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Measurement of fast neutron spectra from the interaction of 20 MeV protons with thick Be and C targets using CR-39 detector

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ABSTRACT

Fast neutron spectral yield from the interaction of 20 MeV protons with thick Be and C targets are measured using CR-39 detectors. An image analysing program (autoTRAK_n) dedicated for neutron spectrum generation and dose estimation is developed based on the analysis of greylevel variations within each track and is used in the present study. The most important parameters for neutron spectrometry, i.e., track depth (length) and angle of all neutron-induced recoil tracks are determined using autoTRAK_n. The methodology is tested successfully to reproduce the spectra of some standard neutron sources which was reported earlier. In this study, autoTRAK_n is applied to generate neutron spectra from the above mentioned reactions, i.e., ^{9}Be(p, n), ^{12}C(p, n) and the neutron yields (total number of neutrons per projectile) for both the reactions are determined by folding the track density with the detector response. The dose equivalents and $H^{*}(10)$-to-fluence ratios are also estimated. All these quantities are automatically obtained from the program. The neutron yield and the dose equivalent for ^{9}Be(p, n) reaction are found to be about 4 times higher than that for ^{12}C(p, n) reaction. The present methodology for neutron spectrum generation is found to be simple and effective and does not involve the complex spectrum unfolding procedures.

1. Introduction

A detailed knowledge of the neutron energy spectra is needed in order to achieve an appropriate level of protection against neutron exposure because of the strong dependence of neutron weighting factor and fluence-to-dose conversion coefficient upon its energy [1]. Moreover, thick target neutron yield (TTYN) measurements typically at medium projectile energy range are scarce in the literature and are important for the radiation protection purposes, especially for positive ion accelerators [2]. Neutron spectrometric measurements usually involves multi-detectors or multi-spheres to cover the wide range of energy distribution for which either active [3–5] or passive [6–8] methods are employed along with the complicated mathematical tool for unfolding the spectrum [9–11] which further requires a response matrix either measured or simulated and a guess spectrum to start with in addition to the experimentally measured detector observables. Particularly for radiation protection purposes, it is also important to discriminate different radiation components because the conversion coefficients available at ICRP [12] are not same for all types of radiations. Furthermore, in case of accelerator radiation environment where the field is often pulsed and has a large influence of RF field, it is often inconvenient to use active detectors [13,14]. In such situations, the best possible method is to use a passive detector such as CR-39, which has an excellent characteristic in charged particle registration [15–17]. These detectors not only register the signal (almost permanently) in time integrated mode, also are insensitive to low LET radiations and RF interference [18,19]. Plenty of works are reported in literature regarding the use of CR-39 detectors for neutron dosimetry based on either dose calibration curves [18,20,21] or LET (Linear Energy Transfer) spectrum measurement [22–24], whereas reports on the use of CR-39 for neutron spectrometry are limited.

Some attempts are already made to implement CR-39 detectors as neutron spectrometers [25–34]. However, each of these methods has its own merits and demerits over the other methods. In this aspect, a new methodology is developed to use CR-39 detectors for neutron spectrum measurement by analysing the 2-dimensional track images obtained from optical microscopes. This method is based on the analysis of greylevel variations within each track thus providing all the relevant track parameters including the depth and angle of each track. The detailed method and the algorithm of this program (autoTRAK) were reported earlier [35]. This program has been modified for neutron spectrum measurement by introducing the angular corrections for each track, detector efficiency, fluence-to-dose conversion coefficient, etc. The modified program, called as autoTRAK_n, was successfully tested to generate

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neutron spectra from some standard sources [34]. The program is also found to be efficient in dealing with high density overlapping tracks without involving the segregation procedure. In case of overlapping, all the merged tracks are counted as a single track by the commonly used image analysing softwares. This is corrected by the segregation procedure, where the overlapping or merged tracks are first identified and then separated automatically by the software based on the regular track geometry. It can also be done manually by marking the track boundaries with the cursor, so that all the merged tracks are counted separately. However, some computational time, especially for high density over lapping tracks, is consumed during the process.

In this work, neutron spectral yield, dose equivalent and the ratio $H^{*}(10)/\Phi$ from the reactions $^{1}H + {}^{9}Be$ and $^{1}H + {}^{12}C$ at 20 MeV proton energy are determined at 90° with respect to the direction of projectiles using CR-39 detectors and the image analysing program autoTRAK_n. The major objective to carry out this investigation is to experimentally determine the thick target neutron yields at this medium energy which is important for the radiation protection and shielding purposes. Another objective of this study is to apply the present methodology for determining the neutron energy spectra and dose related parameters. This approach is found to be simple and effective in terms of less duration of irradiation (about 3–5 min), simplicity in processing the detectors and analysing the data. However, the track revealing and imaging procedures are somehow time consuming and tedious but the recently developed microwave-induced chemical etching (MICE) technique [36] and automatic image analysing software are found to be useful in overcoming these difficulties.

2. Experimental details and methodology

2.1. Irradiation

The CR-39 detectors ($25 \times 30 \times 1.5$ mm^3, Intercast, Composition: $C_{12}H_{18}O_7$) were irradiated with neutrons generated by 20 MeV protons striking thick ^{9}Be and ^{12}C targets. The irradiations were performed at the 6 M irradiation port of the BARC-TIFR Pelletron Accelerator facility. The port is located above the analysing magnet and is suitable for irradiation experiments with beam currents up to a few μA. Since the range values of 20 MeV protons in ^{9}Be and ^{12}C are found to be 2.78 and 2.1 mm respectively, about 3 mm thick targets are found to be sufficient to stop the protons completely. Irradiation details such as the duration of exposure of CR-39 detectors and the number of projectiles bombarded on the ^{9}Be and ^{12}C targets are tabulated in Table 1.

In case of ^{9}Be target, the neutron yield from a total of about 1.5×10^{14} protons (3 min exposure) are found to be sufficient to register countable signals in CR-39 detectors whereas in case of ^{12}C target, the total number of projectiles needed is higher, i.e., 3.1×10^{14} (3 min) due to low neutron yield in the latter case. Nevertheless, the exposure duration in both the reactions is much less compared to any other neutron spectrum measurement techniques, though the exact time of irradiation is subject to the available beam current. All the detectors are irradiated at a distance of 3 inch (7.62 cm) from the source and at an angle of 90° with respect to the direction of the proton beam.

Table 1
Irradiation parameters showing the total number of projectiles hitting the thick targets along with the duration of exposure of CR-39 detectors to the emitting neutrons.

Reaction	Exposure duration of CR-39 detectors (s)	Total charge (μC)	Number of protons
$^{1}H + {}^{9}Be$	60	8.1	5.1×10^{13}
	120	15.0	9.4×10^{13}
	180	23.4	1.5×10^{14}
	240	30.3	1.9×10^{14}
	300	37.8	2.4×10^{14}
$^{1}H + {}^{12}C$	60	16.8	1.1×10^{14}
	120	34.5	2.2×10^{14}
	180	50.1	3.1×10^{14}

2.2. Track development and image capturing

Neutron-induced recoil tracks in all the irradiated CR-39 detectors are developed by chemical etching with 6.25 N NaOH at 70 °C for 9 h. The etched CR-39 detectors are then viewed under optical microscope (Carl Zeiss, AxioScope 1) at 200× optical magnification and the 2-dimensional images are snapped using a 5 MP digital camera attached to the microscope. The images are taken in transmission mode with a higher light intensity inside the tracks compared to the track boundaries. A total of about 100 images for each detector are taken selectively by avoiding the defective structures on the surface of CR-39 detectors. Similar procedure is followed for a pristine CR-39 to make background corrections.

2.3. Analysis of 2-dimensional track images

A program completely dedicated for neutron spectrum generation and dose estimation from the 2-dimensional track images of neutron-induced recoil tracks in CR-39 detectors obtained using simple optical microscopes, called as autoTRAK_n, is developed and tested successfully to reproduce the spectra of standard neutron sources [34]. The same methodology is applied in the present study to determine the neutron spectra, thick target neutron yield and relevant dose parameters from the $^{1}H + {}^{9}Be$ and $^{1}H + {}^{12}C$ reactions at 20 MeV proton energy. The tracks are analysed based on the greylevel variations within each track and all the relevant track parameters such as diameter, major axis, minor axis, area, depth, angle, etc. are determined automatically using autoTRAK_n.

Since the brightest pixel (with highest greylevel value) on the track image is considered to denote the largest track length traversed by neutron-induced recoil protons and the track length is linearly correlated with the range of the particle, it is reasonable to assign the highest range value to the brightest pixel. Then the variation of greylevel values in each track is assigned corresponding range values automatically. The range-energy relationship from the SRIM code [37] is then used to determine the energy distribution of recoil tracks. This distribution is corrected for recoil track angles and is folded with the neutron detection efficiency of CR-39 detector to generate the neutron energy spectrum. The dose related parameters are determined by folding the energy spectrum with the dose conversion coefficient provided by ICRP [12]. The thick target neutron spectral yields and relevant dose values are thus determined for the reactions, viz. $^{1}H + {}^{9}Be$ and $^{1}H + {}^{12}C$ at 20 MeV proton energy.

3. Results and discussion

Fig. 1 represents the recoil tracks in CR-39 detectors induced by the neutrons emitting from the reactions $^{1}H + {}^{9}Be$ and $^{1}H + {}^{12}C$ at 90° with respect to the direction of projectile. It can be observed from the figure that the track density in case of $^{1}H + {}^{9}Be$ reaction is found to be much higher (Fig. 1a) than that for the $^{1}H + {}^{12}C$ reaction (Fig. 1b) indicating a lower neutron yield in the latter case. Nevertheless, the track densities for both the cases are found to be statistically significant to generate the neutron spectra. All the relevant track parameters are analysed by autoTRAK_n program to generate the neutron spectra as shown below.

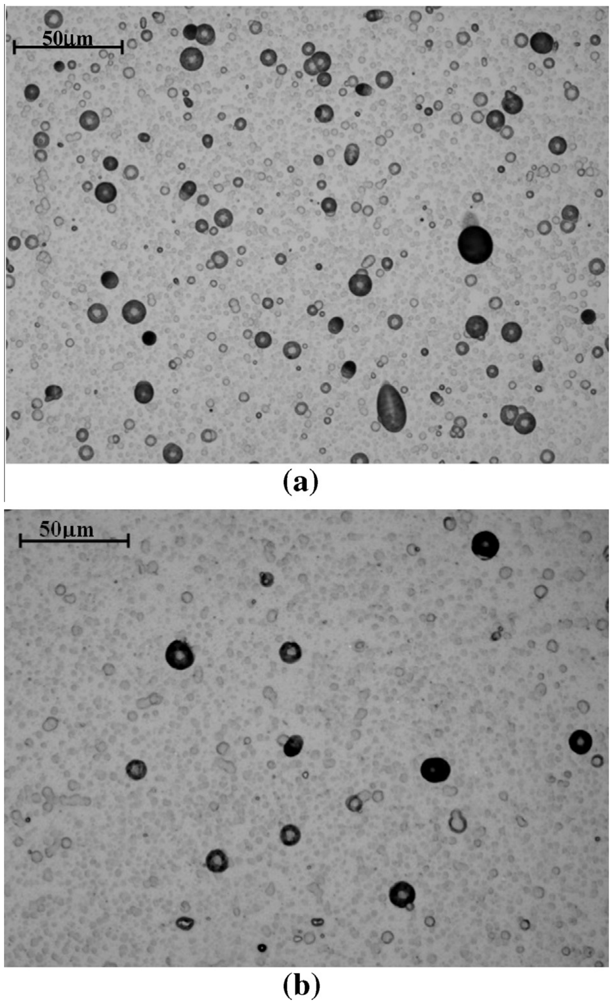

Fig. 1. Recoil tracks in CR-39 detectors due to neutrons emitting from (a) $^{1}H + ^{9}Be$ and (b) $^{1}H + ^{12}C$ reactions at 20 MeV proton energy. The tracks are developed by chemical etching (6.25 N NaOH, 70 °C, 9 h) and imaged at an optical magnification of 200×.

Fig. 2 shows the normalized (unit) neutron spectra for the reactions $^{1}H + ^{9}Be$ and $^{1}H + ^{12}C$ at 20 MeV proton energy. Both the spectra are generated by measuring the neutron-induced recoil tracks in CR-39 detectors and analysing the 2-dimenasional track images by autoTRAK_n. The error bars are provided to indicate the reproducibility of the methodology in generating the neutron spectra which are obtained by regenerating each spectrum for about 30 times, each time selecting a different set of statistically significant number of tracks randomly. As can be seen from Fig. 2, the peak for $^{1}H + ^{9}Be$ reaction is observed to be at slightly lower neutron energy compared to that for $^{1}H + ^{12}C$ reaction. Then both the spectra remain almost flat at higher energies. The mechanism of both the reactions can be described as follows.

The neutron emission mechanism from the Be and C targets when bombarded with 20 MeV protons proceed predominantly through the compound nucleus formation and decay mode. Accordingly, the emitted nucleons have a distribution characterized by a temperature and are symmetric about 90° in the center of mass frame of reference. When measured in the lab frame, a forward peaking is expected due to the kinematics. In case of Be target, the direct reactions are much more probable than C target. Such a reaction gives rise to a harder neutron spectrum, particularly in the forward direction. In case of C target, since natural carbon was used as the target, contributions from ^{13}C, having an

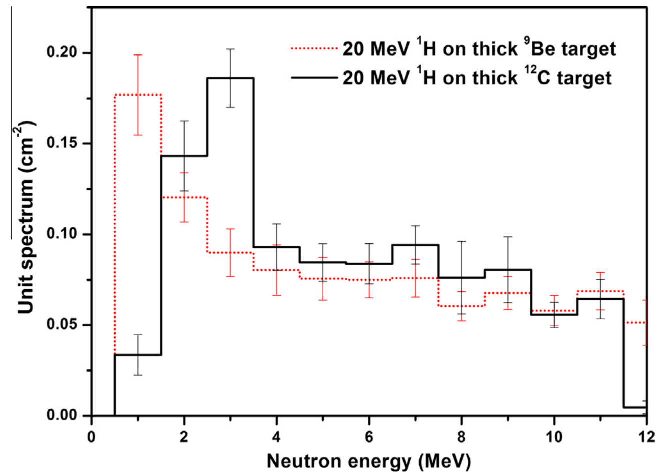

Fig. 2. The unit neutron spectra from $^{1}H + ^{9}Be$ and $^{1}H + ^{12}C$ reactions at 20 MeV proton energy, generated by measurement of track parameters in CR-39 detectors and using the image analysing program autoTRAK_n for the analysis of 2-dimensional track images.

isotopic abundance of about 1.1%, is also expected. However, for the $^{12}C(p, n)$ reaction, the threshold energy is 19.64 MeV [38] referring to the direct reaction where a nucleon is knocked off by the incident projectile. The probability for such a reaction is much lower than the compound nucleus formation at 20 MeV proton energy. For the compound nucleus formation, the Q value is positive (~1.5 MeV), resulting in excitation energy of about 20 MeV. The continuum emission characterized by a temperature of about 2.5 MeV is expected to give rise to neutrons up to about 20 MeV. However, the cross sections for such high energy neutron emission fall rapidly making their measurement difficult. Measurement of the higher energy neutrons by this technique require longer irradiation and in that process the track density in CR-39 detector caused by the larger number of more probable low energy neutrons would be too high to be counted. It is important to mention that, the irradiation, in this study, was performed at 90° with respect to the direction of projectile, thereby causing a reduction in the end point of neutron energy spectrum. Owing to these effects, the signals beyond 12 MeV in the CR-39 detectors are found to be of the order of the back ground contributions, so the spectral ener-

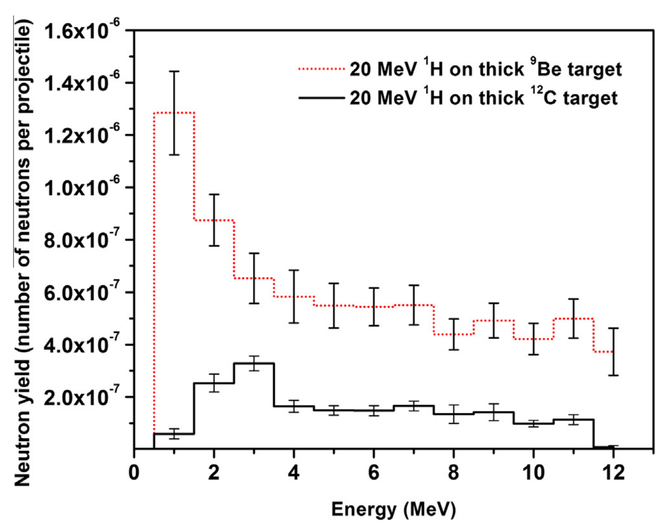

Fig. 3. Neutron spectral yield (total number of neutrons per projectile) for $^{1}H + ^{9}Be$ and $^{1}H + ^{12}C$ reactions at 20 MeV proton energy. The spectra are generated by measurement of track parameters in CR-39 detectors using the image analysing program autoTRAK_n.

Table 2
Thick target neutron yield (TTYN) for $^{1}H + ^{9}Be$ and $^{1}H + ^{12}C$ reactions at 20 MeV proton energy measured with CR-39 detectors and autoTRAK_n image analysing program.

Reaction	Track density (tracks cm^{-2})	Total neutron fluence (cm^{-2})	Total number of projectiles (protons)	Neutron yield (neutron/proton)
$^{1}H + ^{9}Be$	5.35×10^{5}	1.08×10^{9} (±1.1%)	1.5×10^{14}	7.20×10^{-6}
$^{1}H + ^{12}C$	2.63×10^{5}	5.70×10^{8} (±0.7%)	3.1×10^{14}	1.84×10^{-6}

Table 3
Dosimetric quantities estimated with autoTRAK_n for $^{1}H + ^{9}Be$ and $^{1}H + ^{12}C$ reactions at 20 MeV energy protons.

Reaction	Total neutron fluence (cm^{-2})	$H^{*}(10)$ (mSv)	$H^{*}(10)$/projectile (mSv proton^{-1})	$H^{*}(10)/\Phi$ (pSv cm^{2})
$^{1}H + ^{9}Be$	1.08×10^{9} (±1.1%)	445.6 ± 10.2	3.04×10^{-12}	413.0 ± 10.5
$^{1}H + ^{12}C$	5.70×10^{8} (±0.7%)	229.4 ± 3.18	0.74×10^{-12}	402.8 ± 6.2

gies are taken up to 12 MeV contributing maximum to the dose equivalent.

However, the spectral yield (total number of neutrons per projectile) cannot be determined from the normalized (unit) spectra. So the neutron fluence per projectile (proton) for both the reactions is plotted in Fig. 3. The relevant parameters for estimation of thick target neutron yields (TTYN), i.e. total number of neutrons produced per proton, are tabulated in Table 2. As evident from the table, the neutron yield is found to be about 4 times higher for the $^{1}H + ^{9}Be$ reaction than that for $^{1}H + ^{12}C$ reaction. The dose related parameters for both the reactions are compared in Table 3. The dose equivalent per projectile is also found to be about 4 times higher in case of $^{1}H + ^{9}Be$ reaction than that of $^{1}H + ^{12}C$. A comparison of these results with other such studies could not be made due to unavailability of data in literature for this particular energy, projectile and target combinations. Perhaps a few more experiments with similar set up and with different detection techniques would help to compare these results.

4. Conclusion

The neutron energy spectra and thick target neutron yields for $^{1}H + ^{9}Be$ and $^{1}H + ^{12}C$ reactions at 20 MeV energy protons are measured successfully using a simple methodology, i.e. CR-39 detectors and the image analysing program autoTRAK_n dedicated for neutron spectrometry and dosimetry. The dose parameters relevant for radiation protection and shielding purposes are also estimated from the track parameters in CR-39 detectors. The neutron yield and dose equivalent per projectile are found to be about 4 times higher for $^{1}H + ^{9}Be$ reaction than those for $^{1}H + ^{12}C$ reaction. The present methodology is found to be so simple and effective that it can always be used as a back-up or supplementary method while measuring the neutron spectrum using any other sophisticated techniques such as time-of-flight with liquid scintillators, Bonner sphere spectrometry or even activation foils as threshold detectors. The present method also does not require the complex neutron spectrum unfolding procedure. Moreover, the irradiation time is very short, i.e., just about 3 min of exposure is found to be sufficient in the present study, though it would depend on the beam current of the experimental setup. In any case, it is always possible to spare a few minutes to use this methodology as a supplementary technique. However, the track development and imaging processes are found to be time consuming and tedious but are simple procedures, which also can be overcome by using rapid etching techniques and automatic imaging systems. Further work is in progress to integrate the automatic image acquiring process in the autoTRAK_n program which will further reduce the manual steps of imaging setup and capturing and to verify the technique for different etching methods.

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