नाभिकीय अभिक्रिया

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दुर्बल-बंध नाभिक के साथ विविध अभिक्रिया चैनलों का व्यवस्थित अध्ययन

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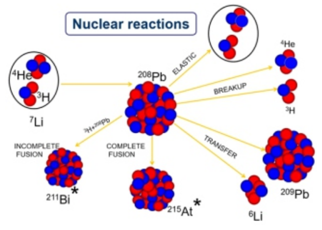

दुर्बल-बंध नाभिक के साथ नाभिकीय अभिक्रिया ।

सारांश

पिछले तीन दशकों में भापअ केंद्र-टीआईएफआर पेलेट्रॉन लीनॉक (एलआईएनएसी) त्वरक सुविधा, मुंबई का उपयोग करके दुर्बल-बंध प्रक्षेपकों (^{6,7}Li, ^{9}Be आदि) के साथ प्रत्यास्थ प्रकीर्णन, संलयन, विघटन एवं हस्तांतरण जैसी विभिन्न नाभिकीय अभिक्रियाओं का अध्ययन किया गया। हमने सभी अभिक्रिया चैनलों हेतु उपलब्ध आकड़ों के समुच्चय के साथ व्यवस्थित अध्ययन किया है। मापों एवं अध्ययनों के विवरण रिपोर्ट में दर्शाये गए हैं।

Nuclear Reactions

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Systematic Study of various Reaction Channels with Weakly-bound Nuclei

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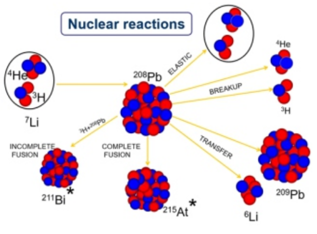

Nuclear Reactions with weakly-bound nuclei.

ABSTRACT

Various nuclear reactions like elastic scattering, fusion, breakup and transfer have been studied with weakly bound projectiles (^{6,7}Li ^{9}Be etc.) using the BARC-TIFR Pelletron LINAC accelerator facility, Mumbai over the last three decades. We have performed systematic studies with the available set of data for all the reaction channels. The details of the measurements and systematic studies are given in this report.

KEYWORDS: *Complete and Incomplete fusion, breakup, alpha production, neutron transfer, systematic study*

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Introduction

Weakly bound nuclei are characterized by predominant cluster structures and low separation energies; *viz*; $^{6}Li \rightarrow \alpha+d$, $S_{\alpha d}$ = 1.46 MeV, $^{7}Li \rightarrow \alpha+t$, $S_{\alpha t}$ = 2.46 MeV, $^{9}Be \rightarrow \alpha+\alpha+n$, $S_{\alpha\alpha n}$ = 1.57 MeV. These small separation energies suggest that these nuclei can easily break in the nuclear or Coulomb field, which in turn can influence the scattering and/or reaction cross-sections [1,2]. A schematic diagram of different possibilities for the breakup in the reaction of a typical two-cluster projectile ^{7}Li interacting with target A is shown in Fig.1. Study of nuclear reactions involving weakly bound projectiles is very interesting because of the observation of several unusual features compared to the case of strongly bound projectiles. With this in view, we have carried out several investigations using BARC-TIFR Pelletron Linac facility over last three decades to understand the reaction mechanisms involving these stable weakly bound projectiles on a range of target nuclei. Energy and angular distributions as well as integrated cross sections were measured for various reaction observables like elastic scattering, transfer, breakup and fusion around Coulomb barrier energies. A suppression in complete fusion cross section at above Coulomb barrier energies [1-13], a drastic change in the energy dependence of the optical potential [1,2], and a large production of α particles [1,2,6,14-16] are some of the important features associated with the above reactions. These observations are known to be largely due to the effect of projectile breakup on other channels. Recently, we have also done a compilation of available experimental data for complete and incomplete fusion, α particle production, neutron transfer and reaction cross sections which was utilised to understand the systematic behaviour with strongly and weakly bound projectiles. These studies help in building the foundation for similar studies with unstable weakly bound nuclei to be available with upcoming radioactive ion beam (RIB) facilities. Some of the results from the systematic study are highlighted in this report.

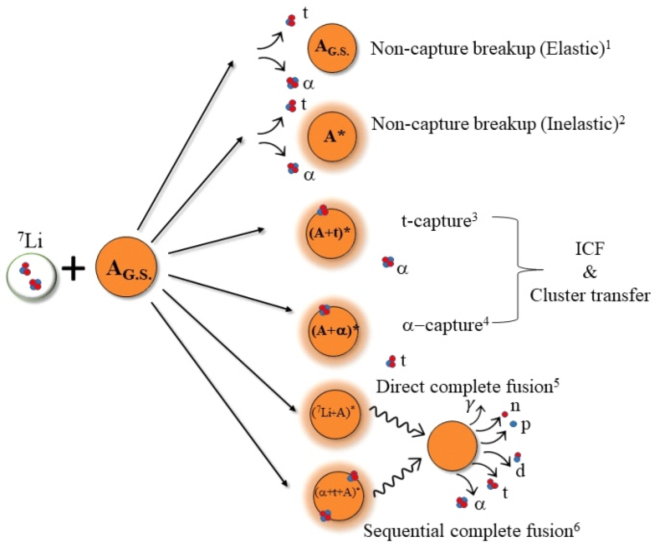

Fig.1: Pictorial representation of various reaction processes involving two-cluster ^{7}Li (α+t) projectile interacting with target A.

Results and Discussion

Fusion cross sections

Fusion cross section is defined as the probability of formation of compound nucleus. The fusion cross sections are mostly estimated by direct detection of evaporation residues or online and/or offline γ-ray de-excitations from the evaporation residues. Fusion can be divided into two parts: Complete and Incomplete fusion. When the entire projectile or all its fragments are captured, then the process is known as Complete Fusion (CF). If only a part of the projectile fuses with the target, then the process is known as incomplete fusion (ICF). In the case of weakly bound nuclei, both CF and ICF processes are important. It is seen in many systems that there is an enhancement of CF cross sections over the one dimensional barrier penetration model calculation. It is also found that CF cross sections are suppressed when compared to predictions based on a coupled channel model at energies above the Coulomb barrier. In addition, reduced fusion cross sections with weakly bound projectiles at energies normalized to the Coulomb barrier were also found to be systematically lower than those with strongly bound projectiles forming a similar compound nucleus (Fig.2(a)). In particular, experiments with ^{6,7}Li and ^{9}Be projectiles on medium and heavy mass targets have led to interesting conclusions on the systematics

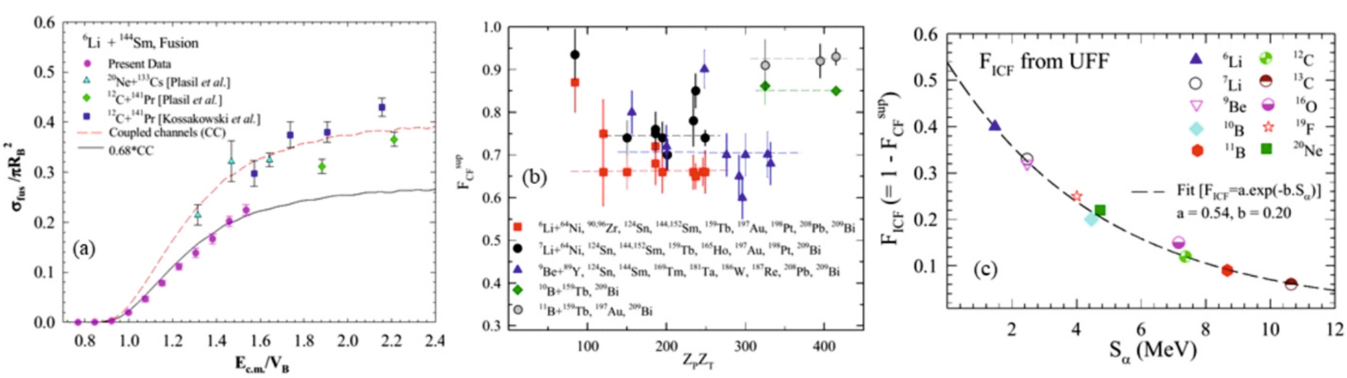

Fig.2: (a) Comparison of reduced fusion cross sections as a function of reduced energy for different systems involving SBP and WBP forming the same CN, (b) Systematics of F^{sup}_{CF} as a function of Z_PZ_T for different systems involving ^{6,7}Li, ^{9}Be, and ^{10,11}B projectiles, (c) ICF fraction (F_{ICF}) obtained for various projectiles as a function of α-separation energy, S_α. Figure taken from Ref. [6].

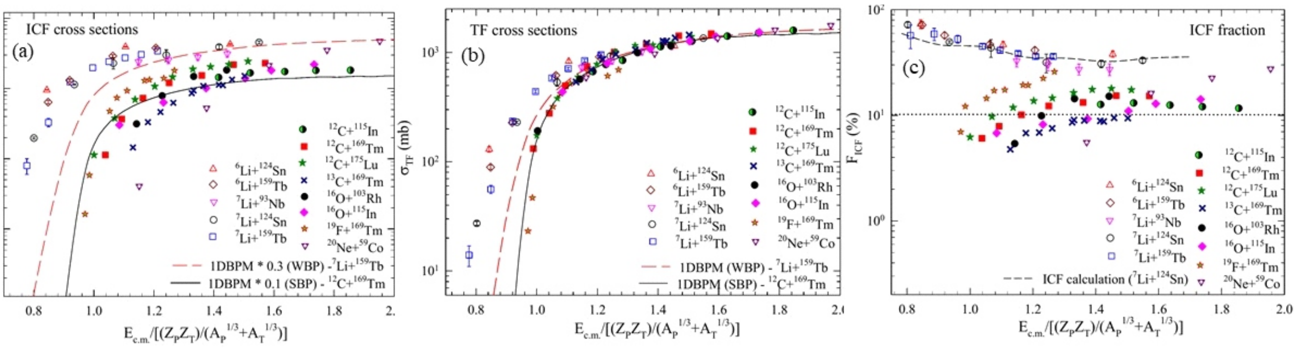

Fig.3: (a) ICF and (b) TF cross sections and (c) ICF fraction as a function of reduced energy for systems involving WBP and SBP. Figure taken from Ref. [6].

of the CF suppression factor. The suppression in CF involving these projectiles is found to be independent of target mass in many studies (Fig.2(b)). Further the suppression factor shows an increasing trend with decrease in the breakup threshold of the projectile (Fig.2(c).

We have also compiled ICF data available for both strongly (^{12,13}C, ^{14}N, ^{16}O, ^{19}F, ^{20}Ne) and weakly bound (^{6,7}Li, ^{9}Be, ^{6,8}He) projectiles. A systematic behaviour of ICF cross sections (σ_{ICF}) is observed for various projectile–target systems as a function of reduced energy (E_{red}) as shown in Fig.3(a). In general, σ_{ICF} for the WBP systems is higher than that for the SBP systems. A comparison of the total fusion (TF) cross sections (σ_{TF}) as a function of reduced energy (E_{red}) for different WBP and SBP systems is shown in Fig.3(b). The TF cross sections are enhanced for ^{6,7}Li WBP systems as compared to the SBP systems at below barrier energies. This can be mainly attributed to larger contribution of ICF for WBP systems at these energies. At above barrier energies, TF cross sections for both WBP and SBP systems are similar and these can explained well by calculations. A quantitative assessment of the relative contribution of ICF to TF cross sections was also made using the percentage ICF fraction ($F_{ICF}(\%) = (\sigma_{ICF}/\sigma_{TF}).100$) as shown in Fig.3(c). The increase of $F_{ICF}(\%)$ at sub-barrier energies in case of WBP may be attributed to the increased importance of ICF driven by breakup and transfer processes as compared to the CF processes. The $F_{ICF}(\%)$ is smaller in case of SBP and it shows a larger variation among values for different systems.

A systematic analysis of the fusion cross sections around the Coulomb barrier energies with stable weakly bound (^{6}Li, ^{7}Li, ^{9}Be) and strongly bound ^{12}C projectiles on various targets was also performed by using the neutron flow model and coupled channels approach. The analysis shows that both models are successful in explaining the near barrier fusion data. Further, it is also observed that the collective degrees of freedom as well as the neutron flow influence the near barrier fusion process involving weakly bound projectiles [12,13].

Inclusive α production

As the weakly bound nuclei have the α+x cluster structure with very low separation energy, the α production cross sections are found to be very large compared to their counterpart. The angular distribution of these α-particles were measured using silicon detector array and the integrated production cross sections were extracted. The yield of evaporation a particles due to the CF contribution can be separated out using the statistical model predictions. The CF part has been estimated from the statistical model calculations using code PACE2 and non-CF inclusive α production cross sections have been determined. The plot of non-CF inclusive α production cross sections with reduced energy for various projectile types (WBP, SBP, RIB) is shown in Fig.4. An increase in cross section with incident energy and a reasonable similarity in the behaviour involving different systems for the same type of projectile nuclei (WBP and SBP) is observed [6,15]. In WBP, two lines corresponding to ^{6}Li, ^{9}Be and ^{7}Li are shown with dotted and dashed lines respectively. The line for RIB is shown by dashed dot dot line while SBP region is shown in hashed region because of slight variation. Overall, three distinct regions *viz*; RIB, WBP and SBP are clearly distinguished from the plot. The significant contribution of breakup of projectile like nucleus after neutron transfer apart

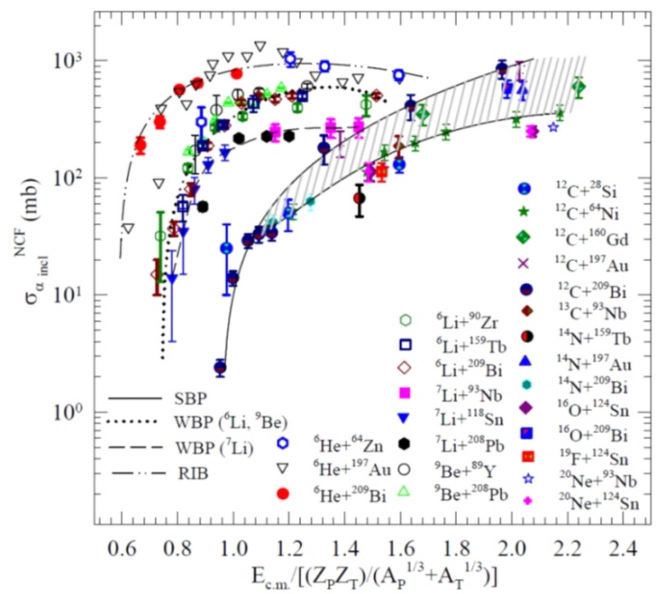

Fig.4: Systematic comparison of inclusive α production cross sections due to non-CF processes for different nuclear systems in three categories: (I) SBP, (ii) stable WBP, and (iii) RIB. Lines are guide to an eye.

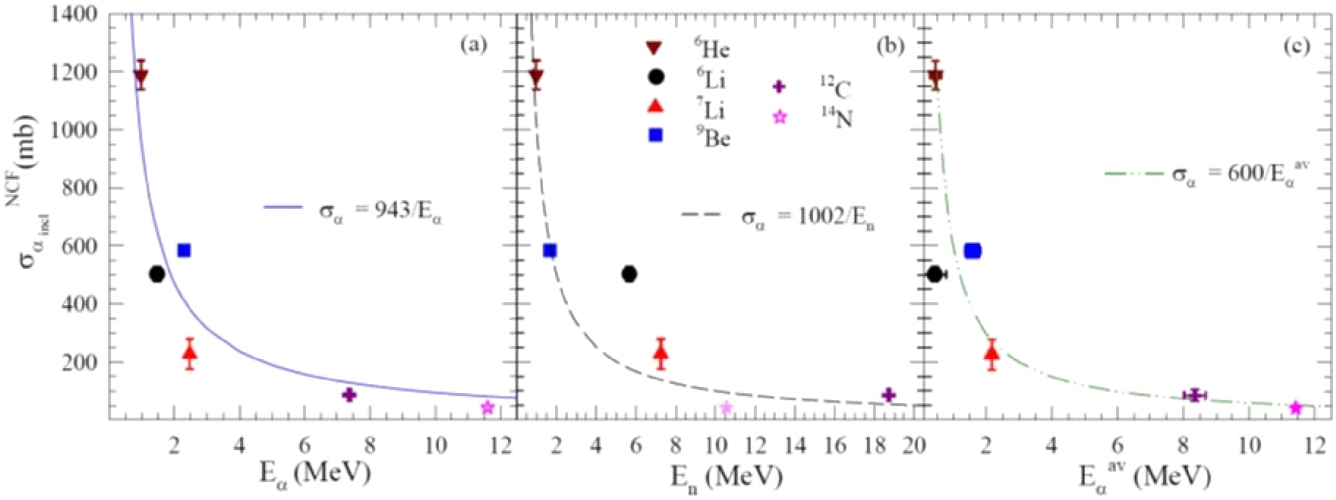

Fig.6: (a) Value of non-CF inclusive α cross section for various projectiles at 1.2Vb as a function of binding energies of (a) α (E_α), (b) neutron (E_n), and (c) average of α binding energies of the projectile and projectile like nucleus after neutron transfer (E_{av}α) is shown. The lines are fit to the data.

from processes like direct breakup of the projectile, capture of a fragment of the projectile by the target leaving α as a spectator suggest that both α and neutron binding energies play a vital role in α production [15]. In view of this, it is suggested that E_{av}α, average of α binding energies of the projectile and projectile like nucleus after neutron transfer is a suitable variable to describe the α production data for variety of projectiles [15].

The non-CF a cross section with heavy target at ≈ 1.2Vb is plotted for all the projectiles and shown as a function of E_α and E_n in Fig.5(a) and (b) respectively. $1/E_\alpha$ and $1/E_n$ behaviour was found to describe the α data of all the systems very well. the α binding energy values of the projectile like nuclei after neutron transfer (from projectile or to projectile from the target) are very similar to the α binding energies of the projectile. Hence a new variable E_{av}α which is equal to $0.7E_\alpha$(of projectile) + $0.3E_\alpha(n-tr)$ (of projectile like nucleus after neutron transfer) which is used in Fig.5(c). This procedure takes into account the dependence on α binding energies of the projectiles and also on neutron binding energies through the process of neutron transfer and the resultant α binding energies of the projectile like nuclei. This procedure gives the best fit to the data.

Neutron transfer

Neutron transfer (stripping and pickup) cross sections were also extracted from offline γ-ray measurements and are plotted in Fig.6 [A-C] for ^{7}Li[17], ^{6}Li[18] and ^{9}Be[19] respectively. As can be seen from the figures [A-C], universal behavior in the cross sections is observed in all the plots. The data was then fitted with modified Wong formula with introduction of neutron separation energies (and transfer probabilities) of the projectile and fitted (shown as lines). From the fit, early onset of these transfer processes as compared to the nominal barrier as observed in data [17-19]. In the case of ^{9}Be, neutron transfer is found to be dominant at below barrier energies [20].

Summary

The systematic study of fusion, α production and neutron transfer with weakly bound projectiles is performed. In the fusion studies, it is observed that the CF cross sections are suppressed above barrier energies with respect to model calculations for total fusion and this amount of suppression is commensurate with ICF cross sections. Also, the suppression factor is found to remain constant for a particular projectile and it increases with decreasing the separation energy of the projectile. Study of ICF cross sections with systems involving strongly and weakly bound projectiles has been performed. The ICF cross sections with WBP systems are higher than that with SBP systems at all the energies. ICF cross sections with WBP increases at below barrier energies, showing the importance of breakup channel. A systematic study of the α-particle production in reactions involving both the weakly and strongly bound projectiles at energies around the Coulomb barrier has been performed and a distinction based on projectile type is obtained. The neutron transfer study suggests early onset of transfer processes as compared to the nominal barrier. Similar studies with upcoming RIBs will be vital in extending these systematics.

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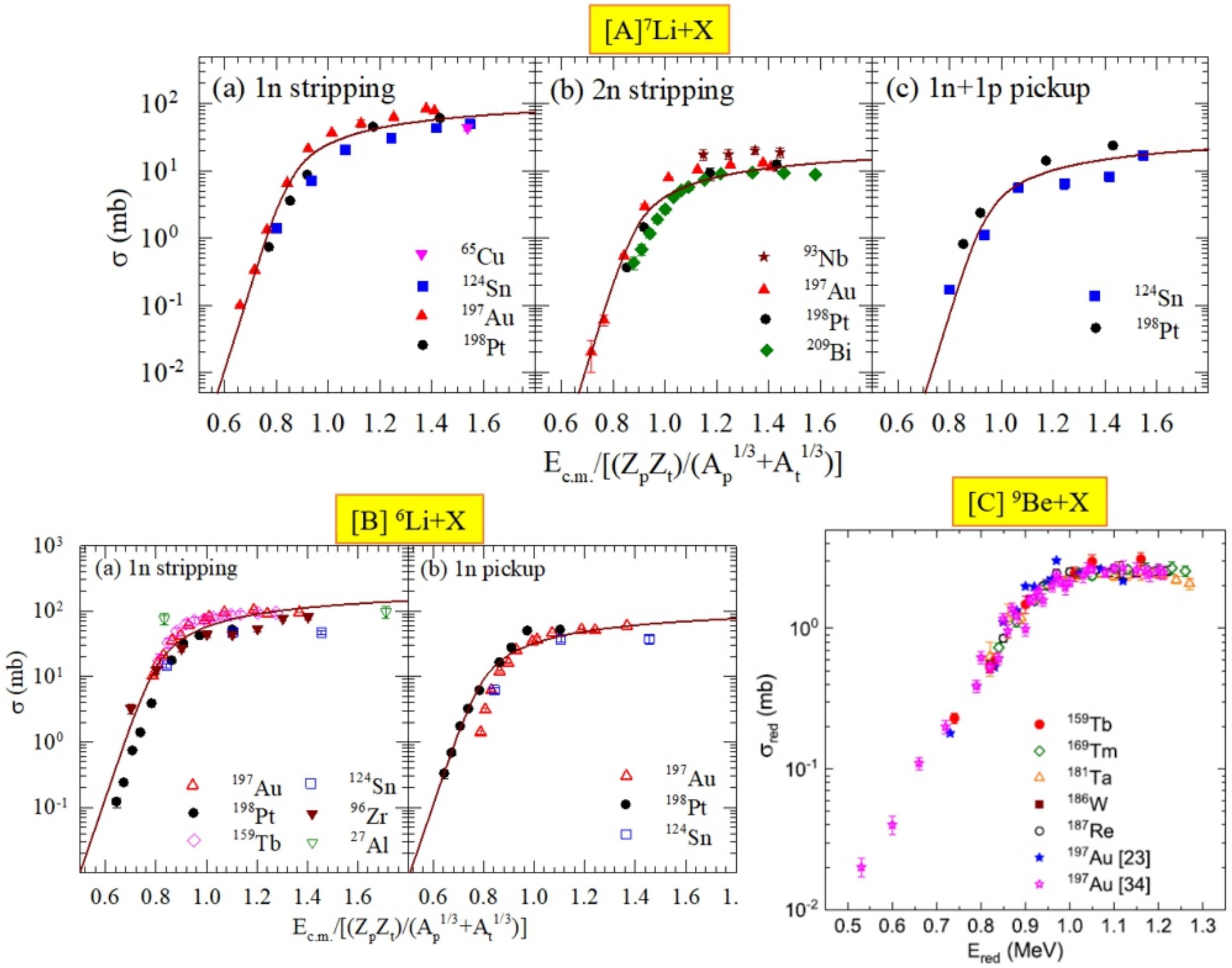

Fig.6: Systematic behaviour of neutron transfer cross sections in [A] ^{7}Li [17], [B] ^{6}Li [18] and [c] ^{9}Be [19] induced reactions.

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