Studies on \((n, \alpha)\) Recoils of \(^{6}\text{Li}\) and \(^{10}\text{B}\) in the Reactor UTR-Kinki by Gas Phase Electrodeposition

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The energies of recoil particles from \((n, \alpha)\) or \((n, 2\alpha)\) reactions of Li and B were investigated by solid state detector and gas phase electrodeposition as previously reported on \(^{228}\text{Th}\) series. Nuclear reactor of UTR-Kinki was used as thermal neutron source. Particles from \(^{6}\text{Li}\) \((n, \alpha)\) \(^{3}\text{T}\) and \(^{10}\text{B}\) \((n, \alpha)\) \(^{7}\text{Li}\) were collected on a sheet of triacetate film by gas phase electrodeposition at atmospheric pressure. The film was etched with 6M-NaOH at 50°C. The tracks thus obtained were taken as photographs with a microscope \((\times 600)\). By counting the number of tracks on the film at various etching times, the energies of \(\alpha\)-particles were evaluated according to the calibration curve of \(^{227}\text{Ac}\) series.

Among various peaks of track density, the two peaks having the evaluated values of 1.85 MeV for \(^{6}\text{Li}\) and 1.48 MeV for \(^{10}\text{B}\) agreed approximately with the theoretical values of 2.05 MeV and 1.47 MeV of \(\alpha\)-particle energies for respective reactions.

Key Words: gas phase electrodeposition, recoil, solid state track detector, triacetate film, \(\alpha\) track method, focusing shade, etching time

1. Introduction
Alpha particles from \(^{227}\text{Ac}\) series have been used for standard tracks on a sheet of cellulose triacetate film in the case of gas phase electrodeposition\(^{1-4}\). The depth of the tracks obtained had a linear relation with the energy of \(\alpha\)-particles. Referring to these results, \((n, \alpha)\) recoils of \(^{6}\text{Li}\) and \(^{10}\text{B}\) irradiated with thermal neutrons in the reactor UTR-Kinki were studied.

2. Experimental
2.1 Irradiation
A trigger type experimental reactor UTR-Kinki (1 W of power) was used for irradiation. In the central stringer of the reactor, an apparatus furnished with target anode and collector cathode was inserted for irradiation with \(10^7\text{n}/(\text{cm}^2\cdot\text{sec})\) of thermal neutron flux.

Figure 1 shows the schematic view of the irradiation apparatus of 100 ml long with 20 mm of outer diameter and 16 mm of inner diameter. In it, anodic and cathodic circular plates made of copper (14 mm diameters) were set. Between both electrodes, there is a conical copper tube with open orifice as a focusing shade. The temperature and pressure inside the apparatus are the same ones with those of the surrounding circumstances.

![Diagram of irradiation apparatus](image_url)

Fig. 1 Equipment for irradiation.

2.2 Sample
On the surface of the anode, lithium hydroxide (Kanto-kagaku, Special Class) of 2~4 mg as Li and boric acid (Wako-junyaku Kogyo, Chemical Pure) of 0.7 mg as B have been pasted with arabic gum and stood for dryness. The cathodic plate is covered with a sheet of
cellulose triacetate film adhered with cellophane at the periphery. Both electrodes have been supplied with electric potentials up to d.c. 1000 V through polyethylene coated wire from the outside of the reactor.

2.3 Measurement of energy

After neutron irradiation of the sample, the cellulose triacetate film is taken out and etched with 6M-NaOH solution at 50°C for a definite time. Subsequently, the film is washed with water and dried to be taken as a photograph under a microscope of 600 times of magnification, followed by counting. Since the depth of a track by each etching time depends upon the energy of an implanted particle and the density of the tracks has a linear relationship with the intensity of the particle, the α-ray spectra can be obtained by this method.

The relation of the track depth with the energy at various etching times has been standardized by α-particles emitted from an 227Ac unit (Radiochemical Centre, Amersham) as follows.

$37 \, \text{kBq (1,} \mu \text{Ci) of the actinium in 1 ml of dilute nitric acid is taken at the centre of a sheet of a filter paper and dried. The paper is put upon a piece of a cellulose triacetate film and left for suitable hours with tight contact. Then, the film is etched as mentioned above, followed by the counting of the numbers of tracks on it. The densities of the tracks are plotted on a graph paper according to the respective etching time$^{5,6}.

3. Results and Discussions

Among the possible nuclear reactions of 4Li, 6Li, 7Li, 10B and 11B with neutron, only 6Li (n, α) 3T and 10B (n, α) 7Li are taken into consideration in the present paper, because the reaction such as 7Li (n, α) 3T and 10B (n, 2n) 3T are too low in Q-values to be concerned with the low neutron energy of the reactor.

As Shinagawa and Tanabe reported$^4$, recoil particles move in air along the lines of electric force. One can figure out these lines in the apparatus by the following simulation on a sheet of carbon paper with silver paste, the schematic section is drawn in the same scale as the apparatus and d.c. potential of several volts is applied to the described electrodes. The equipotential points between them are examined by means of a voltage tester. At every point on the equipotential lines thus obtained, a normal line is drawn to construct lines of electric force.

Figure 2 (A) is the case without a focusing shade. The lines of electric force are parallel and perpendicular to the surfaces of flat electrodes. Schematic views shown in Fig. 2 (B) and (C) are the cases with different focusing shades. For the experiments, copper conical shade of 7 mm high or of 50 mm high has been used, each of which with a smaller orifice of 5 mm in diameter or a larger one of 14 mm. The focusing shade (B) is short-circuited with the anode by direct contact and has no focusing effect on the collector electrode, while that of (C) is insulated from both electrodes and shows the convergence of lines of electric force.
The variation of density of tracks shown in Fig. 3 are the results of Li experiment using 7 mm or 50 mm high shade. After irradiation for 2 hours, cellulose triacetate film on the cathode has been taken out and numbers of a tracks were examined at site by site along a diameter of the round film to know the distribution. The results indicate the focusing effect of the shade on the recoil spray migrating to the cathode. Since the higher cone is shown to be better than the lower for a focusing shade, a shade of 50 mm high has been generally used for experiment.

The characteristics of cellulose triacetate film has been studied as presented in Fig. 4 which shows the decrease of the weight of film with the etching time. The films (135 μm of thickness) cut into 50×50 mm pieces have been etched in 6M-NaOH solution and one of the pieces was taken out every 1 hour up to 15 hours, followed by drying. The decrease of the weight was proportional to the etching time and its increment was ±3 mg/25 cm²·hr. The film used in the present paper did not shrink nor soften even after 30 hours treatment in 6M-NaOH at 50°C.

As shown in Fig. 5, the spectra of 227Ac decay series were obtained by etching the film stepwisely. This result serves as a standard in determining α-energies of a sample. The α-energy of each daughter nuclide in that series corresponds to each etching time as shown in Table 1, when a peak of the track density is obtained in the spectrum as mentioned in the section (2.3).

![Fig. 5 Alpha spectra of 227Ac decay series by using cellulose triacetate film as detector.](image)

Table 1 Etching time for each nuclide

<table>
<thead>
<tr>
<th>Peak</th>
<th>α-Energy (E MeV)</th>
<th>Step of series</th>
<th>Etching time (t hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5.007</td>
<td>252Pa → 227Ac</td>
<td>11.25</td>
</tr>
<tr>
<td>B</td>
<td>5.710</td>
<td>252Ra → 252Rn</td>
<td>12.75</td>
</tr>
<tr>
<td>C</td>
<td>5.980</td>
<td>252Th → 252Ra</td>
<td>13.58</td>
</tr>
<tr>
<td>D</td>
<td>6.620</td>
<td>252Bi → 252Tl</td>
<td>14.58</td>
</tr>
<tr>
<td>E</td>
<td>6.820</td>
<td>252Rn → 252Po</td>
<td>15.33</td>
</tr>
<tr>
<td>F</td>
<td>7.380</td>
<td>252Po → 252Pb</td>
<td>16.83</td>
</tr>
<tr>
<td>G</td>
<td>7.450</td>
<td>252Po → 252Pb</td>
<td>17.64</td>
</tr>
</tbody>
</table>

The linearity of a calibration curve is explained as follows. The energy E of α-particles has the relationship with its range R as Eq. (1)³⁹, where “a” and “n” are suitable constants.

$$R=aE^n$$ (1)

In logarithmic form, it become to be

$$\log R=\log a+n \log E$$ (2)

As mentioned before, R may be proportional to the etching time t, Eq. (3) is obtained by substituting R in Eq. (2) by tK, where K is a proportional constant.

$$\log t=\log a+n \log E−\log K$$ (3)

Figure 6 shows the several spectra of track density according to etching time in several different experimental conditions of gas phase.
Height of focusing shade: (a) 15 mm (b) 8 mm (c) 5 mm
Amount of sample: 2mg as Li
Applied voltage: 0V or 1000V

Fig. 6 Etching profiles in several experimental conditions of gas phase electrodeposition for \(^{6}\text{Li} \rightarrow \alpha\) \(^{3}\text{T}\) reaction. Comparison of results for non and d.c. 1000V application.

electrodeposition for \(^{6}\text{Li} \rightarrow \alpha\) \(^{3}\text{T}\) reaction.

Generally speaking, during the shorter etching time than about 5 hours the track density become comparatively less as the electrode interval is larger. But, the tendency is reversed at least in the case of non-electric field when longer range of time is considered. The both electrodes have been kept apart by inserting a focusing shade of 5, 8 or 15 mm height. The density of tracks is smaller in the case of non-electric field as compared with the case of 1000 V application. These difference become the largest in the case of 8 mm shade, though it is hardly noticeable in the case of 5 mm shade. These results indicate that the 8 mm interval of the electrodes is more effective to collect ionic spatters than the 15 mm interval, i.e., higher charge ions due to the recoil at the target is remaining more in the shorter course. On the other hand, the result in the case of 5 mm can be understood by the fact that the recoil force is strong enough to neglect the attraction of 1000 V. Since the range of \(\alpha\)-particle produced by \(^{6}\text{Li} \rightarrow \alpha\) \(^{3}\text{T}\) reaction is calculated to be \(1.04\pm0.02 \text{ cm}^2\), the \(\alpha\)-particle started from the sample may disappear within 15 mm thickness of air before arriving at the collector. But in spite of this expectation, as can be seen in Fig. 6 the spectral intensity obtained with 15 mm high shade at more than 5 hours is not so low as that with the 5 mm but is rather very close to that with the 8 mm. This contradiction may be caused by the recoil spray with neighbouring materials in sample, because such a spray may also be subjected to the neutron irradiation and further recoil spray may fly up to the collector. We have reported several examples of such a spray in the case of a decay of radioisotope, e.g., on the flight of \(\text{H}_3\text{PO}_4\).

Shade: 8 mm high, Field application: d.c. 1000 V, Amount of sample: 4 mg as Li
Recoil spectrum on triacetate film
Blank test spectrum of the film

Fig. 7 Recoil spectra of \(^{6}\text{Li} \rightarrow \alpha\) \(^{3}\text{T}\) reaction by gas phase electrodeposition after 3 hr of irradiation time in UTR-Kinki. Comparison of recoil spectra with blank test.

Figure 7 shows a typical recoil spectrum of \(^{6}\text{Li} \rightarrow \alpha\) \(^{3}\text{T}\) reaction in comparison with blank test spectrum of triacetate film used, under the
same conditions of gas phase electrodeposition with a shade of 8 mm high, field application of 1000 V and 4 mg of sample as Li. Here one can see the peaks at the etching times of 2.5, 5.0, 8.0, 11.0, 13.0 and 19.0 hours, which correspond respectively to the energy of 1.02, 2.10, 3.40, 4.90, 5.80 and 8.50 MeV for implanted particles, according to the calibration curve shown in Fig. 6. The curve shown by dotted line in Fig. 8 is the result of the blank test, for cellulose triacetate film.

Among these peaks, the highest peak of 2.10 MeV is close to the literature value of 2.05 MeV\(^9\) which is the \(\alpha\) energy of \(^{6}\text{Li} \langle n, \alpha \rangle ^{4}\text{T}\) reaction. The other peaks do not correspond to any particles implanted nor the blank test peaks for the cellulose triacetate film, except 3.40 MeV peak which pretend the 2.72 MeV peak of \(^{4}\text{T}\). Though the reaction due to \(^{7}\text{Li} \langle n, \gamma \rangle ^{8}\text{Li}\) has the capture cross section of \(\Sigma = 2.84 \times 10^{-4}(\text{cm}^2/\text{g})\)^9, this reaction is negligible as compared with the activation cross section of \(\Sigma_{\text{act}} = 7.14\text{cm}^2/\text{g}\) of \(^{6}\text{Li} \langle n, \alpha \rangle ^{4}\text{T}\)^9. For the explanation of these uncertain peaks, we have to consider some impurities in the sample as well as in the constructing materials of irradiating apparatus, or the effect of further activation nuclear reaction after loading on the collector surface. In this connection, \(^{16}\text{O} \langle n, \alpha \rangle ^{12}\text{C}\) reaction in triacetate film having Q value of 1.819 MeV and the calculated \(E_\alpha\) of 1.415 MeV\(^9\) may be suspected as the cause of 1.02 MeV peak of blank test and 1.08 MeV peak of the sample shown in Fig. 7.

Figure 8 shows a recoil particle spectra for \(^{10}\text{B} \langle n, \alpha \rangle ^{7}\text{Li}\) reaction. The Q value of this reaction is 2.316 MeV\(^9\), which is allotted by inverse mass ratio according to the conservation of the momentum for the recoils\(^11\); 1.475 MeV to \(\alpha\)-particle and 0.84 (branching ratio, 93.6\%)\(^11\) MeV to the recoil \(^{7}\text{Li}\). In Fig. 8 we can see 0.4 MeV peak at 1 hour etching time which could be attributed to 0.84 MeV \(^{7}\text{Li}\) that has been retarded by its comparatively large mass and charge and discriminated well from the \(^{16}\text{O} \langle n, \alpha \rangle ^{12}\text{C}\) peak of 1.02 MeV mentioned above. The peak of 1.67 MeV at 4 hours may correspond to 1.475 MeV \(\alpha\)-particle. The origin of the peaks 6.0, 10.0 and 17.0 hours can not be explained as the case of Fig. 7.

Further effort should be needed to make a more reliable calibration curve by using other kinds of \(\alpha\) energy species ranging in the lower \(\alpha\) energy than those from \(^{227}\text{Ac}\) decay series.

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References
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9) E. Segre: "Experimental Nuclear Physics", 77.88
要 旨

UTR-Kinki 炉内における $^6\text{Li}$, $^{10}\text{B}$ の $(n, \alpha)$ 反応体の気相塩着に関する研究

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UTR-Kinki炉内照射の $^6\text{Li}(n,\alpha)^7\text{T}$, $^{10}\text{B}(n,\alpha)^7\text{Li}$ 等の反応における反応放射をフォーカス・シェードを用いた気相塩着法でトリオレートフィルム上に捕集し、そのフィルムに生じたトラックの深さから、α粒子など注入された粒子のエネルギーを検討した。そのフィルムは50℃の6 M水酸化ナトリウム溶液で一定の時間エッチングしたのも、顕微鏡（倍率600倍）で写真撮影し、印画紙に焼き付け、トラック数を求めた。

エッチングの処理時間とトラック数の関係からエネルギーを求めた結果、種々の原因不明のトラック密度のピークも認めたが、$^6\text{Li}$ からのα粒子は1.85MeV, $^{10}\text{B}$ からのものは1.48MeVも見出し得た。これは、$^6\text{Li}$ からの理論値の2.05MeV, $^{10}\text{B}$ からの1.47MeVの値と比較するとほぼ同一の値と考えられる。