ENERGY LOSS OF RADIOACTIVE IONS ^{22}Mg AND ^{21}Na IN MYLAR

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Abstract: Stopping power and energy loss straggling of the radioactive ions ^{22}Mg and ^{21}Na in Mylar foils 1.32715 mg/cm^2, 2.6543 mg/cm^2 and 4.0513 mg/cm^2 of thickness were determined. The experiment was performed by bombarding the radioactive ion beam produced by the CRIB facility of the University of Tokyo located at RIKEN, Japan in 2011. The experimental results are compared with theoretical calculation. The obtained values are also confirmed with Bohr's formula and Bragg's law over the investigated energy range.

Keywords: *stopping power, energy loss straggling, radioactive ions, ^{22}Mg, ^{21}Na, Mylar foil.*

1. Introduction

The radioactive ion beam of ^{22}Mg, ^{21}Na play important roles in direct measurement of stellar reactions such as $^{22}Mg(\alpha, p)$, $^{21}Na(\alpha, p)$ in αp-process [1, 2, 3]. The investigation of energy loss decides accuracy of the experimental values of the experiments. It is necessary to estimate the energy loss of radioactive heavy ions in nuclear materials. Mylar ($H_8C_{10}O_4$) is a popular material which is often used in beam production technique. It is meaningful to investigate stopping power and energy loss straggling of the particles in Mylar foils. In our works, we measured stopping power and energy loss straggling of the radioactive ions ^{22}Mg and ^{21}Na, respectively, at 3.73 MeV/u and 3.44 MeV/u, in different thickness of Mylar foils. The foils are 1.32715 mg/cm^2, 2.6543 mg/cm^2 and 4.0513 mg/cm^2 of thickness. The experiment was carried out in the framework of the direct measurement of the ^{22}Mg + ^{4}He system at CRIB (CNS Radioactive Ion Beam separator) facility of the Center for Nuclear Study (CNS) [4], the University of Tokyo in October, 2011. The aim of this work is investigating energy loss of heavy radioactive ions through popular nuclear experiment material Mylar foil and study if theoretical calculation, such as Bohr's theory [5] and Bragg's law can be relied on for the use in our applications. The results were compared with other theoretical calculation of Bohr formula and Bragg's law with a good agreement.

2. Experiment

We performed the ^{22}Mg and ^{21}Na beam production by using CRIB spectrometer located at RIKEN (fig. 1). The radioactive ions were produced via $^{3}He(^{20}Ne,^{22}Mg)n$ and $^{3}He(^{20}Ne,^{21}Na)d$ reactions by bombarding a Havar-window 2.5 μm cryogenic gas target [6] of ^{3}He at 90 K with the primary beam ^{20}Ne at 6.2 MeV/u from AVF cyclotron. The RI beam was more preferentially populated at achromatic focal plane F2 using dipole magnets and identified by beam monitors PPACs [7]. We separated and purified ^{22}Mg and ^{21}Na successfully on target at F3 plane after coming through the Wien filter. The table 1 shows details of beam production.

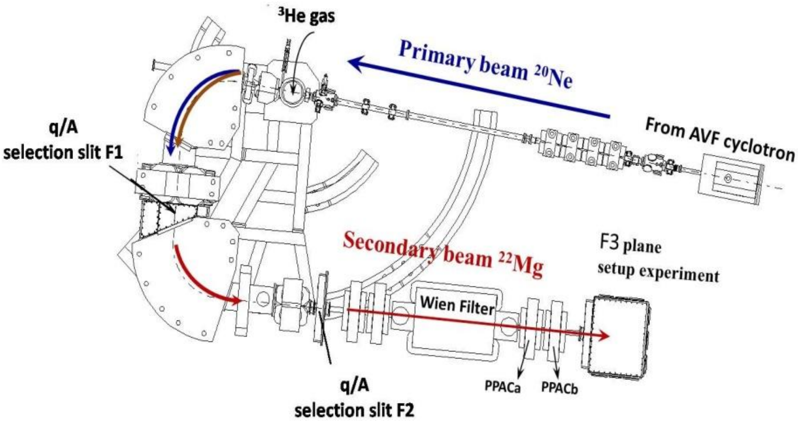

Fig 1. A plane view of CRIB spectrometer of the University of Tokyo at RIKEN, Japan.

Table 1. Condition of radioactive beam production.

^{20}Ne	^{3}He *Target*	^{22}Mg *at F3*	^{21}Na *at F3*
500 enA	0.72696 mg/cm^2	700 cps	400 cps

The experiment was set up in a chamber at F3 connecting to high speed vacuum pump system. The chamber was evacuated up to approximately 10^{-6} mbar. The thickness of Mylar foils was checked by measuring energy loss of the triple alpha sources ^{237}Np, ^{241}Am and ^{244}Cm. The monoenergetic particles went through Mylar foil fixed in a holder covering a collimator with 4 mm in diameter in front of a silicon detector, see figure 2 for the experimental setup.

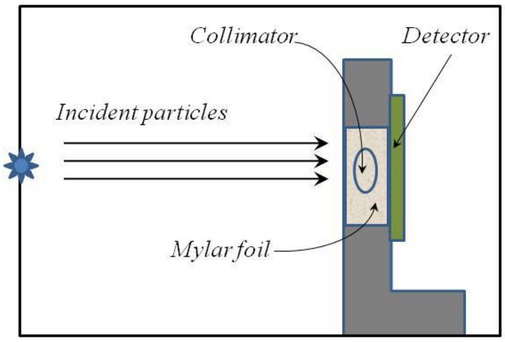

Fig. 2. Schematic of the detection system at F3 used for measuring energy loss ^{22}Mg, ^{21}Na in Mylar foils

We performed two separated measurements for ^{22}Mg and ^{21}Na in Mylar foils with 1.32715 mg/cm^2, 2.6543 mg/cm^2 and 4.0513 mg/cm^2 of thickness. The spectra were obtained by a detector system including preamplifier made by GSI [8], main amplifier MA8000 and ADC 32CH Peak Sensing CAEN Mod V785 [9]. Experimental data were stored in a hard disk of computer as binary files. The spectra pulse-height measured by silicon detector have been calibrated using the triple-alpha source ^{237}Np, ^{241}Am and ^{244}Cm and different charged states (10+, 9+, 8+, 7+ and 6+) of the primary beam ^{20}Mg from the AVF cyclotron. Figure 3 illustrates a good energy calibration for heavy ions by using various energies of ^{20}Ne ions from the AVF cyclotron.

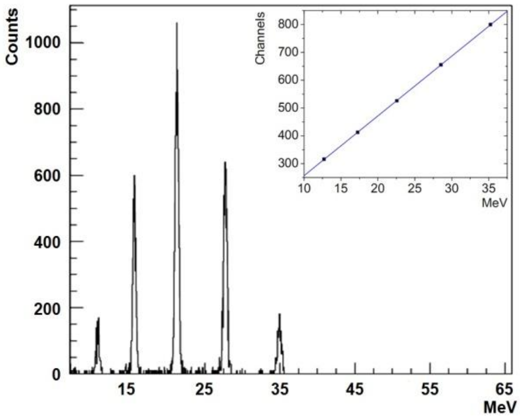

Fig 3. Energy spectrum was measured at different charge states of ^{20}Ne beam used to calibrate the detector. The inset shows the energy calibration for the measurement extracted from the spectrum.

3. Results and discussion

We use ROOT program [10] for analyzing data. The resultant peaks are nearly of Gaussian distributions. Therefore, the experimental data have been extracted by fitting Gaussians from the foot of the low energy side to the foot of the high energy side of the peak centroids. The uncertainties of the results are estimated to be 11% for the ions including the errors in fitting the spectra, beam energy profile and system resolution.

The difference between particle energy peaks and the width of peaks are related to energy loss and energy loss straggling of particles in the target. Figure 4 shows the different peaks of ^{22}Mg obtained by detector after Mylar foil and without Mylar foil at incident energy 3.73 MeV/u.

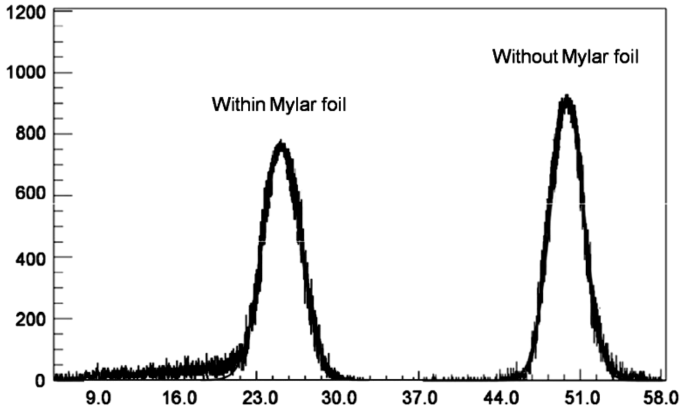

Fig 4. Energy spectrum of ^{22}Mg at 3.73 MeV/u was measured with and without Mylar foils of 4.0513 mg/cm^2 in the thickness

The result determined on the spectrum has a nearly Gaussian distribution. Therefore, the corresponding energy loss straggling can be obtained by extracting the full width at maximum of the peak (FWHM). The difference of the two dispersive peaks resulted from the detector with and without the foil gives the variance of the energy loss. The energy straggling Ω related to the energy peak is described:

$$\Omega = \frac{\delta E}{2\sqrt{2\ln 2}} \tag{1}$$

where δE is FWHM associated with the standard deviations at the energies of the incident particles. The energy loss straggling at an average energy (E_{av}) in the foil is defined:

$$\Omega^2 = \Omega_1^2 - \Omega_2^2 \tag{2}$$

where Ω_1^2 and Ω_2^2 are energy straggling of the peaks of incident particle energy and energy of particles reaching the detector, respectively. The average particle energies (E_{av}) in the foils have been determined by dividing the measured energy loss ΔE by the thickness of the target and $E_{av} = E_i - \Delta E/2$, where E_i is the incident particle energy. In the work, the experimental data are compared with theoretical calculation. The energy loss straggling of low charge ions of high energy given by Bohr's theory is simply defined:

$$\Omega_B^2 = 4\pi.Z_1^2.Z_2.e^4.N.\Delta x, \tag{3}$$

where Ω_B, $Z1$, $Z2$, N and Δx are Bohr's energy loss straggling, the projectile atomic number, the target atomic number, the atomic density and the target thickness, respectively.

Figure 5 and 6 show the results of energy loss straggling determined in the experiment, see table 2 for details, and calculated from eq. (3) for ^{22}Mg and ^{21}Na in Mylar foils, respectively. As can be seen, for both cases, the shapes of the curves are the same with Bohr's theory and they are approximately 1.1 ÷ 1.4 times higher than the calculation but, in general, the results presented indicates these experimental data are roughly in good agreement with Bohr results in the energy range 2.5÷3.5 MeV/u of incident energy. The data which are closer Bohr's estimation maybe due to the fact that all target electrons are considered to be free and contribute to the energy loss suggested by Bohr's theory. The higher data could be explained by the limit in the energy of the validity of the simple Bohr's theory and the influence of correlation effects [11] which have not been carried out. In addition, the difference between experimental data and the prediction of the theory may be caused by inhomogeneity of the foils and the charge-state fluctuation of heavy ion in target. This problem is also consistent with other works [12, 13] into consideration.

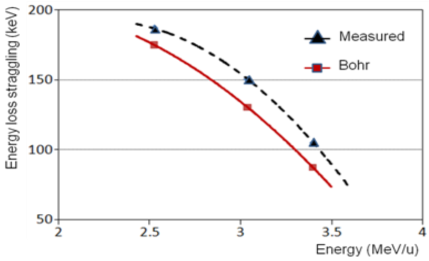

Fig 5. Energy loss straggling as a function of average energies of ^{22}Mg in the Mylar foils. The dash curve is experimental values compared with Bohr's calculation.

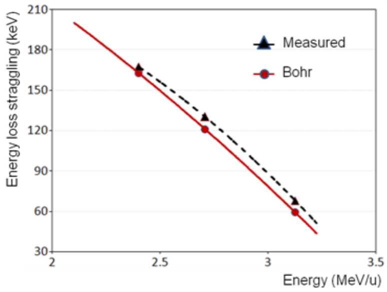

Fig 6. Energy loss straggling as a function of average energies of ^{21}Na in the Mylar foils. The dash curve is experimental values compared with Bohr's calculation.

Table 2. Average incident energies inside target Mylar foil, reduced energy loss straggling and relative energy loss ΔE/E of ions in the material.

Ion ^{21}Na → Mylar foil			Ion ^{22}Mg → Mylar foil		
$E_{av}(MeV/u)$	Ω^2/Ω_B^2	$\Delta E/E$ (%)	$E_{av}(MeV/u)$	Ω^2/Ω_B^2	$\Delta E/E$ (%)
3.125	1.312	10.015	3.396	1.460	9.739
2.708	1.158	26.979	3.036	1.338	22.753
2.400	1.059	43.236	2.524	1.144	47.680

In order to remove the thickness dependence and to display the reflection with the particle energies, the measured results have been normalized to Bohr straggling. The figs 7, 8 illustrate the reduced energy loss straggling of the experimental data determined by eq. (2) and calculated by eq. (3) for ^{22}Mg and ^{21}Na, respectively. It can be seen that energy loss straggling of ^{22}Mg roughly rises in the region E < 2 MeV and slight increases in the region energy 2.5 ÷3.4 MeV/u following logarithmic function. The straggling of ^{21}Na is roughly developing with exponential function in the estimated energy range. As the results, the energy loss straggling of particles roughly depends on incident energy of the particles in the interested energy range. Because of limited experimental points, the prediction which is out of the energy range above needs to be measured to have a complete estimation for a widen broad.

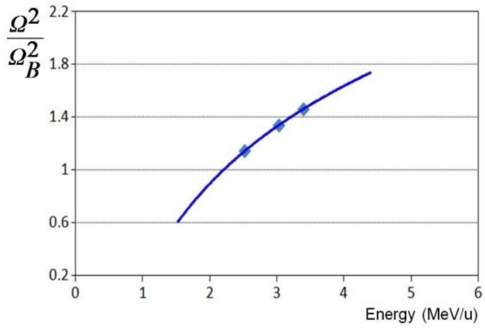

Fig 7. *Experimental reduced energy loss straggling for ^{22}Mg as a function of mean energies in the Mylar foils*

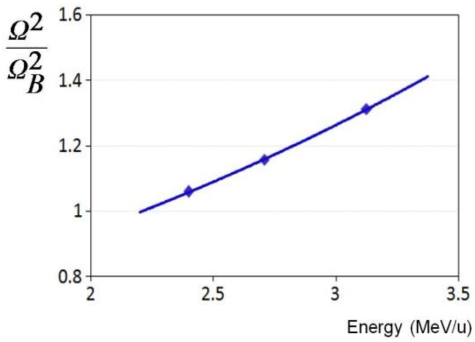

Fig 8. Experimental reduced energy loss straggling for ^{21}Na as a function of mean energies in the Mylar foils

Stopping power dE/dx of ^{21}Na and ^{22}Mg at the average energies (E_{av}) in the target was determined by dividing the measured energy loss ΔE in the thickness of the target and $E_{av} = E_i$

- *ΔE/2*, where E_i is the incident particle energy. The results of the measurements of the particles in Mylar foils are shown in Figs. 9, 10.

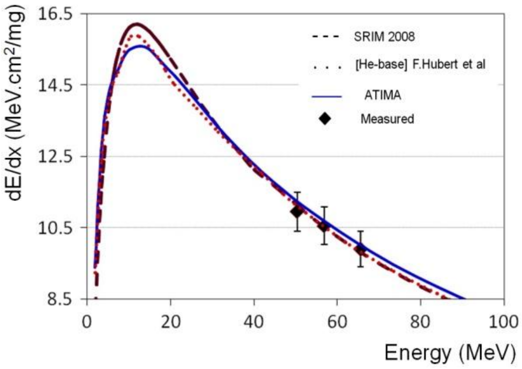

Fig 9. Stopping power of ^{21}Na as a function of average incident energy of thickness in Mylar compared to values calculated with various codes [14, 15, 16]. The dash curve is prediction of SRIM2008 [14], the continuing curve is prediction of ATIMA [15] and the dot curve is data from ref. [16].

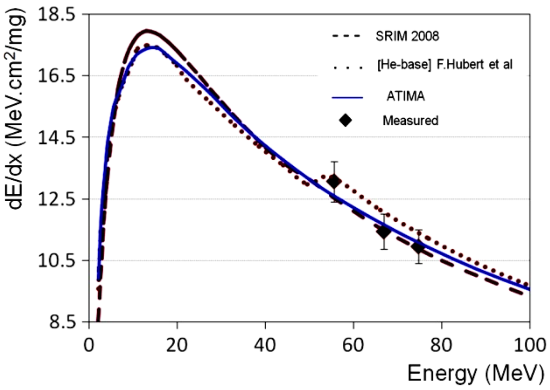

Fig. 10. *Stopping power of ^{22}Mg as a function of average incident energy of thickness in Mylar compared to values calculated with various codes [14, 15, 16]. The dash curve is prediction of SRIM2008 [14], the continuing curve is prediction of ATIMA [15] and the dot curve is data from ref. [16].*

The results of this experiment are compared with SRIM2008, ATIMA and database from ref. [16] and they are generally in a good agreement with the codes. As can be seen, the stopping power of the particles declines following an exponential function in the considered energy region. This is also predicted by theoretical calculation of the codes. For the isotope ^{21}Na, stopping power is exactly estimated by all the theories [14, 15, 16]. Whereas, the ^{22}Mg is compatible with all the calculations in the energy range E > 60 MeV and it roughly tends to the forecast of database in ref. [16] since energy E < 60 MeV. In general, the measured values of the stopping power are more tendentious to database of F. Hubert, et al. ref. [16] than others. The compatibility with the calculations points out a good applicability of Bragg's law for stopping measurement in the mentioned energy regions of the ions. And the theory of energy loss calculation does not depend on radioactivity of the ions, this demonstrates that particles coming through materials are affected by shell interaction and we need much more experimental data to modify the shell correction of the Bethe-Bloch. The small deviation of the results in this experiment collated with theory may be caused by the homogeneity, which influences the density of the absorber, of the Mylar foils. However, with the results presented here, it is thought that the stopping power of heavy ions less than 100 MeV in Mylar can be estimated reasonably with the theoretical calculation.

4. Conclusion

The energy loss straggling of radioactive ions ^{21}Na, ^{22}Mg in nuclear material Mylar foil was measured. It was found that, in the energy region underestimated, the obtained energy loss straggling roughly depends on incident energy. However, from other works [17, 18], it is predicted that there is an energy region in which the energy loss straggling could not depend on incident energy of the particles. The stopping power of ^{21}Na, ^{22}Mg in Mylar was also determined. The results point out that the radioactivity of particles does not affect on the energy loss of the particles. The compatibility allows us to forecast energy loss of heavy ions by the codes. However, because of limited experimental data, the prediction which is out of the energy range needs to be measured to have a complete estimation for a widen broad in future works.

Acknowledgement

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ĐỘ MẤT NĂNG LƯỢNG CỦA ^{22}Mg VÀ ^{21}Na

TRONG VẬT LIỆU MYLAR

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Tóm tắt: Công suất dừng và độ mất năng lượng phân tán của các hạt ^{22}Mg và ^{21}Na trong Mylar foil có bề dày 1.32715 mg/cm^2, 2.6543 mg/cm^2 and 4.0513 mg/cm^2 đã được khảo sát. Thực nghiệm được tiến hành bởi việc cho chùm hạt không bền ^{22}Mg và ^{21}Na đi qua vật liệu Mylar tại phòng thí nghiệm CRIB của Đại học Tổng hợp Tokyo, đặt tại RIKEN, Nhật Bản vào năm 2011. Kết quả thực nghiệm đã được đánh giá dựa trên sự so sánh với các giá trị tính toán theo lý thuyết Bohr và định luật Bragg cho thấy lý thuyết dự đoán tương đối gần với giá trị thực tế đo được trong vùng năng lượng khảo sát.

Từ khóa: *stopping power, energy loss straggling, radioactive ions,22Mg, 21Na, Mylar foil.*