Measurements of ^{9}Be(d,x) and ^{9}Be(p,x) Cross Sections at Low Energy

Kimiya ISHII, Kentaro OCHIAI, Isao MURATA, Hiroyuki MIYAMARU and Akito TAKAHASHI
Department of Nuclear Engineering, Osaka University,
2-1 Yamadaoka, Suita,Osaka, 565-0871, Japan
E-mail: kimiya@newjapan.nucl.eng.osaka-u.ac.jp

The cross sections and S(E)-factors for ^{9}Be(p,α) and (p,d) reactions were measured for proton energies from about 30 to 300 keV. The measured S(E)-factors for ^{9}Be(p,x) reactions increased as the proton energy decreases below 50keV. However our measured S(E)-factors increase more slowly with energy change than the other measured data and moreover more rapidly than the theoretical data.

1. INTRODUCTION

Differential cross section data of charged-particle emission from light elements with incident low-energy protons/deuterons are useful for estimating dose-rate (PKA, KERMA) and material damage in a fusion reactor. Beryllium (^{9}Be) metal and ^{9}Be-compound material are prospective candidates for fusion-reactor materials. The use of neutral beam injector with several hundred keV and several amperes has been reported recently for elevating the temperature and density of plasma. To study plasma-particle/first-wall interaction problems on low energy nuclear reactions, we have measured charged-particle emission cross sections of ^{9}Be (d,x) and ^{9}Be (p,x) reactions at low energy, where x = p, d, t and α, since, up to now, there are only few experimental data available for differential charged-particle emission cross sections of the ^{9}Be(d,x) and ^{9}Be(p,x) reactions at low energy.

We had already reported that the measured astrophysical S(E)-factors [1] for every branch of the ^{9}Be-d reaction increased as the deuteron energy decreases below 300 keV [2]. Unexpectedly the increase rate of the S(E)-factors was much higher than the theoretical data. In the present study we confirmed the similar tendency of the increase through the comparison of, measured data for ^{9}Be-p reaction and our previously measured data for^{9}Be-d reaction.

2. EXPERIMENTAL PROCEDURE

All the experiments were carried out at the Cockcroft-Walton type accelerator, OKTAVIAN of Osaka University, Japan. Figure 1 shows the schematic view of experimental system with components in the vacuum chamber. A beryllium metal (100 μm in thickness) is bombarded by proton or deuteron beam. The beam is induced into the target through three apertures (ϕ=10, 7 and 0.8 mm). At the lower energy region (the energy of proton beam was below 40 keV and that of deuteron is below 100 keV), we use H_3^+ or D_3^+ molecular beam instead of single atomic beam. Charged-particles emitted by the nuclear reactions are detected by Si-Surface Barrier Detector (Si-SBD). Depletion layer of this detector is about 200 μm. In front of the Si-SBD, we set an aluminum foil (3 μm in thickness) as an absorber and not to detect Rutherford scattering particles. The Si-SBD is smoothly movable between the angle from 30 to 160 degree with respect to the beam direction keeping a solid angle for the measurement of angular-distributions of the cross sections. The beam irradiation point of the target is adjusted by a manipulator with a stepping motor to keep the flesh surface point. A Faraday cup for beam-current monitor is set up at the backward of the beryllium target. A current integrator monitors the induced particles as a target current. We measure real beam current by the Faraday cup without target and calibrate the number of incident particle.

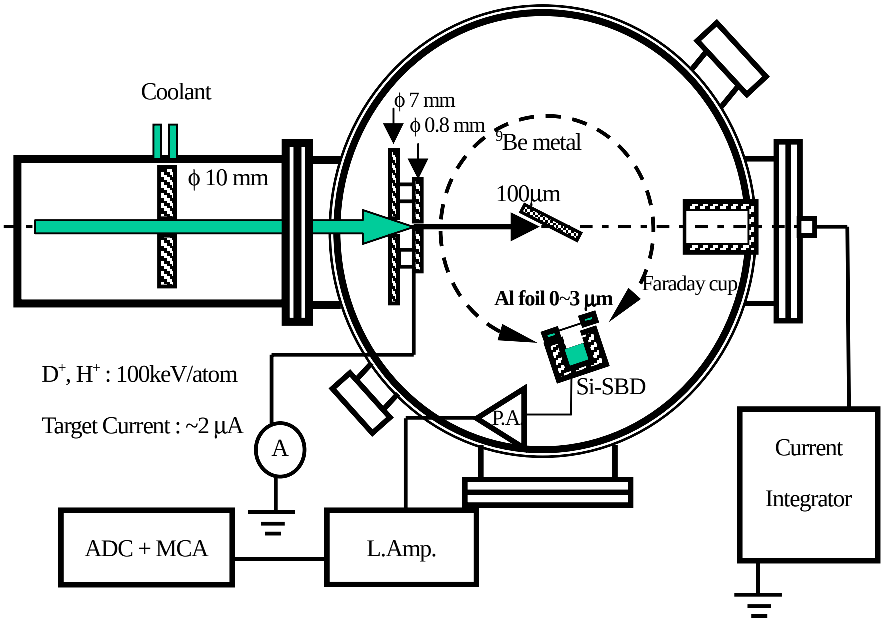

Figure 1 Experimental arrangement

3. EXPERIMENTAL RESULT

3.1 Astrophysical S(E)-factor and ^{9}Be-d nuclear reaction

The astrophysical S(E)-factor is defined by the relation

$$\sigma(E) = S(E) E^{-1} \exp(-2\pi\eta) \tag{1}$$

Where η is the Sommerfeld parameter given by

$$2\pi\eta = 2\pi Z_1 Z_2 e^2 / \hbar v = 31.29 Z_1 Z_2 (\mu / E)^{1/2}$$

The quantities Z_1 and Z_2 are the nuclear charges of the interacting particles in the entrance channel, μ is the reduced mass in units of AMU, and E is the center-of mass energy in units of keV. In the case of non-resonant reactions, the S(E)-factor varies slowly with energy. In solid target, electron clouds surrounding the interacting nuclides act as a screening potential. So, the projectiles see reduced Coulomb barrier. The ratio of the bare cross section(σ_b(E))and the cross section with an electron screening effect(σ_s(E)) is

$$f(E) = \frac{\sigma_s(E)}{\sigma_b(E)} \approx \exp\left(\frac{\pi\eta U_e}{E}\right) \quad . \qquad (2)$$

Where U_e is the height of Coulomb barrier(e.g. U_e ∼$Z_1Z_2e^2/r_i$ approximation, with r_i is an atomic radius ;U_e 450 eV at Be-d/p reaction)

Table1 shows astrophysical S(E)-factors obtained from the measured cross sections of ^{9}Be(d,p), (d,t_0), (d,a_0) and (d,a_1) at E_{lab}. =90-290 keV, respectively.

Table 1. S(E)-factors of ^{9}Be-d nuclear reactions below E=290 keV

<E>$_{lab.}$ KeV	S-factor MeV·barn			
	^{9}Be(d,α_0)^{7}Li	^{9}Be(d,α_1)^{7}Li*	^{9}Be(d,p_0)^{10}Be	^{9}Be(d,t)^{8}Be
90	3.5±0.70	5.7±1.2	2.0±0.40	0.85±0.18
140	1.9±0.38	3.1±1.1	1.4±0.30	0.40±0.075
190	2.7±0.55	4.2±0.83	1.7±0.35	0.52±0.10
240	4.3±0.85	6.5±1.3	2.6±0.5	0.85±0.18
290	5.7±1.2	7.6±1.5	2.8±0.55	0.95±0.2

Measured S(E)-factors slightly decreased as E decreases. However, each S(E)-factor at E=90 keV enhanced about twice larger than the one at E =140 keV. We assumed that it was not due to the resonance effect, because exited levels of ^{11}B* which enhance S(E)-factors of ^{9}Be-d reactions have not found up to now. We suggest that S(E)-factors increase due to an electron screening effect. According to C.Rolfs et al.[3], the effect cannot be disregarded and become important for the understanding of the low-energy data at the energy region below $E/U_e \leqq 100$. Unexpectedly our measured S(E)-factors were enhanced at E= 90keV(E/U_e 200) and increase rate of our measured S(E)-factors was much higher than the theoretical data(eq.(2)). We confirmed the similar tendency of the increase through the comparison of measured data for ^{9}Be-p reaction.

3.2. The nuclear reaction of ^{9}Be-p

Figure 2 shows the ^{9}Be-p reaction branches, as Figure 3 Energy spectrum.

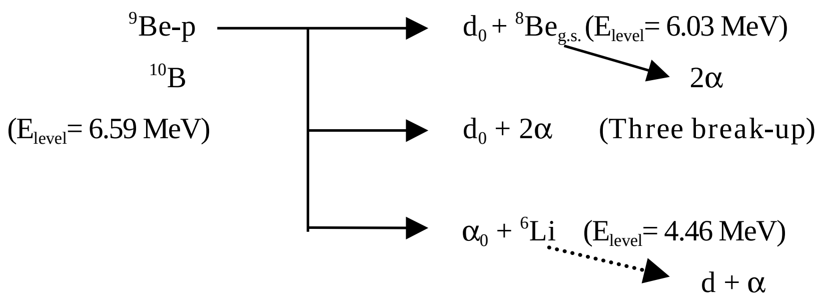

Figure 2 Branches of ^{9}Be-p nuclear reactions at low energy

The Q-value of ^{9}Be-p reaction is not enough large to separate peaks of the emitted particles with absorber foil.

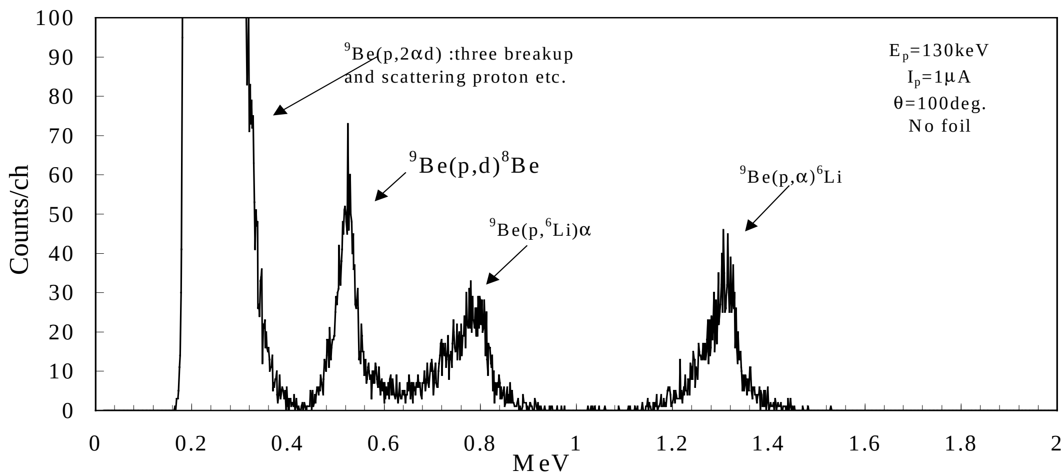

Figure 3 Energy spectrum of the charged-particles emitted from ^{9}Be-p nuclear reaction

The reactions of $^{9}Be(p,\alpha_0)^{6}Li$ and $^{9}Be(p,d)^{8}Be$ were measured for proton energies from about 30 to 300 keV(lab.) in backward angles(over 80 degree(lab.)). The total cross section was estimated from extrapolating approximation curve to measured angular distributions. Figure 4 shows the S(E)-factors obtained from out measurement and other's[4].

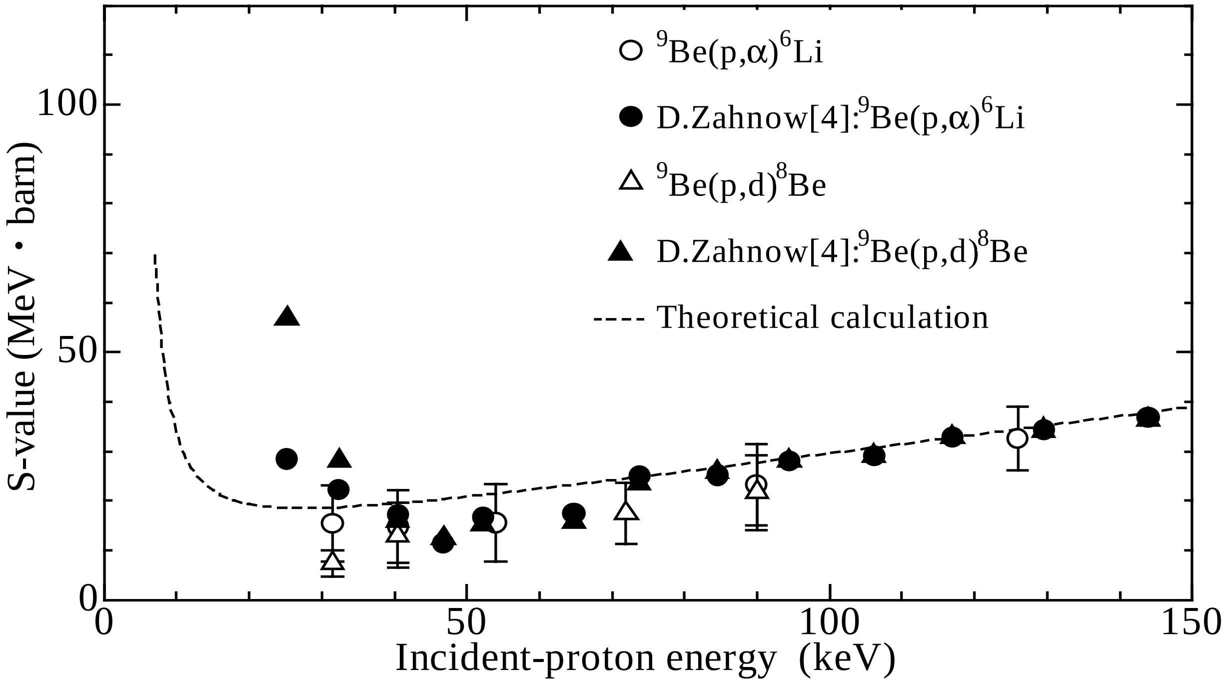

Figure 4. S(E)-factors of ^{9}Be-p nuclear reactions

As for our measurement data, the S(E)-factor of $^{9}Be(p,\alpha)^{6}Li$ reaction increases as proton energy decreases below 50 keV. That of $^{9}Be(p,d)^{8}Be$ reaction does not have the same tendency. Other measured S(E)-factors increased together as proton energy decreases below 50 keV. Theoretical curve is calculated briefly from other measured data and the equation (2). We can see a rapid enhancement about 10 keV in calculation data, while about 40 keV in other and our measured data. Our measured S(E)-factors increase more slowly with energy change than the other measured data and more rapidly than the theoretical data.

4. SUMMARY

The reactions of $^{9}Be(p,\alpha_0)^{6}Li$ and $^{9}Be(p,d)^{8}Be$ were measured for proton energies from about 30 to 300 keV in backward angles.

The increase of the S(E)-factors were observed toward lower energies region below 50 keV. However our measured S(E)-factors increase more slowly with energy change than the other measured data and more rapidly than the theoretical data. This result is consistent with our previous ^{9}Be-d experiment. The S(E)-factors increased as deuteron energy decreases below 100 keV. From our study, we estimate that the equation (2) which approximate the S(E)-factor considering with the electron screening effect needs some other parameters. For example, we presume that they include isotopic effect of incident particle or target sample. To approximate this phenomenon more precisely, we need improved experiments at lower energy region.

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