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SYSTEMATIC INVESTIGATION OF THE ^{12}C(D,PΓ)^{13}C REACTION AROUND 1450 KEV DEUTERON ENERGY – A PROPOSED METHOD FOR ACCELERATOR ENERGY CALIBRATION

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Abstract

In this work we carried out the investigation of the ^{12}C(d,pγ)^{13}C reaction around 1450 keV deuteron energy based on literature cross section data compared own measurements. The aim of this study to give a more precise resonance energy value of ^{12}C+d reaction to applied it in accelerator energy calibration using deuteron beam as the most precise method.

I. Introduction

In the frame of a Coordinated Research Project organized by the International Atomic Energy Agency (IAEA-CRP), among other tasks, the experimental determination of fundamental cross section data for deuteron induced gamma ray emission analysis was carried out in our laboratory [1]. To determine the cross sections in the function of energy, an accurate energy scale calibration is required.

Several absolute methods are suitable for particle accelerator energy calibration, for example measuring narrow nuclear reaction resonances and/or neutron threshold [2], using non-resonant nuclear reactions [3], cross over techniques at higher energies [4], and techniques based on Rutherford backscattering spectrometry (RBS) [5].

To our best knowledge, using deuteron beams, only the $^{16}O(d,n)^{17}F$ reaction at 1829.2±0.6 keV has been applied to the precise absolute energy calibration of accelerators [6]. The implementation of the neutron threshold reaction is rather complicated since the high background of neutrons from d+d reactions can hide the small neutron yield around the threshold energy, as we observed earlier [7]. Therefore, a narrow nuclear reaction resonance, detecting gamma-rays, is preferable.

In the framework of the IAEA-CRP project, we repeated the total cross section measurements for the 3089 keV gamma line of the $^{12}C(d,p\gamma)^{13}C$ reaction as well as for the particles from the $^{12}C(d,p_1)^{13}C$, $^{12}C(d,p_0)^{13}C$ and $^{12}C(d,d_0)^{12}C$ reactions in the 0.74-2.0 MeV energy range. As a novel approach, the gamma and particle yields were detected simultaneously. Furthermore, we carried out the evaluation of the gamma ray and particle production cross sections taking literature data into account, too.

For the ^{12}C+d nuclear reactions at the studied energy range, a pronounced compound nucleus mechanism is present besides the direct mechanism. Consequently, certain resonances appear in the excitation function. Close to 1450 keV deuteron energy, a fairly narrow and quite intense resonance can be observed. The energy of this resonance has been established as 1449±1.5 keV with a width of 7 keV [8]. The existence of this kind of narrow and strong resonance with well defined energy is unique among the deuteron induced nuclear reactions. As the preparation of a carbon target is simple, this nuclear resonance is a possible option for accelerator calibration using gamma-ray detection. With this method, the necessity of measuring a narrow proton resonance before switching to a deuteron beam can be avoided. However, to apply this resonance for energy calibration, its position has to be determined as accurately as possible. In this paper, we focus on the region around 1450 keV deuteron energy to give an updated resonance value, taking advantage of the simultaneous detection of gamma-rays and particles. The complete measured and evaluated cross-section datasets for the 0.74-2.0 MeV energy range will be presented elsewhere [9].

II. Experimental

The measurements were carried out at the 5 MV Van de Graaff accelerator of Atomki. The available ions for analysis are H $^+$, D $^+$, and ^{4}He $^+$. The assortment of ions and their energy range (0.6-3.8 MeV) provided by the accelerator makes it possible to apply most of the ion beam analytical techniques: PIXE, PIGE, RBS, Scanning Transmission Ion Microscopy (STIM), Elastic Recoil Detection Analysis (ERDA) etc.

Self-supporting carbon foil (thickness: 1.9×10^{18} atom/cm^2) with an evaporated palladium layer on its surface (thickness: 2.7×10^{17} atom/cm^2) was chosen as a target. The number of target nuclides was determined with RBS using alpha beams of 1.5 MeV energy directly before and after the cross section measurements under the same experimental conditions. The uncertainty of the target thickness determination was 3%.

For the detection of gamma-rays, a Canberra Model GR4025-7600SL coaxial type HPGe detector (crystal: 59.5 mm diameter, 170 cm^3 volume) was applied at an angle of 55° relative to the incident beam direction with a distance of 9.5 cm between the front face of the crystal and the samples. Particles from Rutherford backscattering and nuclear reaction were detected with an ORTEC Ion Implanted Silicon detector with 13 keV energy resolution. For the elimination of high intensity backscattered particles, we used a copper collimator with a diameter of 3 mm before the particle detector. The number of bombarding particles was determined through the backscattering of deuterons from the Pd layer. For more detailed description about the methods, see [9].

The energy of the beam, as well as the energy stability was regularly assessed measuring the resonance at 991.81±0.04 keV in the ^{27}Al(p,γ)^{28}Si reaction, the resonance at 1416.9±0.1 keV in the ^{23}Na(p,γ)^{24}Mg reaction, as well as using the ^{7}Li(p,n)^{7}Be reaction at the 1880.60±0.07 neutron threshold. Based on these measurements, an uncertainty of 3.0 keV was assigned to the beam energy.

III. Data fitting process

The fitting procedure of the resonance peak was performed with the Fityk software package [10]. Because complex background elimination was required, we applied a linear background combined with a step function.

After the background elimination, we carried out the peak fitting using split Gaussian function (include two Gaussian function with different FWHM). The resonance energy was calculated from the centre position taking the thickness of target into account, as in the following equation

$$E_0 = E_r + \frac{\Delta}{2} \quad , \qquad (2)$$

where E_0 is the energy of the incident ion, E_r is the resonance energy and Δ is the thickness of the sample in keV [11].

IV. Results and discussion

Based on the collected cross section data from literature concerning the $^{12}C(d,p\gamma)^{13}C$ and $^{12}C(d,d_0)^{12}C$ reactions, supplemented with our measurements, we was able to determine more precise value for the energy of the resonance.

In figure 1, the final result of the fitting process of the excited function around 1450 keV deuteron energy based on the 3089 keV gamma line of the $^{12}C\ (d,p\gamma)^{13}C$ reaction is shown as an example.

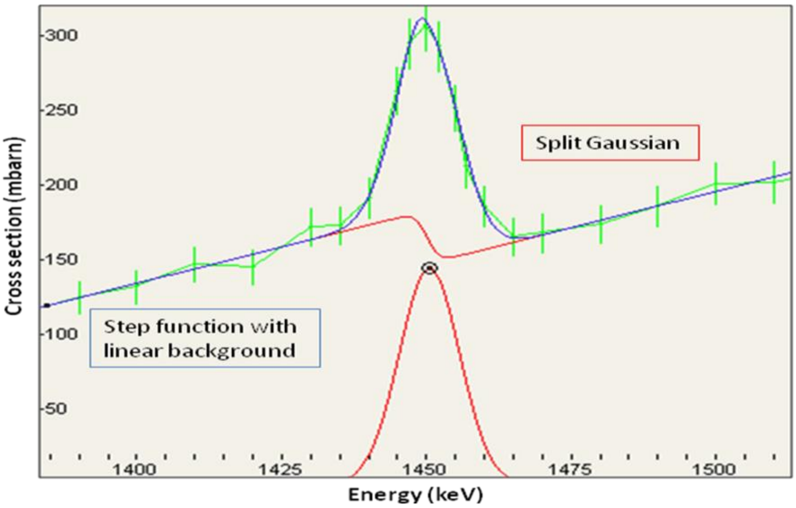

Figure 1. Fitting process of the excited function around 1450 keV deuteron energy based on the 3089 keV gamma line of the ^{12}C (d,pγ)^{13}C reaction

We calculated the resonance energy as above mentioned. The uncertainty of the resonance energy was determined considering the error of the fitting process and, where it was possible, we also estimated the energy spread of the accelerator. These errors are much higher than the uncertainty of the target thickness.

Table 1 shows the integrated results of the evaluation process with some other literature data, including the most important information, namely

- source of data,
- thickness of target in keV, calculated at 1450 keV deuteron energy with SRIM 2013 [12],
- type of nuclear reactions,
- calculated energy of resonance with uncertainty, taking the error of the target determination and the energy spread of the accelerator into account.

Table 1/a. Summary of the experimental data and fitting process concerning the ~1450 keV resonance of ^{12}C (d,pγ)^{13}C and ^{12}C (d,d_0)^{12}C reactions

Source of data	Reaction	Thickness of sample in keV, calculated at 1450 keV deuteron energy	Fitted value (keV)	Error of fitting (keV)	Resonance energy (keV)	Uncertainty of resonance energy	Nr.
Present work	$^{12}C(d,p\gamma)^{13}C$	10.5	1450.36	0.51	1445.11	3.20	1
Present work	$^{12}C(d,d_0)^{12}C$	10.5	1451.04	0.68	1445.79	3.20	2
Present work	$^{12}C(d,p_1)^{13}C$	10.5	1450.72	0.77	1445.47	3.20	3
Present work	$^{12}C(d,p_0)^{13}C$	10.5	1451.37	0.85	1446.12	3.20	4
[13]Tryti et al. (1973)	$^{12}C(d,p\gamma)^{13}C$	2.13	1449.04	0.53	1447.98	1.50	5
[14]Elekes et al. (2002)	$^{12}C(d,p\gamma)^{13}C$	6.03	1452.77	0.70	1449.75	1.70	6
[15]Kokkoris et al. (2007)	$^{12}C(d,p_1)^{13}C$	5.62	1448.00	4.91	1445.19	4.91	7
[16]Kokkoris et al. (2006)	$^{12}C(d,p_0)^{13}C$	5.62	1448.00	9.75	1445.19	9.75	8
[17]Debras et al. (1977)	$^{12}C(d,p_0)^{13}C$	5.64-28.2	1438.16	15.66	1429.70	15.66	9
[18]Carvalho et al. (2008)	$^{12}C(d,p_0)^{13}C$	3.66	1445.56	7.48	1443.73	7.48	10

Table 1/b. Summary of the experimental data and fitting process concerning the ~1450 keV resonance of ^{12}C (d,pγ)^{13}C and ^{12}C (d,d_0)^{12}C reactions

[19]Kashy et al. (1960)	$^{12}C(d,p_0)^{13}C$, $^{12}C(d,p_0)^{13}C$, $^{12}C(d,d_0)^{12}C$	4.9	1446.00	n.c.	1443.55	n.c.	11
[16]Kokkoris et al. (2006)	$^{12}C(d,d_0)^{12}C$	5.62	1448.00	n.c	1445.19	n.c	12
[20]Jarjis (1979)	$^{12}C(d,p_0)^{13}C$	-	1439.29	n.c	1439.29	n.c	13
[21]Papillon and Walter (1997)	$^{12}C(d,p\gamma)^{13}C$	2.92	1413.20	3.40	1411.74	3.40	14
[22]Jeronimo et al. (1963)	$^{12}C(d,d_0)^{12}C$	1.41-2.82	1481.65	7.10	1480.59	7.10	15

Based on the evaluated data, we determined the weighted average of the resonance energies. Some data were omitted from the calculation because of the unknown errors of literature data, the obviously inaccurate energy calibration or insufficient number of data points. The omitted data are presented in the second part of table 1. The uncertainty of the obtained resonance energy was calculated using the following equation:

$$\sigma = \sqrt{\frac{1}{\sum_{i=1}^{n} \frac{1}{\sigma_i^2}}} \quad , \qquad (3)$$

where σ is the error of the weighted average, σ_i is the uncertainty of each measurement.

From the data evaluation and calculations, we obtained 1447.5 ± 0.9 keV as the resonance energy. This new value takes account of the target thickness and includes all available, well-established experimental data to the best knowledge of the author. The resonance energies from which the weighted average is calculated are presented in Figure 2.

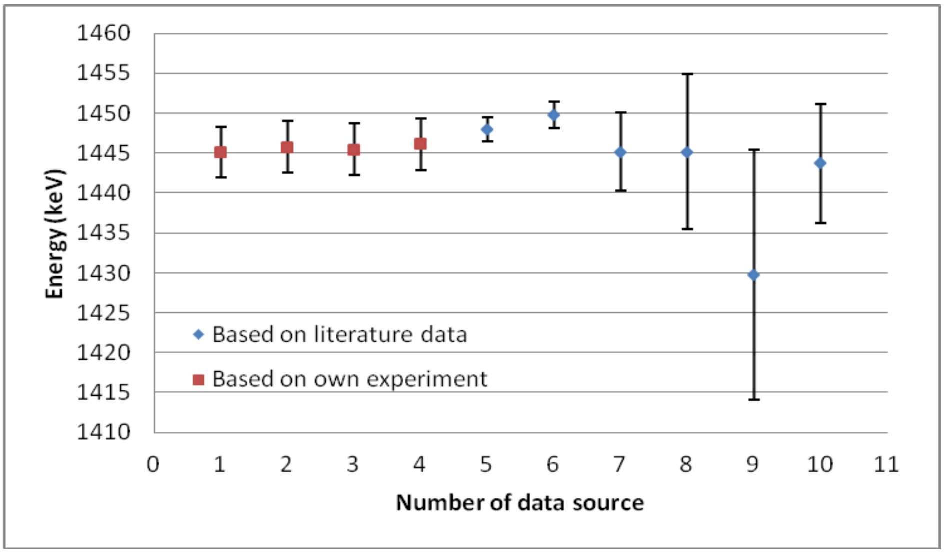

Figure 2. Experimental data of ^{12}C+d resonance close to 1450 keV

Based on the experimental data fitting process, we also determined the width of the resonance, but in this study we cannot get a more precise value than 7 keV, obtained by Tryti et al. in 1973 [13].

V. Conclusion

In this study we carried out the systematic investigation the resonance of the ^{12}C+d reactions around 1450 keV deuteron energy as potential choice for accelerator calibration.

As a first step we collected the literature data on the ~1450 keV resonance of the ^{12}C (d,pγ, p_1,p_0)^{13}C and $^{12}C(d,d_0)^{12}C$ reactions. In our own cross-section measurements for the $^{12}C(d,p\gamma)^{13}C$ reaction, we simultaneously detected the resulting particles and gamma-rays, as a novel approach aiming an improved consistency. We also measured the cross-section in the function of energy for the $^{12}C(d,d_0)^{12}C$ reaction. Based on 10 data sources for the region around 1450 keV, applying a fitting and averaging process, we obtained 1447.5 ± 0.9 keV for the resonance energy. For the width of the resonance, we accept 7 keV, given by Tryti et al. We suggest using the 1447.5 ± 0.9 keV resonance of the $^{12}C(d,p\gamma,\ p_1,p_0)^{13}C$ and $^{12}C(d,d_0)^{12}C$ reactions as a new values to calibrate accelerator energies for deuteron beams.

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