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Preliminary Experiments for Fast Neutron Radiography Using the D-Be Reaction

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The D-Be reaction was investigated with a 4.5 MV Van de Graaff accelerator and a 600 kV Cockcroft-Walton accelerator. Fast neutron yields were measured for deuteron beams with energy from 200 keV to 3 MeV bombarding a thick beryllium target. Also angular distributions for emitted neutrons were measured at several deuteron energies. Fast neutron radiography was carried out with simple samples at the 4.5 MV Van de Graaff accelerator. The preliminary experiment results indicate that the D-Be reaction at lower deuteron energies can be used for fast neutron radiography, if the gamma rays are sufficiently shielded.

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1. Introduction

Fast neutron radiography has been widely investigated in quite a few laboratories in the recent years. Both, reactor based [1-3] and accelerator based [4-6] neutron sources have been used for fast neutron radiography. So far the accelerators used for fast neutron radiography are mainly the cyclotron and Van de Graaff accelerators. Their dimensions are quite large and not suitable for in-situ and transportable equipment. The radio frequency quadrupole (RFQ) accelerator can handle the high current ion beam extracted from an ion source and accelerate it up to an energy of a few MeV. An RFQ is more compact compared to a cyclotron or a Van de Graaff accelerator, so an RFQ based fast neutron radiography is suitable for the in-situ applications. AccSys has designed several types of RFQ based neutron sources [7], which can be used for neutron radiography. The fast neutron radiography with a neutron tube has also been investigated [8], which is more suitable for mobile applications.

In accelerator based and neutron tube based neutron sources, D-D and D-T reactions were usually used to reach high neutron yield. In most cases titanium disks with adsorbed D or T gas were used as target, but the manufacture of Ti-D/T targets for high current beams is difficult and the lifetime of Ti-T targets are usually not very long. Alternatively, if a gas target is used, problems may be experienced with the entrance window to the gas target cell. Also the Be (d, n) reaction can produce high fluxes of fast neutrons. Thick beryllium targets are easy to manufacture and have a very long lifetime. They are of significant advantage in in-situ and transportable applications. But there are few experimental data of neutron yields produced by deuteron bombarded thick beryllium targets in the energy range from several hundred keV to a few MeV. Segre reported total neutron yields for deuteron energies of 400 keV, 600 keV and 800 keV [9]. Hawkesworth presented a yield curve for deuteron energies from 0.3 MeV to 6 MeV [10]. Meadows measured neutron spectra and yields at 0^{o} for deuterons with energies between 2.6 MeV and 7.0 MeV bombarding a thick beryllium target [11]. Neutron spectra and yields for higher neutron energies have been measured [12-14], and the fast neutron radiography has been carried out with the Be(d, n) reaction at PTB with a deuteron energy of 13 MeV [6]. Here an imaging system with fast timing capability combined with the Time-of-Flight (TOF) technique was employed, so that the gamma-ray image could be separated from the neutron image.

In this paper we studied the possibility to use a high current deuteron beam bombarding a thick beryllium target at rather low energy to produce a fast neutron source. The corresponding neutron yield in the energy range of 200 keV – 3 MeV was measured and compared with existing data.

To investigate the possibility and methodology of using this kind of neutron source for fast neutron radiography with an imaging system working in integration mode, demonstration experiments of fast neutron radiography were carried out with a deuteron beam and a thick beryllium target at the 4.5 MV Van de Graaff accelerator at Peking University. The experiments showed that gamma-rays emerging with the neutrons in D-Be reaction can interfere film based fast neutron radiography.

2. Neutron yield of deuteron bombarded thick Be target

2.1 Experiment set up

Neutron yields for deuteron energies between 1 MeV and 3 MeV were measured at the 4.5 MV Van de Graaff accelerator at Peking University. The accelerator can operate with a voltage down to about 1 MV. The target was a thick beryllium metal wafer. The target chamber was designed as a long cylinder to suppress the escape of secondary electrons. The deuteron beam intensity was several μA. A beam current integrator monitored the deuteron beam hitting the beryllium target. For measuring the neutrons two calibrated De Pangher long counters without collimators were used: one as fixed monitor, while another for the measurement of the neutron flux at the angles from 0° to 150° at different deuteron energies.

Neutron yields at deuteron energies between 200 keV and 500 keV were measured at the 600 kV Cockcroft-Walton accelerator at the China Institute of Atomic Energy. The target was the same one used before at the 4.5 MV Van de Graaff accelerator. A similar method as above mentioned was used, but the maximum angle measured was 135°.

2.2 Measurement results

Based on the experiments for deuteron energies from 9.4 to 13.6 MeV [14], Brede gave an empirical formula for the neutron yield in forward direction from deuterons bombarding thick beryllium targets:

$$Y_{\mathrm{n}}\left(E_{\mathrm{d}}\right) = AE_{\mathrm{d}}{}^{B}\,. \tag{1}$$

Y_{n} is the neutron yield in units of neutrons/sr/μC and E_{d} is deuteron energy in MeV, A and B are fitting coefficients. Meadows' experiments showed that the formula (1) can be used for lower deuteron energy, and he determined $A = 1.909\times10^{7}$ n/sr/μC and $B = 2.84$ for neutron energies of $E_{\mathrm{n}} > 0.05$ MeV by his experiment with deuteron energies ranging from 2.6 MeV to 7.0 MeV [11]. Our experiments indicate that the formula (1) is still true when the deuteron energy is above 1.5 MeV, but for deuteron energies below 1.5 MeV the fitting coefficients should be modified to $A = 1.065\times10^{7}$ n/sr/μC and $B = 4.39$. The measurement results and the experimental curves are shown in Fig. 1, in which the data at $E_{\mathrm{d}} = 1$ MeV are a bit lower than the fitting curve. The uncertainty of these data are larger because the terminal voltage is close to the low-voltage limit of 4.5 MV Van de Graaff where the beam transmission is low.

The angular distribution of the neutrons from 200 keV, 500 keV, 2 MeV and 3 MeV deuterons bombarding a thick beryllium target are shown in Fig. 2. Each yield was normalized to the yield at 0° at the respective energy.

The total neutron yield was calculated by integrating the angular dependent neutron. The total neutron yields are listed in table 1. Fig. 3 compares data in this experiment and data reported by Hawkesworth [10] and Segre [9].

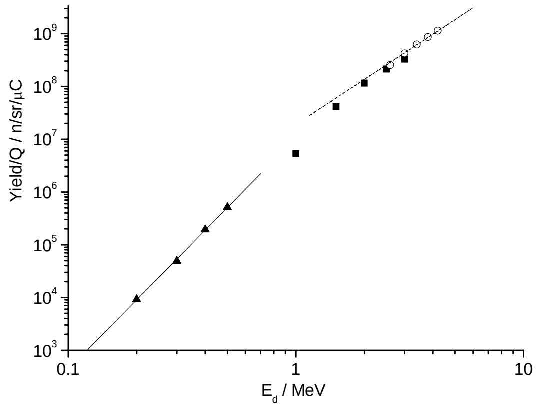

Fig. 1: The ^{9}Be (d, n) thick-target yield in forward direction. The dash curve is an extrapolation fitting of the experiment data (○) given by Meadows [11]. The squares (■) are data measured at 4.5 MV Van de Graaff and the triangles (▲) are data measured at the 600 kV Cockcroft-Walton accelerator. The Fitting is shown as a solid curve.

Table 1. Neutron yield for different deuteron energy.

Energy / MeV	0.20	0.50	2.0	3.0
Yield / n/μC	8.8×10^{4}	5.8×10^{6}	8.6×10^{8}	1.70×10^{9}

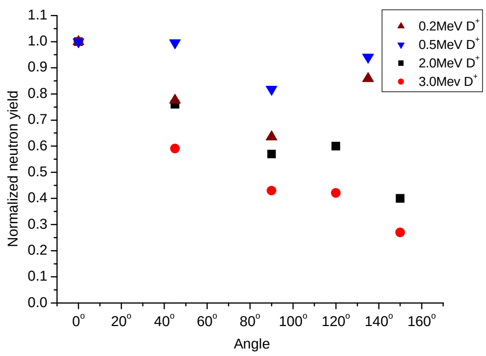

Fig. 2: Relative neutron yields at different angles for different deuteron energies. All data are normalized to the neutron yield at 0^{o} at the respective deuteron energy.

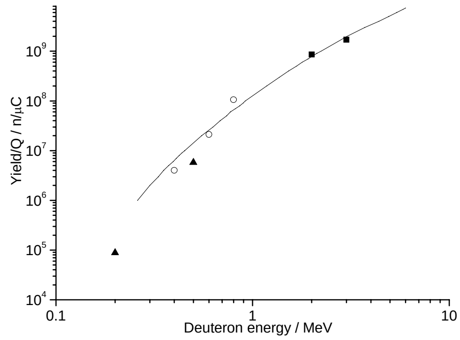

Fig. 3: The ^{9}Be (d, n) thick-target total yield. The curve is given by Hawkesworth in [10] and data (○) reported in [9]. The total neutron yields measured in this experiment are plotted as (■) at 4.5MV Van de Graff and (▲) at 600kV Cockcroft-Walton accelerator

3. Fast neutron radiography with 4.5 MV Van de Graaff

3.1 Experiment set up

Fast neutron radiography was carried out with scintillators and AGFA D7 films. The scintillator is home-made and composed of polypropylene and ZnS(Ag). It was a 2 mm thick disk with 8 cm diameter, which was placed on the rear side of the film as shown in Fig. 4. The beam spot on the target was about 3 mm in diameter. The distance between target and film was 35 cm. The neutron flux was about 10^6 neutrons/cm^2/s at the film plane. The sample was a hollow steel cylinder, 6 cm in height and 7 cm in diameter. The hole had three different diameters along the axis, which were 5 cm, 3 cm and 1 cm, respectively. Neutrons scattered in the sample were neglected during this stage, thus the sample was placed next to the film. There was no shielding against gamma-rays emitted from the beryllium target. Exposure time was 45 minutes. Radiographs with and without sample were taken.

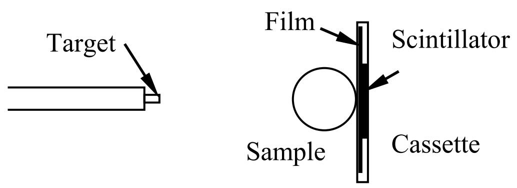

Fig. 4: Fast neutron radiography set-up

3.2 Experiment results

Fig. 5 shows a fast neutron radiograph without a sample (flat field image). The darker round area corresponds to the position of the scintillator, which was exposed to both, gamma-rays and the light emitted from the scintillator. The remaining area was exposed only to gamma-rays. The AGFA D7 film is sensitive to gamma-rays, but the home-made scintillator is not sensitive to gamma-rays. The exposure level in the scintillator area is much higher than in the other part, which shows that the exposure in scintillator area was mainly due to fast neutrons. Fig. 5 also shows that the scintillator was not fully uniform and had some defects.

Fig. 6 is a fast-neutron radiograph of the hollow steel cylinder sample mentioned above. Again the round area (Section I) corresponds to the position of scintillator, and the exposure of the outside area (Section II) was mostly due to gamma-rays. The square shaped white area is the image of the sample; both upper corners of the cylinder are in section II. Section III corresponds to the smallest hole, which can be considered as a pure fast neutron image, because the gamma-ray contribution was blocked by the 6 cm thick steel. This experiment indicates that gamma-rays emitted from the D-Be reaction might influence the image quality in fast neutron radiography when a film is used.

4. Conclusion

The measurements of neutron yields from deuteron beams bombarding thick beryllium targets showed that a fast neutron yield of 2.5×10^{12} n/s can be obtained with a 2 MeV, 3 mA deuteron beam, which is not too difficult to produce with a RFQ accelerator. The measurement results are consistent with previous experiments, too.

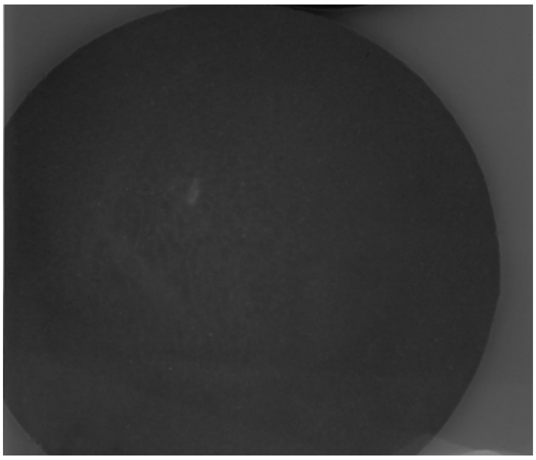

Fig. 5: fast neutron radiograph without sample. (enhance contrast of image to show details)

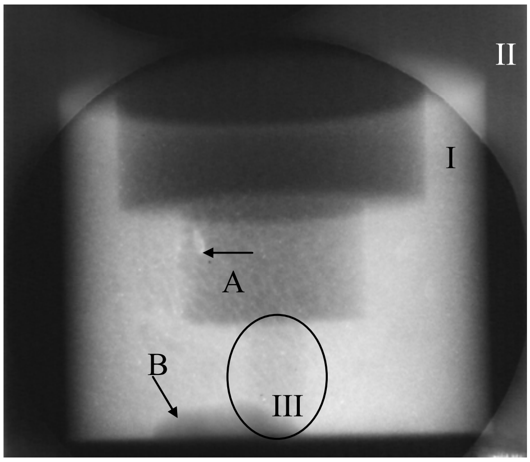

Fig. 6: Fast neutron image of a hollow steel cylinder. A is a defect of the scintillator. B is a defect occurred in film postprocessing.

The experiment with the scintillator-film imaging system indicated that gamma-rays emitted with the neutrons from a D-Be neutron source may have significant influence on the fast neutron image. The gamma-rays should be shielded or detectors of low gamma sensitivity should be used. On the other hand, special techniques could be used to obtain both, fast neutron and gamma-ray images with D-Be reaction simultaneously. Scintillator-film systems do not have a linear response to dose, so the quantitative measurement of the gamma-ray contribution to the image is difficult. A CCD based imaging system is under construction at Peking University. With this system the quantitative measurements can be completed.

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