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Study of Light Charged Particle Production Double Differential Cross Sections from Proton-actinide Reactions at 360 MeV

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Double-differential cross section (DDX) data of nucleon-actinide reactions is crucial for the study of nuclear waste transmutation by accelerator driven systems. Charged particle emission data is strongly required as well as the neutron data up to several Gev. In the present study, we measured double-differential cross sections of light charged particle productions for proton induced reactions on ^{232}Th at 360 MeV. The experiment was carried out at the PHASOTRON facility of the Joint Institute for Nuclear Research (JINR) in Dubna.

The light charged particles (LCPs) emitted from nuclear reactions were detected by ΔE-E counter telescopes. Eight detector systems were used. Four of them were comprised of two plastic scintillator plates and BGO crystal. The other four consisted of two silicon semiconductor detectors and two scintillation counters, a cubic CsI(TI) (40 mm long) crystal and plate plastic scintillator. The four identical detectors on each side were placed at laboratory angles of 20°, 40°, 70° and 105° with respect to the beam axis. Resultant DDX spectra of protons and deuterons were compared with intranuclear cascade (INC) model.

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I. INTRODUCTION

The accelerator driven system (ADS) has been recognized as one of the most attractive options for the nuclear transmutation of the high level nuclear waste. We may expect ADS to reduce the hazard level of the nuclear waste dramatically and to operate as the energy generator. To realize ADS, it is necessary to conduct various fundamental researches and technical developments. Double-differential cross section (DDX) data of nucleon-actinide reactions is very important for the nuclear waste transmutation facilitated by ADS. Since charged particle emission data is strongly required as well as neutron data up to several GeV, we plan conducting the light charged particle (LCP) measurements with typical actinide targets. The new experimental data is used to test theoretical models. At the Kyushu University the new IntraNuclear Cascade Model (INC) has been developed, which describes LCP production cross-sections. Its high predictive power has been demonstrated in a mass range from on ^{9}Be to ^{209}Bi [1-3]. It is very important to examine its validity in the heavyer mass range.

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II. EXPERIMENT

The experimental setup is shown schematically in Fig. 1. The self-supporting target in a vacuum chamber of 400-mm outer diameter was bombarded with 360-MeV proton beams from PHASOTRON The beam intensity was $\sim 10^8$ protons/sec and the beam spot on the target was approximately 13 mm in diameter The target used in this experiment was 77-μm-thick ^{232}Th. LCPs emitted from nuclear reactions were detected by ΔEE spectrometers. For energy calibration the elastic proton-proton scattering experiment was also carried out using a polyethylene target.

As seen in Fig. 1, we used two different types of spectrometers. They were positioned on the opposite side with respect to the beam axis in the same reaction plane. The right-side one (high-energy module) was comprised of two plastic scintilators (3 mm thick and 5 mm thick) and a BGO scintillator (60 mm in diameter and 200 mm long for 20 and 160 mm long for 40, 70, and 105) connected with photomultiplier tubes (PMTs). The left-side one (low-energy module) consisted of two silicon layer (50 μm thick and either 2000 μm thick for 105 or 300 μm thick for 20, 40, and 70) and two scintillation counters, a cubic CsI(Tl) (40 mm long) scintillator and a

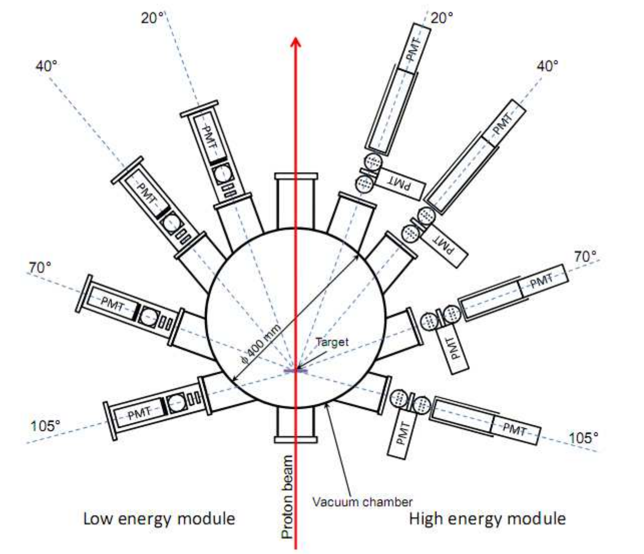

Fig. 1. (Color online) Schematic view of the experimental setup.

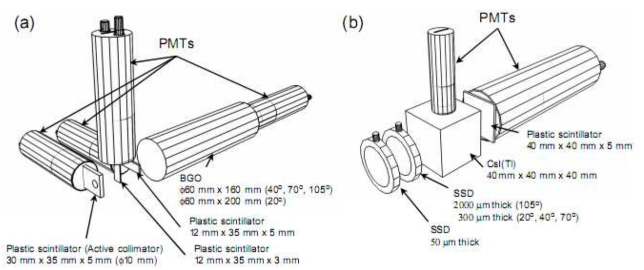

Fig. 2. Layout of the spectrometers. (a) high-energy module, (b) low energy module.

plate plastic scintillator (5 mm thick), connected with PMTs. Detailed schematic of the spectrometers is illustrated in Fig. 2. The four identical detectors on each side were placed at the laboratory angles of 20, 40, 70, and 105 with respect to the beam axis.

III. ANALYSIS

Data analysis procedure is the same as in Ref. 1. ADC channels of the experimental raw data were calibrated into energies deposited to the scintillators by the light response function and the elastic scattering peak of the polyethylene target. The light response of BGO is given by the following power law expression,

$$L(Z, A, E) = a_1(Z, A)E^{a_2(Z,A)}, \quad (1)$$

where $a_1(Z, A)$ and $a_2(Z, A)$ are the fitting parameters. The systematics of these parameters were taken from Ref. 4. In Ref. 4, the response function for CsI(Tl) is expressed as

$$L = \int dx c_a K \frac{\alpha K(dE/dx)}{1 + \alpha K(dE/dx) - \beta(\alpha K dE/dx)^2}, \quad (2)$$

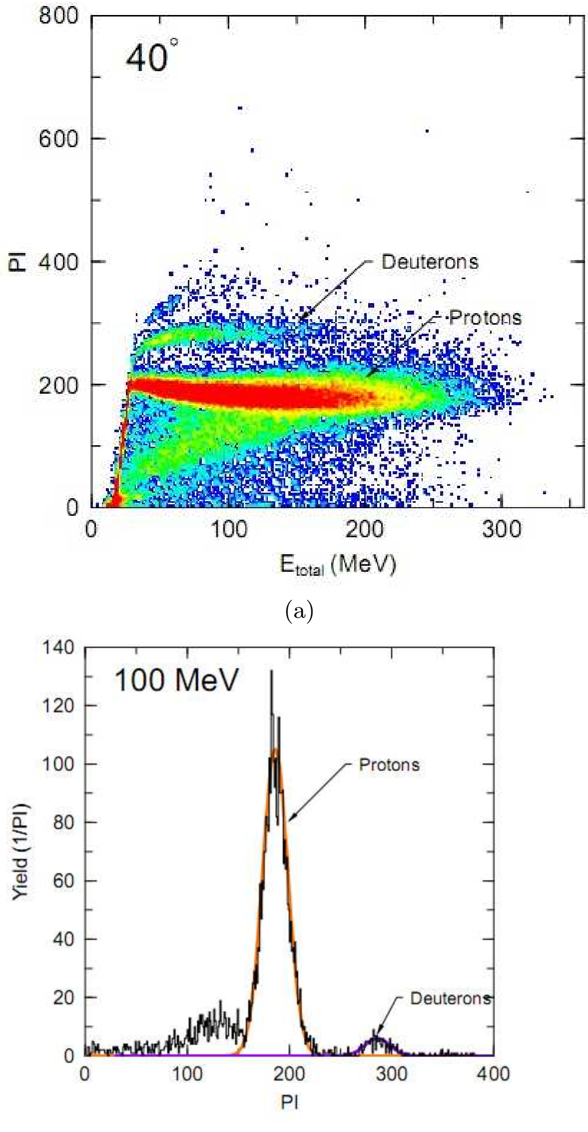

Fig. 3. (Color online) (a) Two-dimensional plot of PI versus E_{tot} at 40° for the 360-MeV $p+^{232}$Th reaction. (b) PI projection spectrum at $E_{\mathrm{total}} = 100$ MeV.

where c_α, αK, and β are fitting parameters.

In order to identify different particles (protons and deuterons), the PI technique was used. The particle identification quantity, PI, is given by

$$PI = E_{total}^b - (E_{total} - \Delta E)^b, \quad (3)$$

where E_{total} is the total energy deposited in the spectrometer $\Delta E$is the energy deposited in the ΔEdetectors, and $b$denotes the parameter representing the range of each particle. In this study $b = 1.73$ was employed. The deposit energy calculation was performed by the Bethe-Bloch equation. As an example of the particle identification the two-dimensional plot of PI versus E_{total} at 40 for the reaction p ^{232}Th at $E = 360$ MeV is shown below in Figs. 3(a) and 3(b).

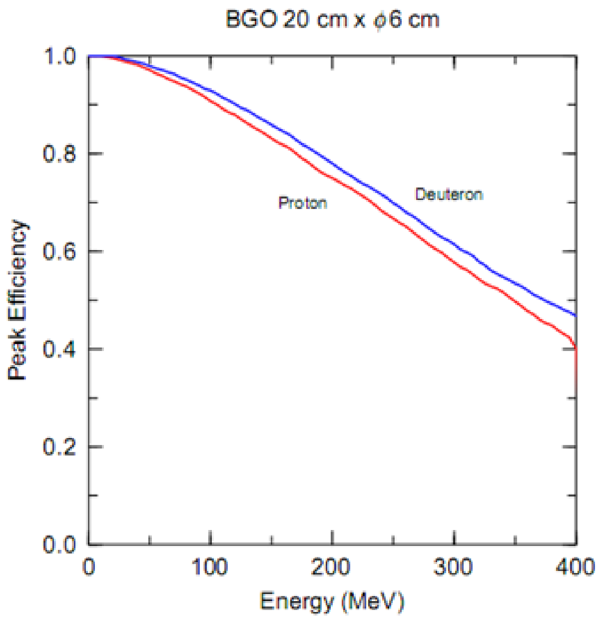

Fig. 4. (Color online) Peak efficiency of the BGO detector.

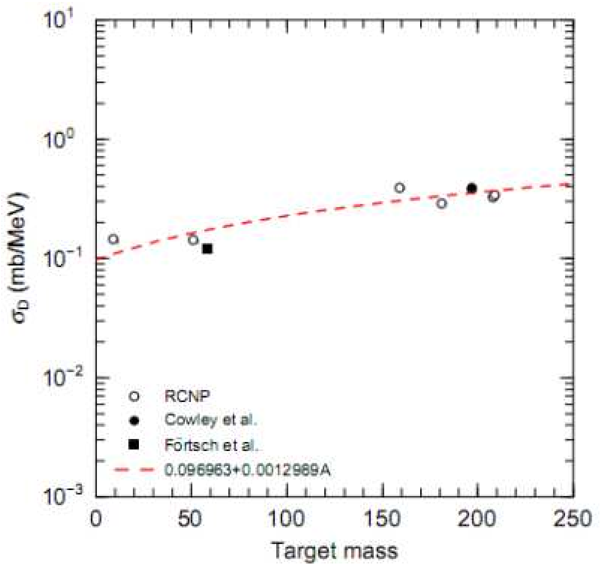

Fig. 5. (Color online) Mass dependence of the normalization factor σ_D of Eq. (5) at emission energy $E_{p'} = 105$ MeV. A fit to the experimental data is displayed with a dashed line as a function of target mass number A.

The double-differential cross sections were obtained by the following way : First, PI projection spectra was generated for each energy bin with a 10-MeV width. Next, the proton and deuteron events were counted up for each spectral peak by performing Gauss fitting (see the Fig. 3(b)). The number of proton and deuteron events was corrected in terms of the peak efficiency. In the present analysis, proton and deuteron peak efficiencies of the BGO and CsI(Tl) scintillators were obtained from simulation results of the PHITS [5] code. In the simulation, the scintillator was included along with their precise dimensions and monochromatic proton/deuteron beams up to 500 MeV. In this calculation, we set the default value for the Proton-nucleus and deuteron-nucleus reactions (JQMD [6] and NASA formula for deuteron). Finally we determined the double-differential cross sections for each energy bin, which are given by

$$\frac{d^2\sigma}{d\Omega dE} = \frac{Y}{PS_t\phi\Delta\Omega\Delta E}, \qquad (4)$$

where ΔE is the bin size of the energy and $\Delta\Omega$ is the spectrometers solid angle. P is the peak efficiency mentioned above, S_t is the surface density of the target, Y is the yield per ΔE at the detection angle of interest, and φ is the number of incident protons.

Since we could not obtain the number of the incident protons, we determined magnitude of the DDXs using the Kalbach systematics. The form for the MSD part of the angular distributions is given by

$$\frac{d^2\sigma}{d\Omega dE} = \sigma_D \frac{a}{\sinh a} \exp\left(a \cos\theta\right), \qquad (5)$$

where θ is the emission angle, σ_D is a normalization factor related to the angle-integrated cross sections as a function of emission energy and $a$denotes the slope parameter as a function of the ratio of emission energy to incident energy, which has been parametrized by Kalbach [7]. According to Refs. 7 and 8, the quantity of σ_D is independent of incident energy. We, therefore, estimated the factor σ_D of DDXs for 360-MeV proton induced reactions on ^{232}Th by using our previous data of 392-MeV (p, xp') reactions on ^{9}Be, ^{51}V ^{159}Tb, ^{181}Ta, ^{197}Au, ^{208}Pb, and ^{209}Bi [1-3].

From this figure, σ_D at $A = 232$ was found to be 0.398 mb/MeV Magnitude of DDX for ^{232}Th target was assumed to be given by

$$DDX(E_{p'}, \theta = \theta_0) = \frac{Y(E_{p'}, \theta = \theta_0)}{Y(E_{p'} = 105MeV, \theta = \theta_0)} \cdot DDX_{Kalbach}(E_{p'} = 105MeV, \theta = \theta_0), \qquad (6)$$

where $E_{p'}$ denotes the proton energy and θ are the detection angles. $Y$is the proton yield corrected by the peak efficiency in a certain energy bin at the detection angle θ $DDX_{Kalbach}$ shows magnitude of DDX at

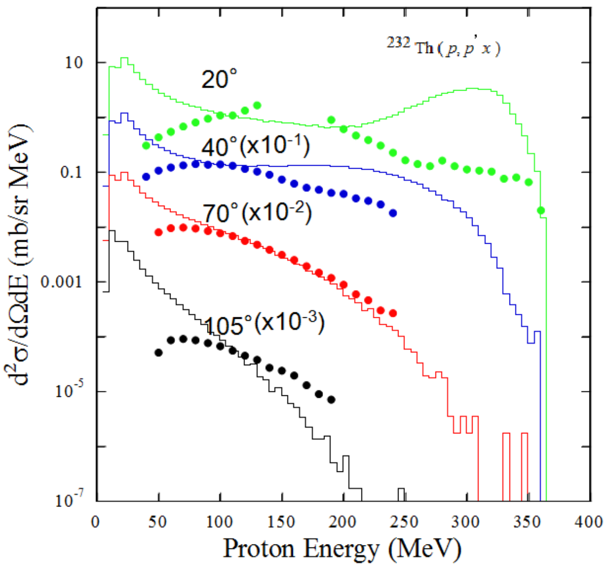

Fig. 6. (Color online) Preliminary results of the measured proton DDXs for the 360-MeV proton induced reactions on ^{232}Th. Curves are the INC results.

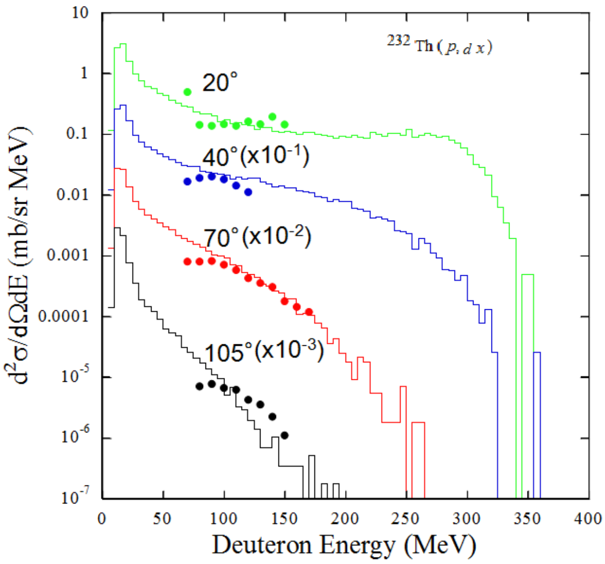

Fig. 7. (Color online) Preliminary results of the measured deuteron DDXs for the 360-MeV proton induced reactions on ^{232}Th. Curves are INC results.

$E_{p'}$ = 105 MeV and $\theta = \theta_0\,(\theta$ = 20°, 40°, 70°, and 105°) calculated with the Kalbach systematics with σ_D = 0.398 mb/MeV.

Figure 6 shows the measured DDXs for the 360-MeV p+^{232}Th reactions obtained by the high-energy module. The present measured spectra has similar features to those in Ref. 1.

IV. SUMMARY AND CONCLUSIONS

We measured light charged particle production double- -differential cross sections for 360-MeV protons on ^{232}Th. Spectral energies of protons and deutrons were obtained with the ΔE-E method at the laboratory angles of 20°, 40°, 70°, and 105°. In the present article, the experimental procedure and preliminary results were presented. More detailed analysis and an additional experiment should be performed in order to obtain reliable data.

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