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QUASI-MONOENERGETIC NEUTRON SOURCES

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A review is presented on 1) the structure, 2) the neutron yield and spectrum, and 3) examples of applications of the quasi mono-energetic ^{7}Li(p,n) neutron source for neutron energies above 30 MeV. The characteristics of the source like neutron intensity and spectrum are described together with the application of the source to neutron-induced cross section studies, characterization and development of neutron detectors, shielding benchmark experiments and the irradiation test of micro-electronic devices. Recent progress in the attempt to improve source intensity and the tail correction method are also mentioned.

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1. Introduction

Monoenergetic neutron sources are indispensable for studies of neutron-induced cross-sections, response functions of neutron detectors and dosimeters, and for irradiation test of semiconductors and so on [1]. Below 20 MeV, purely monoenergetic neutrons are obtained via the ^{7}Li(p,n), T(p,n), D(d,n) and T(d,n) reactions except for the 8-13 MeV region. Above around 25 MeV, however, only quasi mono-energetic sources are available because of the occurrence of multi-body breakup processes as shown inFig.1 [2].

In this energy region the ^{7}Li(p,n) reaction provides a quasi monoenergetic neutron source of high intensity. The fraction of the peak component in the neutron spectrum is around 50 % for ten's of MeV protons. The source has been used in various laboratories: the Crocker Nuclear Laboratory, University of California (UC), Davis (En≤ 65 MeV) [3], the Institute de Physique Nucleaire, Louvain-la-Neuve (≤75MeV) [4], TRIUMF (Tri-University Meson Factory), Vancouver (200-500 MeV) [5], the Svedberg Laboratory (TSL), Uppsala (50-150 MeV) [6], Cyclotron Laboratory, Indiana University, Bloomington (30-200 MeV) [7], iThemba Labs, South Africa [8,9], TIARA, JAEA [10], RCNP Osaka University [11], RIKEN [12] and at CYRIC, Tohoku University, Japan [13]. Recently, the ^{9}Be(p,n) reaction is also used as a quasi-monoenergetic neutron source for studies of neutron-induced activation cross-sections [14].

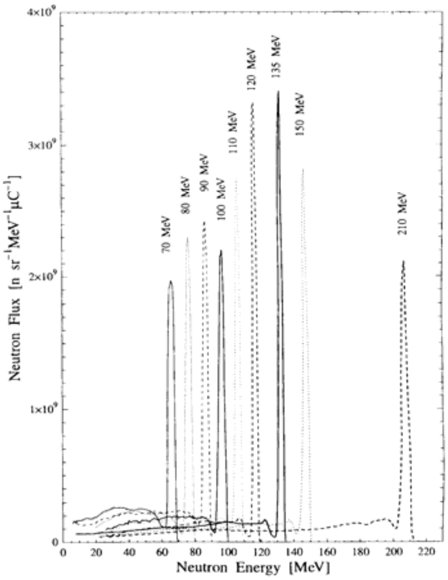

Fig.1 Neutron spectra from the ^{7}Li(p,n) source [2].

These quasi-monoenergetic neutron sources have been used for cross-section studies of neutron-induced reactions, characterization and calibration of neutron detectors and dosimeters, and irradiation tests of micro-electronic devices. They were used efficiently also for shielding benchmark experiments taking advantage of the narrow energy distribution in the peak.

However, there have been problems inherent to the source; one is the limitation in the neutron intensity and the other is the existence of continuum neutrons which requires the use of difficult correction methods to the measured data and limits the utilization of those radiation fields. Recent efforts resulted in marked progress to overcome the problems.

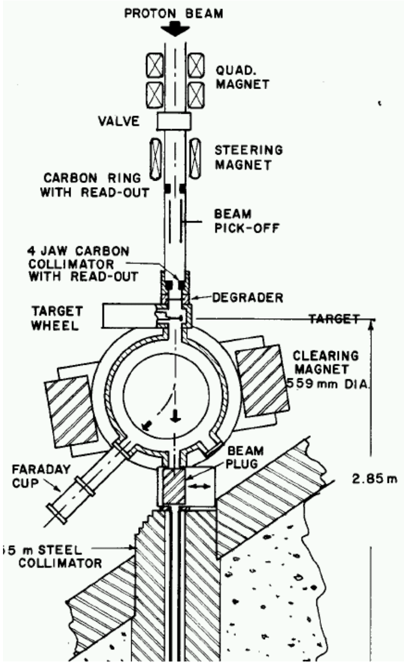

Fig.2; ^{7}Li(p,n) source at UC Davis [3]

This paper presents a review on the 1) characteristics, 2) application and 3) upgrading of quasi-monoenergetic sources toward higher intensity and elimination of the effect of beakup neutrons (i.e. tail correction).

2. Characteristics of quasi-monoenergetic neutron source

2.1 The ^{7}Li(p,n) neutron source

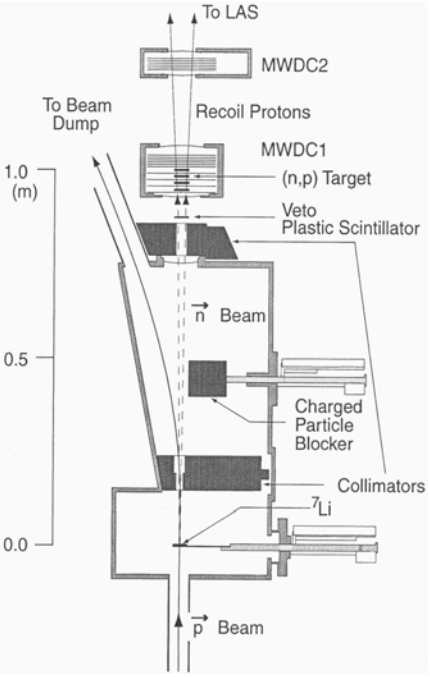

Fig.3 ; Neutron source at RCNP [9]

Figure1 illustrates the layout of the ^{7}Li(p,n) source at UC Davis ($E_n \leq 65$ MeV) [2], where various pioneering works in neutron-induced nuclear-physics and nuclear data research were performed. Neutrons are produced by energetic protons hitting a lithium metal target of appropriate thickness to obtain mono-energetic peaks with energy spreads of ~1.0 MeV. In this target setup most of the incident protons pass through the lithium target without reaction. These protons are swept out of the neutron beam into a shielded beam dump by a bending magnet because they would produce a large amount of background if they hit the end of the beam tube. Furthermore, there are rather thick shielding materials around the experimental area, the lithium target and the beam dump to shield neutrons emitted to non zero-degree directions. Generally, for collimating the beam and shielding the experimental setup, the experimental area is far away (typically several meters) from the neutron source . This leads to a limited neutron flux for the experiment. As shown in Table 1 which summarizes the parameters of various lithium sources, in the case of UC Davis, the distance is about 3 meters and the maximum neutron flux is about $6{\cdot}10^5$ n cm^{-2} s^{-1} for a ~1 MeV thick target even at a rather large beam current of 10 μA . The sources at UCL Leuvain-le-Neuve, Uppsala University and TIARA, JAEA were constructed using a similar concept. In the original design

Table 1; Comparison of ^{7}Li(p,n) neutron source

	Energy	ΔE	distance	Flux (n/cm$^2{\cdot}$s)	Current	Reference
UC Davis	40~60 MeV	1 MeV	3 m	$6{\cdot}10^5$	10 μA	2
Louvain	65 MeV	2 MeV	3.3 m	10^6	10 μA	3
Uppsala	25~180 MeV	1 MeV	3 m (8 m)	$3{\cdot}10^5$	10 μA	5
TIARA	30-85 MeV	2 MeV	5.2 m	$1.2{\cdot}10^5$	3 μA	8
TRIUMF	200 MeV	0.7MeV	~ 1 m	10^5	0.3 μA	4
RCNP	300 MeV	1 MeV	~ 1 m	$3{\cdot}10^5$	0.5 μA	9
CYRIC	20~90 MeV	1 MeV	0.7 m	~10^7	10 μA (H$^-$)	11

On the other hand, the sources at RCNP (Fig.3) and TRIUMF employ rather short distances to compensate for the low intensity of the proton beams. Moreover, in these cases, there is no need of a thick shielding because the detectors employed are not sensitive to background neutrons.

2.2 Neutron spectrum and intensity of the ^{7}Li(p,n) source

As shown in Fig.1, the neutron spectrum of the ^{7}Li(p,n) reaction consists of a mono-energetic peak due to the ^{7}Li(p,$n_{0,1}$) process and a continuum which is attributed to the breakup process [2,15]. The spectral shape of the continuum neutrons for 0-deg was studied at TIARA [15] and RIKEN [2] with a TOF method and a proton-recoil telescope method. It was found that it can be described by a three-body phase-space distribution [15,16] corresponding to the ^{7}Li(p,n^{3}He)α process in the 40- 90 MeV region as shown in Fig.4. In the higher proton energy region, however, the spectrum tends to be harder than predicted by the phase-space distribution (see Fig.1), probably due to the increasing contribution of a quasi-free scattering process. Therefore, in this energy region, it is necessary to consider the additional components.

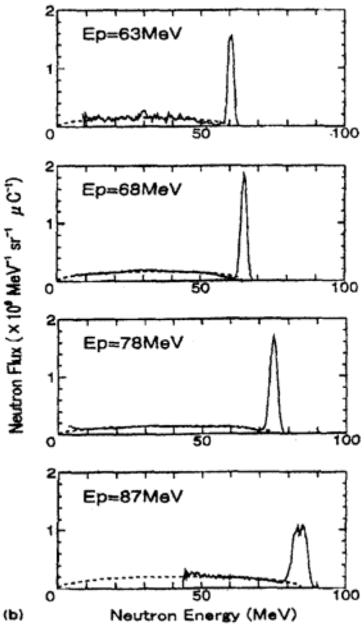

Fig.4: Comparison of the experimental continuum ^{7}Li(p,n) spectra (solid line) with a three-body phase space distribution (dotted line) [15,16]

The continuum neutrons are inherent to the source reaction. Therefore, in many cases, the continuum component produces back-ground which can be eliminated by taking data in a whole energy range, from lower energy up to the maximum energy required and apply appropriate data analysis procedures using an unfolding method with the help of theoretical calculation. However, the correction is generally difficult because of unknown energy dependence of the quantity of interest and statistical uncertainties in each reaction rate mainly due to the limited neutron intensity. Therefore, new approaches to correct for the effect of continuum components are highly desired as well as the increase of neutron intensity. These problems are discussed in sect. 4.

The differential cross section of the peak neutron production is known fairly well [17,18]. The cross section at 0-deg is almost constant around 35 mb/sr above around 30 MeV[17,18], and the angular dependence is also described universally in terms of the momentum transfer (Fig.5) [17,18]. Therefore, the yield and the angular dependence of the peak neutrons can be estimated fairly accurately by the calculation if the target thickness is known.

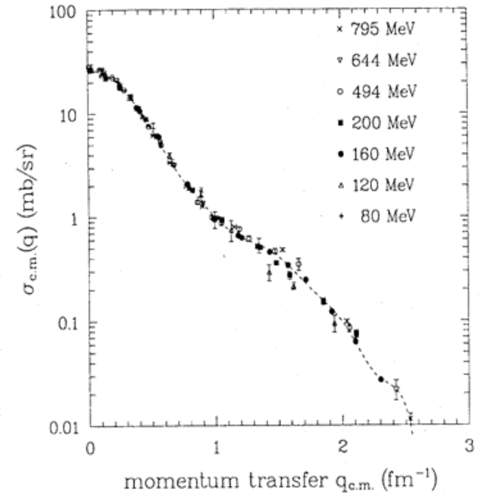

Fig.5; Angular distribution of the ^{7}Li(p,$n_{0,1}$) neutrons in terms of a momentum transfer [17,18].

3. Utilization of the ^{7}Li(p,n) source

This section describes shortly various applications of quasi-monoenergetic neutron sources.

3.1 Study of neutron induced reaction cross-sections

Neutron-induced activation cross sections are important for radiation safety and play an important role in the evaluation of dose rate e.g. at accelerator facilities. Measurements of activation cross sections can only be done with monoenergetic neutrons [19,20]. Here typical examples are shown. Figure 6 illustrates the results for ^{209}Bi(n,Xn) reactions which are useful to obtain the information on the spectrum of neutron fields. The cross sections were obtained by Kim et al through systematic measurement by using the ^{7}Li(p,n) neutrons at TIARA (<80 MeV) and RIKEN (70-210 MeV). The results for the ^{12}C(n,2n) reaction is also shown in Fig. 6(b) [19].

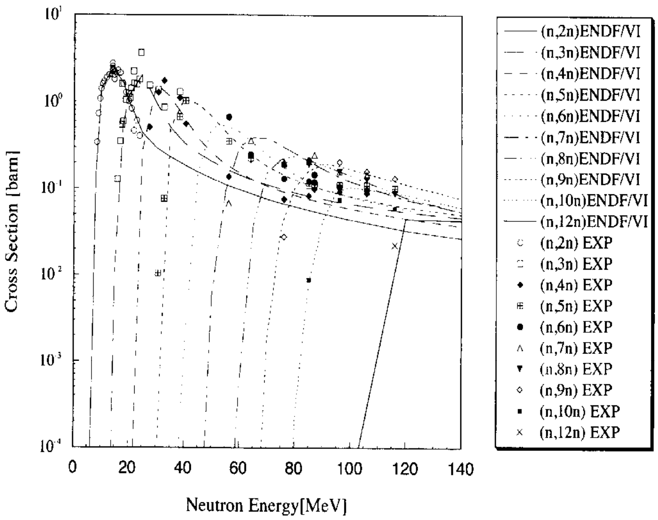

Fig.6(a): ^{209}Bi(n,Xn) cross sections [19].

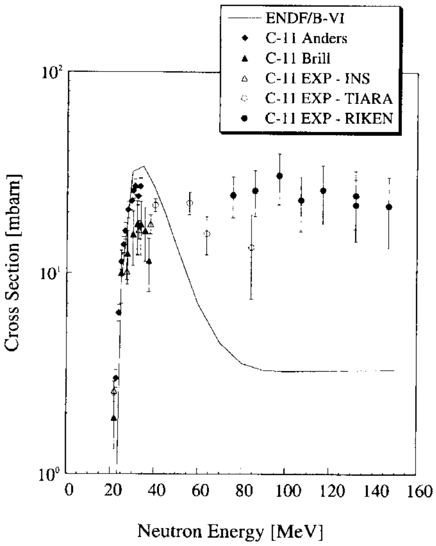

Fig.6(b): ^{12}C(n,2n) cross section [19].

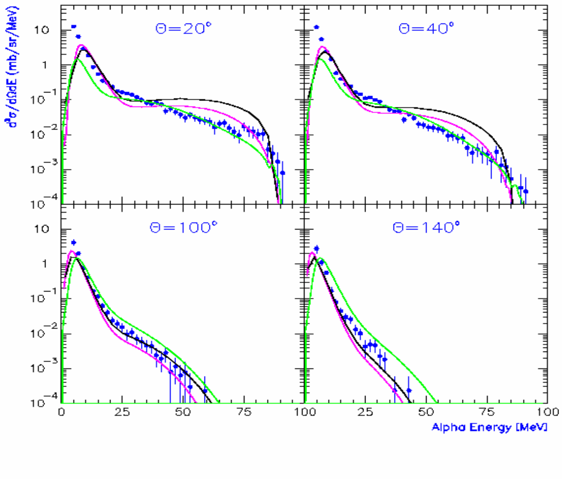

Fig.7(a): Double-differential (n,xα) cross sections of Si at 96 MeV[21].

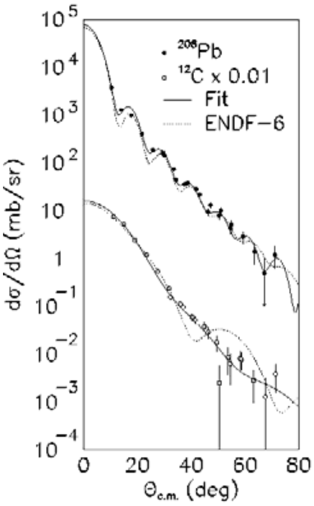

Fig.7(b);Neutron elastic scattering cross sections at 96 MeV [21]

In these studies, the contribution of background neutrons was eliminated by use of the cross section data obtained with theoretical calculations [19]. In the case of the ^{209}Bi(n,Xn) reaction, the correction can be done reasonably well because the shape of the calculated excitation function was consistent with the calculation. However, in the case of the ^{12}C(n,2n) reaction, a straight forward correction based on calculations may lead to incorrect results because of different energy dependence between the calculation and the experiment.

The ^{7}Li(p,n) source has been used successfully for the measurement of cross sections of charged-particle production [21,22] and neutron scattering [21,23] at UC Davis, UCL, TSL, TIARA/ Tohoku University In these cases, the correction for the background neutrons can be done experimentally by selecting only peak neutron events using the TOF (time-of-flight) information of the detectors.

3.2 Response functions of neutron spectrometer and dosimeter

The ^{7}Li(p,n) source contributed significantly to the measurement of response functions of neutron detectors and dosimeters[14,23]. Mono-energetic neutrons are essential for passive detectors which have no ability of energy discrimination.

Figure 8 illustrates examples of response measurements for a liquid scintillation counter BC501A, 5”-diameter by 5” thick at TIARA and RIKEN [2, 24]. Only the peak neutron events were selected using the TOF information. Comparison of the results with calculations indicated deficiencies of the Monte Carlo codes SCINFUL and CECIL as shown in Fig.8 [2,24]. These problems were traced to be due to the improper light-output and reaction cross section data employed. The code SCINFUL-R which is the revised version of SCINFUL now reproduces the measured response functions well and predicts the neutron detection efficiency within ~10 % up to 80 MeV [24]. Similarly, the same procedure is applied to other detectors like CR39, neutron rem counters, Bonner spheres and so on [25-26].

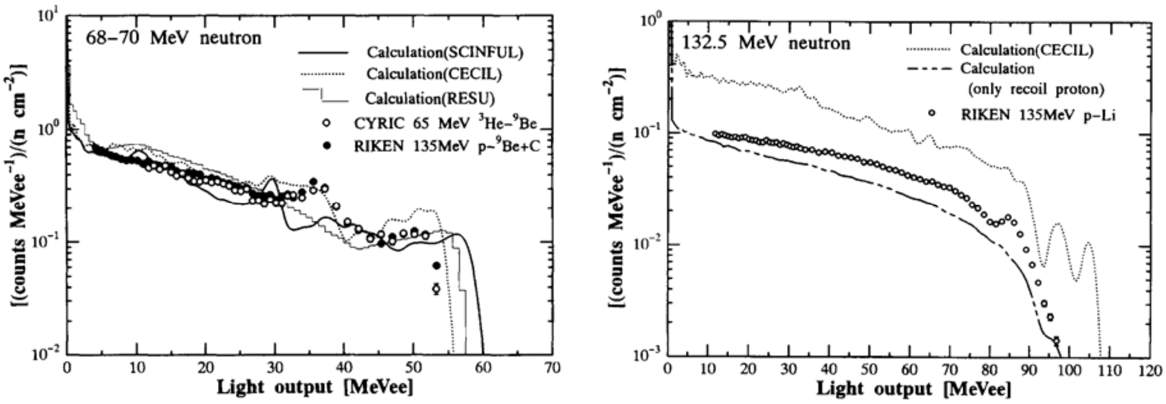

Fig.8; Measured response functions of a BC501A scintillation detector to 68-70 MeV neutrons (left) and 132.5 MeV neutrons, compared with calculated ones. [24,2]

3-3 Neutron irradiation of microelectronics devices

In recent years, a monoenergetic neutron beam is used for neutron irradiation experiments for single-event-upset (SEU) of semiconductor micro-electronics devices. Mono-energy neutrons enable us to study the energy dependence of the SEU sensitivity. Such experiments are conducted in TSL, RCNP and Tohoku University, etc. In these experiments, high neutron intensity with low background is essential to carry out experiments efficiently. A higher neutron flux is also very important to make data corrections for background neutrons using unfolding techniques.

For the reasons described in section 4, neutron sources with much higher intensity were installed at TSL and Tohoku University, and used succesfully for the irradiation test of microelectronics devices in collaboration with industry [21] .

3.4 Shielding benchmark experiment

In TIARA, the ^{7}Li(p,n) source was used to make shielding benchmark experiments for iron, concrete and polyethylene which are the major shielding material [25-27]. The experiments were conducted with the geometry shown in Fig.9(a). The shielding materials were bombarded with well-collimated ^{7}Li(p,n) neutrons and the neutron spectra behind the materials were measured using BC501A scintillation detectors, Bonner spheres and neutron dosimeters.

The results were compared with calculations using various Monte Carlo codes. Typical results are shown in Fig.9(b). They indicate problems in the codes and the data base. This experimental data facilitated the improvement of the codes.

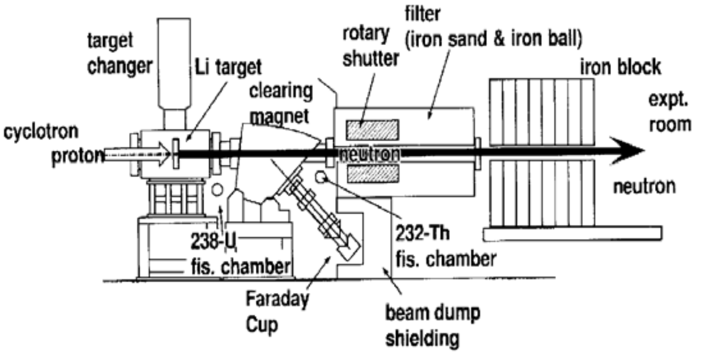

Fig.9(a); Experimental setup in the neutron shielding benchmark experiment using a quasi-monoenergetic neutron beam at TIARA [25]

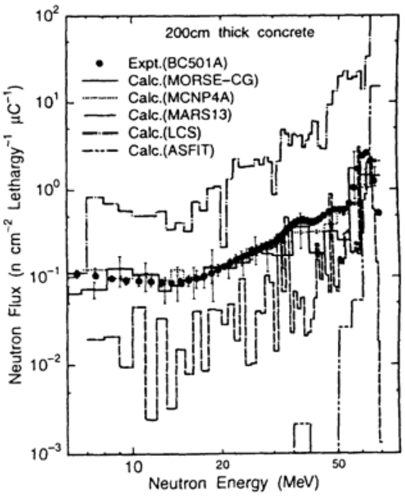

Fig.9(b): Example of a shielding benchmark experiment at TIARA

4. Recent progress in quasi-mononeneregtic source development

As described above, the ^{7}Li(p,n) source has been used effectively for various basic and applied works. Nevertheless, there have been very serious problems inherent to the source which limited the use of it, namely, the 1) limited neutron flux and 2) the existence of continuum background neutrons. For more effective utilization of the source these drawbacks should be eliminated.

4.1 Upgrading of the ^{7}Li(p,n) source

For the first problem, the low neutron flux, an increase of the proton beam current is one simple solution, but it induces a high load to accelerators and increases the activation and damage of accelerator components. The TSL laboratory of Uppsala University and CYRIC Tohoku University took another approach. The TSL laboratory modified the existing source to enable a shorter distance between the source and the experimental area from ~ 11 m to ~ 3 m and succeeded in increasing the neutron flux by about one order of magnitude at the same proton beam current. The layout of the new facility is shown in Fig.10.

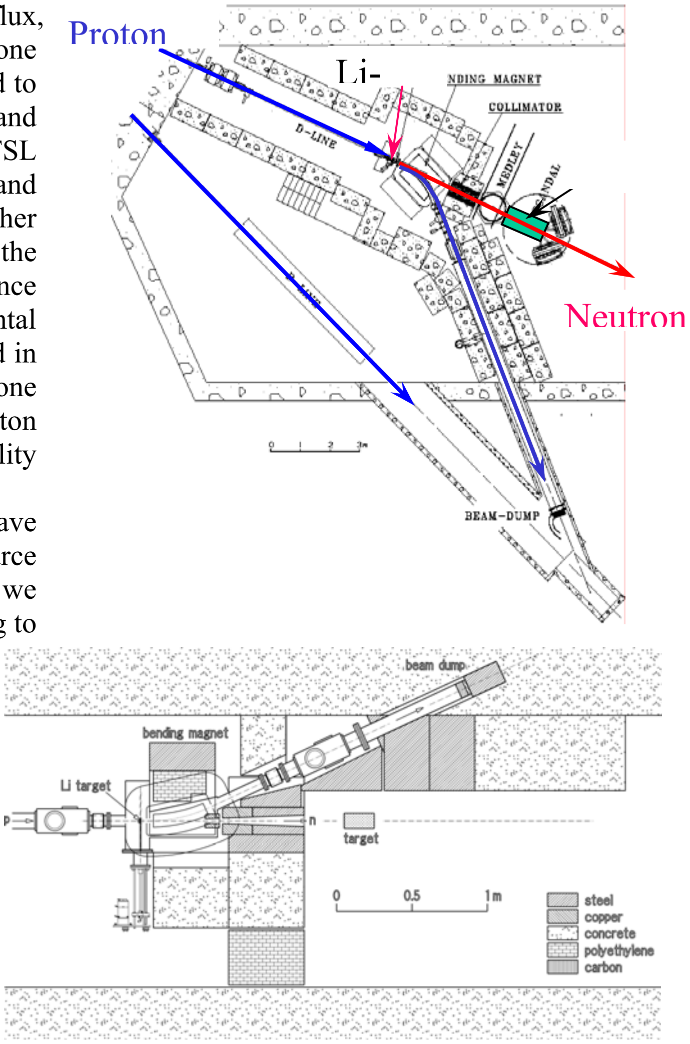

Fig.10; ^{7}Li(p,n) neutron sources at TSL, Uppsala univ., (upper) [20] and CYRIC, Tohoku univ.[27], for higher intensity

In CYRIC, Tohoku University, we have designed and constructed a new source shown in Fig.10. In this design, we employed a modular structure of shielding to enable a source-detector distance as short as 75 cm. This is applicable in cases where very light shielding is sufficient, e.g. in experiments where the physical process investigated has a very high threshold energy. As summarized in Table 1, the neutron flux available for experiments is the highest world-wide, at present. For investigation of neutron-induced cross sections, the distance is usually 1 to 1.5 m with a conical collimators of Cu and Fe of 75 cm length between the target and the experimental point. For effective shielding, a special design was applied to the dipole magnet for the beam dump. The shield proved to be appropriate also for SEU experiments for semiconductor devices. The high neutron flux is very useful as shown by the facts that the SEU could be observed even in DRAM devices, which are insensitive to SEU, during irradiation times of a few hours. Furthermore, fragment-production cross sections could be measured within an experiment lasting only several hours, applying a high efficiency Bragg curve counter for fragment detection [28,29].

4.2 Development of tail correction methods

As mentioned in Sect.3, the data correction for the contribution of the continuum neutrons (tail correction) are difficult and disturb the progress of the experiments. Recently, Nolte et al and Sisterson et al reported an interesting method to eliminate or reduce the contribution experimentally for the ^{7}Li(p,n) and ^{9}Be(p,n) sources[9,14]. Figure 11 illustrates the principle of the method. It is based on the fact that the spectrum of the tail component is almost the same at 0 deg and at larger angles, e.g. at 16-deg. Therefore, the subtraction of the data obtained at 16-deg from the ones measured at 0-deg provides approximately the data which would be obtained in a true monoenergetic spectrum - although the tail components cannot be eliminated completely. This method has a potential to eliminate the problems associated with the tail correction and thereby promote the experiments using mono-energy sources.

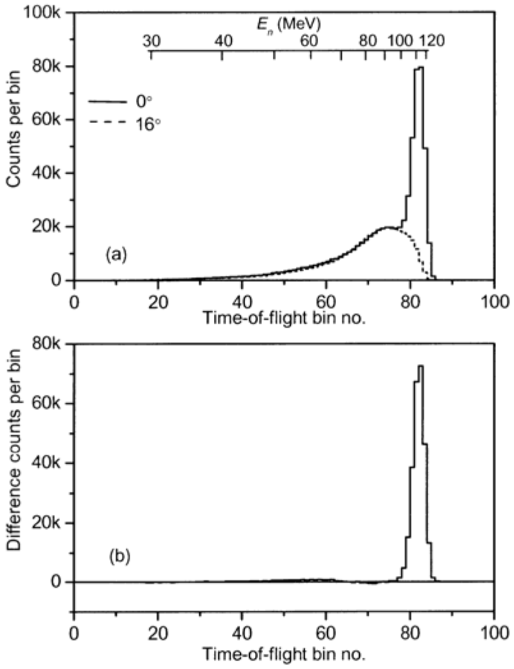

Fig.11;Schematic view of experimental method for tail correction of the Be(p,n) source [14].

We have also studied the applicability of the method to the ^{7}Li(p,n) source around 70 MeV by measuring the angle-dependent spectrum and found that the method may be applied to the source which may result in higher neutron flux at equivalent energy resolution

5. Summary and outlook

The status and recent progress in monoenergetic neutron sources above 20 MeV was reviewed. Monoenergetic neutrons are essential in various basic and applied area. Recent research indicated the possibility of drastic progress in the fields owing to the improvements of the intensity and the tail correction method.

Nevertheless, the characteristic of the ^{7}Li(p,n) and the Be(p,n) which are the most promising sources, are not clear enough, in particular for the continuum tail. Therefore, benchmark studies on the properties of these sources, performed by an international collaboration between laboratories using these sources, would be very useful.

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References

[1] *Proc. IAEA Advisory Group Meeting on Intermediate Energy Nuclear Data* (Oct., 1991), *INDC(NDS)-245* (Feb. 1991, IAEA)

[2] N.Nakao, T.Nakamura, M.Baba, Y.Uwamino, N.Nakanishi, H.Nakashima, Sh.Tanaka, *Nucl. Instrum. Methods* A362 (1995) 454

[3] J.A.Jungerman and F.P.Brady, *Nucl. Instrum. Methods,* 89 (1970) 167

[4] A.Bol., P.Leleux, P.Lipnik, P.Macq and Ninane, *ibid.,* A256 (1983) 169

[5] R.Helmer, *Can. J.Phys.* 65 (1987) 588

[6] H. Conde, S.Hultqvist, N.Olsson, T.Ronnqvist, R.Zorro, J.Blomgren, G.Tibell, Hakansson, O.Jonsson, A.Lindhom, L.Nilsson, P.-U.Renberg, A.Brocksteds, P.Ekstrom, M.Osterlund, F.P.Brady, and Z.Szeflinski, *Nucl. Instrum. Methods,* A292 (1990) 121

[7] A.V.Prokofiev, S.Pomp, J.Blomgren,,O.Bystrom, C. Ekstrom,, D.Reistad, U.Tippawan, V.Ziemann, and M.Osterlund, This proceedings

[8] http://www.tlabs.ac.za/public/Links.htm, Ref.12

[9] R.Nolte, M.S.Allie, P.J.Binns, F.Brooks, A.Buffler, V.Dangendorf, J.P.Meulders, F.Roos, HSchumacher, B.Wiegel, *Nucl. Instrum. Methods.*,A476, (2002) 369

[10] Su.Tanaka, T.Nakamura, M.Baba, M.Imamura, H.Hirayama, K.Shin, Sh.Tanaka, R.Tanaka, *Proc. 2nd Int'l Symposium on Advanced Nuclear Energy Research -Evolution by Accelerators-"*, (January 24-26, 1992, Mito), 342

[11] http://www.rcnp.osaka-u.ac.jp/Divisions/np1-a/n0/index.html

[12] http://www.rarf.riken.go.jp/rarf/exp/e4/smart.html, see also ref.2

[13] A.Terakawa, H.Suzuki, K.Kumagai, Y.Kikuchi, T.Uemori, H.Fujisawa, N.Sugimoro, K.Itoh. M.Baba, H.Orihara, K.Maeda; *Nucl. Instrum. Methods.*,A491, (2002) 419, http://www.cyric.ac.jp

[14] J.S.Sisterson, F.D.Brooks, A.Buffler, M.S.Allie, D.T.L.Jones, M.B.Chadwick; *Nucl. Instrum. Methods.,* B240 (2005) 617

[15] M.Baba , Y.Nauchi, T.Iwasaki, T.Kiyosumi, M.Yoshioka, S.Matsuyama, N.Hirakawa, T. Nakamura, Su.Tanaka, S.Meigo H.Nakashima, Sh.Tanaka, N.Nakao, *Nucl. Instrum. Methods* A428 (1999) 454

[16] G.G.Ohlsen, *Nucl. Instrum. Methods,* 37 (1964) 240

[17].T.N.Taddeucci, C.A.Goulding, T.A.Carey, R.C.Byrd, C.D.Goodman, C.Caarde, J.Larsen, D.Horen, J. Rapaport, E.Sugarbaker, *Nucl.Phys.,* A469 (1987) 125

[18] S.G.Mashnik, M.B.Chadwick, P.G.Yoing, R.E.MacFarlen, and L.S.Waters, *LA-UR*-00-1067

[19] E.Kim, T.Nakamura, A.Konno, Y.Uwamino, N.Nakanishi, M.Imamura, N.Nakao, S. Shibata and S.Tanaka: *Nucl. Sci. Eng.,* 129 (1998) 1

[20] E.g., R.Michel, W.Glasser, U.Herpers, H.Schuhmacher,H.Brede, V.Dangendorf, R.Nolte, P.Malmbork, A.Prokofiev, A.M.Smirnov, I.Rishkov, D.Kollar, J.P.Meulders, M.Duijivestijin, and A.Koning, *Proc. In. Conf. Nuclear Cross Section for Sci.Technol.,* Oct. 2004, Santa fe, AIP-769 (2005) 861,

[21] E.g., J.Blomgren.; *idem.,* (2005) 730

[22] Y.Nauchi, M.Baba, T.Sanami, T.Iwasaki, N.Hirakawa, T.Nakamura, S.Tanaka, S.Meigo, Y.Watanabe, M.Harada, and H.Takada: *Proc. Int. Conf. Nuclear Data for Sci. & Technol.*, (1997 Trieste) 613

[23] M.Ibaraki, M.Baba, T.Miura, Y.Nauchi, Y.Hirasawa, N.Hirakawa, H.Nakashima, S.Meigo. O.Iwamoto, and S.Tanaka., S.Meigo, *Nucl. Instrum. Methods* A446 (3) (2000) 625

[24] S.Meigo, *Nucl. Instrum. Methods* A 401 (1997) 365

[25] N.Nakao, H.Nakashima, T.Nakamura, Sh.Tanaka, Su.Tanaka, K.Shin, M.Baba, Y.Sakamoto, and Y.Nakane, *Nucl. Sci. Eng.,* 124 (2) (1996) 228

[26] N.Nakao, H.Nakashima, Su.Tanaka, Y.Sakamoto, Y.Nakane, Sh.Tanaka, K.Shin, and M.Baba, *J. Nucl. Sci. Technol.,* 34 (1997) 348

[27] H.Nakashima, N.Nakao, Sh.Tanaka, T.Nakamura, K.Shin, Su.Tanaka, H.Takada, S.Meigo, Y.Nakane, Y.Sakamoto and M.Baba, *ibid.,* p.243

[28] M.Baba; *Proc. In. Conf. Nuclear Cross Section for Sci.Technol.,* Oct. 2004, Santa Fe, AIP-769 (2005) 884,

[29] M.Hagiwara, .Sanami, M.Baba, T.Oishi,S.Kamada,, T.Okuji, M.Baba, *CYRIC Annual Report 2004*, Cyclotron and Radioisotope Center, Tohoku University, p. 41 (2005)