the existence of very intense GT resonance state with $B_{GT} \approx 3$ at about 9.6 MeV. This state could also be observed in the nuclear reaction $^6$Li($^6$He,$\alpha$).

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| | $V_c$ MeV | $R_c$ fm | $a_c$ fm | $V_{Ls}$ MeV·fm | $R_{Ls}$ fm | $a_{Ls}$ fm | $V_{Is}$ MeV | $R_{Is}$ fm | $a_{Is}$ fm |
|---|---|---|---|---|---|---|---|---|---|
| $s$-wave | 95 | 2.435 | 0.68 | - | - | - | -2. | 2.435 | 0.68 |
| $p$-wave | -36 | 2.435 | 0.68 | -5. | 2.435 | 0.68 | 2. | 2.435 | 0.68 |
| $d$-wave | -36 | 2.435 | 0.68 | - | - | - | -2. | 2.435 | 0.68 |

Table 1: Parameters of $^6$Li-N WS potential i).

## FIGURE CAPTIONS

Figure 1.

Gamow-Teller strength $B_{GT}$ as a function of total three-body energy. Solid curve is obtained with potential i); total GT strength in the $\beta$-decay window is $B_{GT}(int)$=0.312 . Dashed curve corresponds to potential ii); $B_{GT}(int)$=0.15. The calculation with a three-body plane wave is represented by the dash-dotted curve ($B_{GT}(int)=2.\times10^{-4}$). This is given to illustrate the effect of the "final state interaction" in the process.

Figure 2.

Spectra of $^6$Li in the units of branching ratio. Meaning of the curves is the same as in Fig. 1.

Figure 3.

Spectra of neutrons in the units of branching ratio. Meaning of the curves is the same as in Fig. 1.

Fig. 1

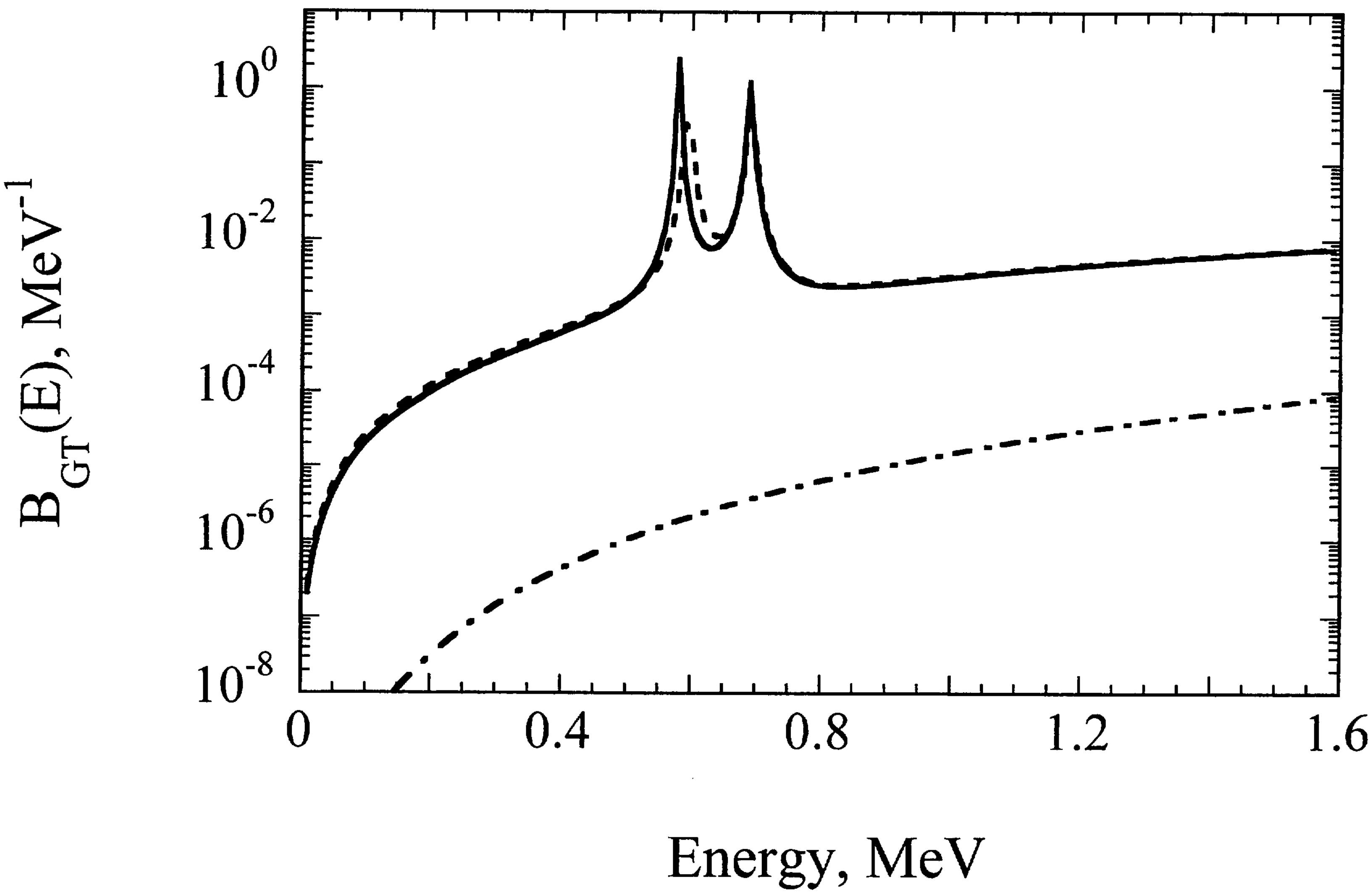
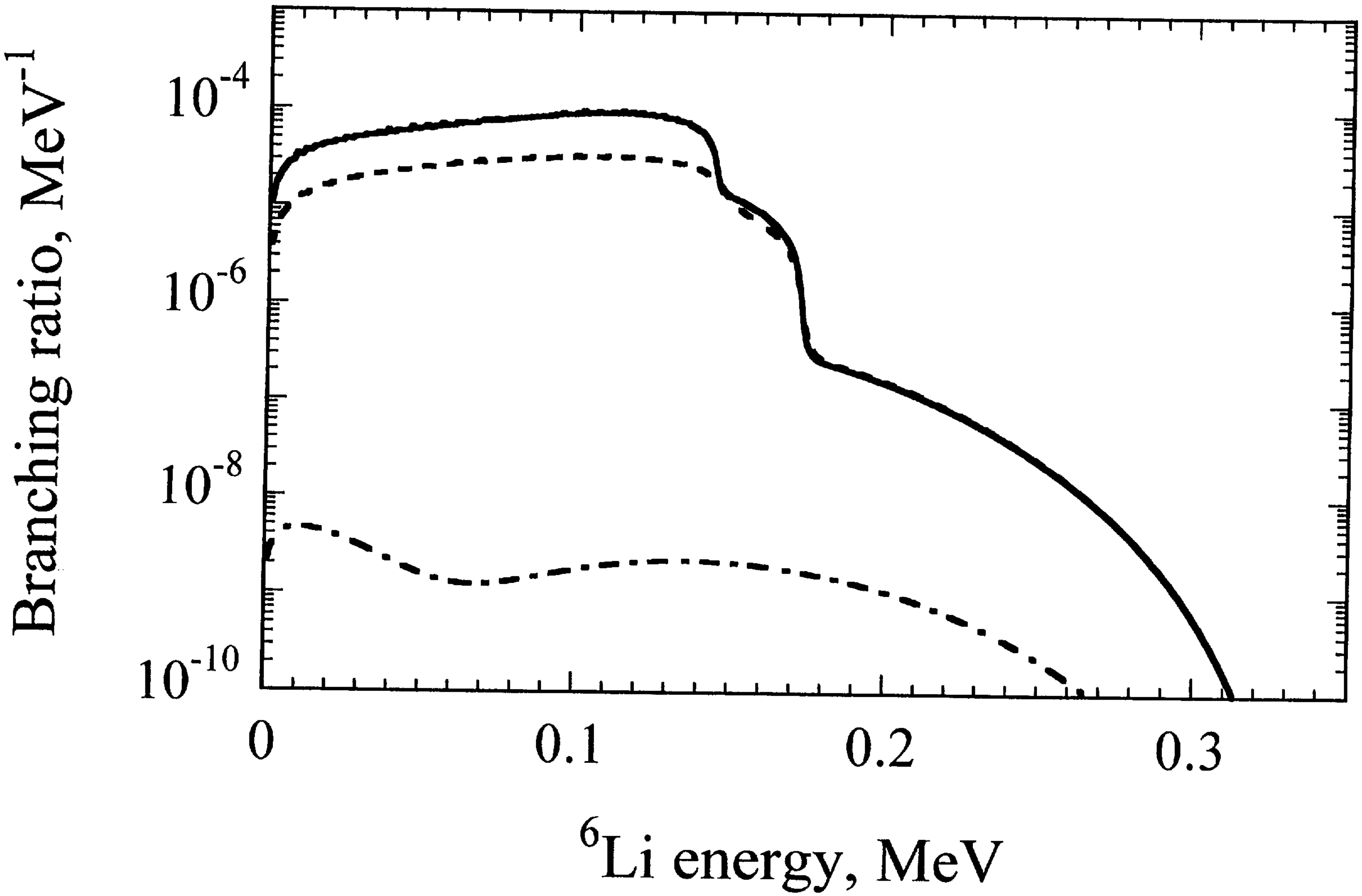
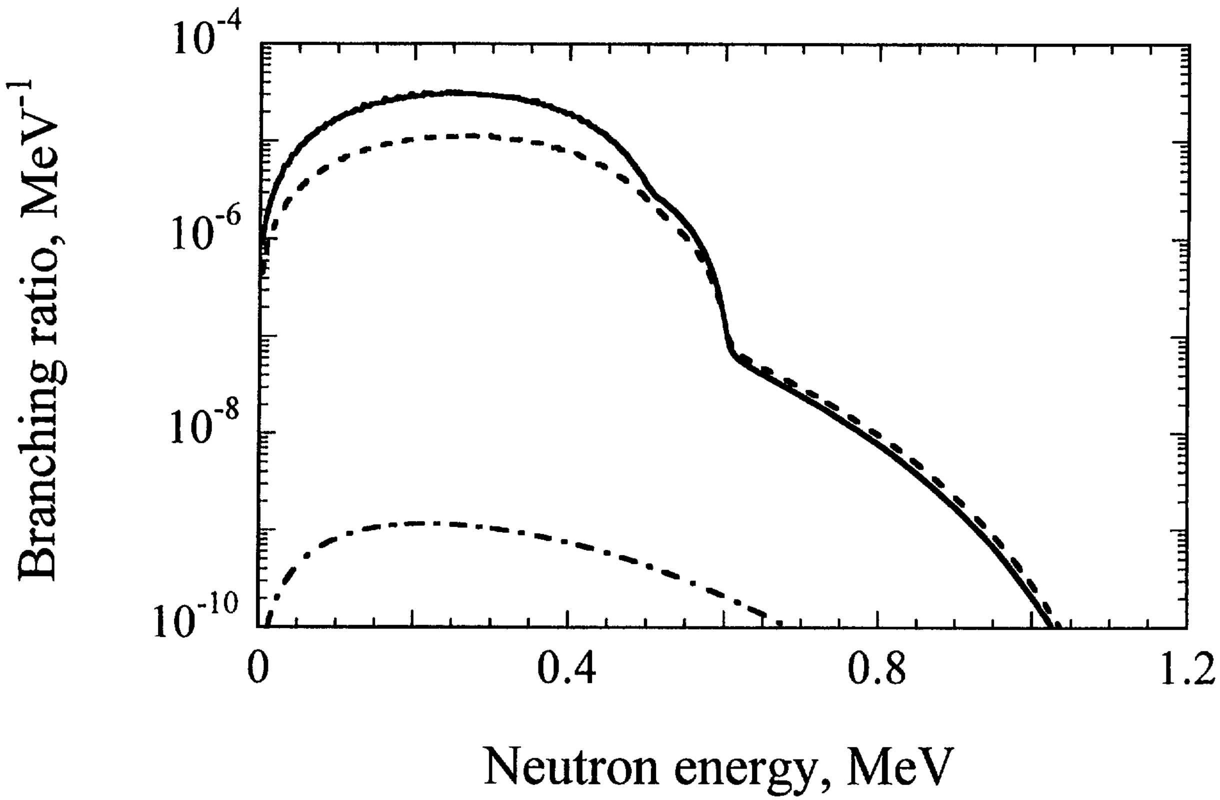


Fig. 2



Branching ratio, MeV$^{-1}$
$10^{-4}$
$10^{-6}$
$10^{-8}$
$10^{-10}$
0
0.1
0.2
0.3
$^{6}$Li energy, MeV

Fig. 3



$10^{-4}$
$10^{-6}$
$10^{-8}$
$10^{-10}$
0
0.4
0.8
1.2
Branching ratio, $MeV^{-1}$
Neutron energy, MeV