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Cross Section Measurement of the Fusion Evaporation Reaction $^{238}\text{U}(^9\text{Be}, 5n)^{242}\text{Cm}$

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Abstract: The excitation function of the $^{238}\text{U}(^9\text{Be}, 5n)$ reaction was obtained for the first time. By using a stack of uranium targets, 20 experimental data were obtained by the on-line irradiation without changing beam energy. Taking the advantage of the long lifetime and α decay mode of the residue nucleus ^{242}Cm , the off-line measurement of the α radioactive was performed to obtain its yields. The maximum cross section is about 1 mb. The curve's shape and the maximum's position agree with the present model. The value of the cross section will help us to develop the related models, and push the nuclear studies in the transuranium region.

Key words: transuranium; fission-evaporation residue; excitation function; α decay; stack-target technique

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1 Introduction

The nuclide in the transuranium region is a hot topic at present, not only in the nuclear structure but also in the nuclear power. In this mass region, the hot fissionable compound nuclei produced in the fusion reaction deexcited mainly by fission and little by fusion-evaporation. The competition between these two channels are very sensitive to some nuclear properties, such as the fission barrier, shell effect, level density of the collective states and nuclear viscosity^[1-4]. Measuring the fusion-evaporation cross section will give us the insight of these subjects. However, the small cross section is one of the main difficulties encountered during these experimental investigations. So usually, to verify the feasibility of the experiments, the cross section of the interest must be calculated or measured as the first mission. One more challenge arises, where the theoret-

ical results give similar overall behavior but differ a lot in the value. So the experimental cross section will verify the validity of the models, and afterwards, promote the nuclear studies in the transuranium region.

In this experiment, we choose to measure the $5n$ evaporation channel in $^9\text{Be}+^{238}\text{U}$ reaction. This hot fusion-evaporation system produces neutron-rich compound nucleus, and is expected to have high fission barrier. Consequently, the fission probability will be restrained, which will result in the high survival probability of the evaporation residues, ^{242}Cm here. This actinide nucleus has long lifetime ($t_{1/2}=163$ d), and it decays by α emission(100%). The lifetime is long enough to decay out the short-living fission products, and is suitable to gain sufficient statistics by off-line measurement within a limited time. According to the theoretical prediction, the most populations located over the energy window between 40 and 60 MeV, which is

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available at the accelerator in the Institute of Modern Physics, Chinese of Academy of Sciences (IMP,CAS) in Lanzhou.

2 Experiments

The evaporation residue nuclide ^{242}Cm were yielded by ^9Be beam projected towards a stack of 20 uranium targets. The beam with energy of 63 MeV was provided by SFC of IMP,CAS in China. Each of the target is composite of one uranium target and one self-support aluminum foil with about 0.3 mg/cm^2 thickness which is used both as a beam-energy degrader and a catcher for the recoils of the reaction residues. The diagram of the experiment setup is

shown in Fig. 1. The uranium targets were prepared by molecular plating technique^[5], uranyl nitrate onto the 0.8 mg/cm^2 aluminum foil to a thickness of about $100\text{ }\mu\text{g/cm}^2$. The thickness of the uranium deposited on the aluminum backing is determined by spectrophotometry, and is chosen to be thin enough to let the compound nucleus escaped from it. In the reaction chamber, the uranium targets were placed on the end of the beam line before the Faraday cup, as the uranium layers faced away from the upstream of the ion beam. The aluminum backing is used as a degrader only. By the way, since the beam need to be incident on all of the 20 targets, the collimation of the whole system was corrected carefully. The detail information of the targets is listed in Table 1.

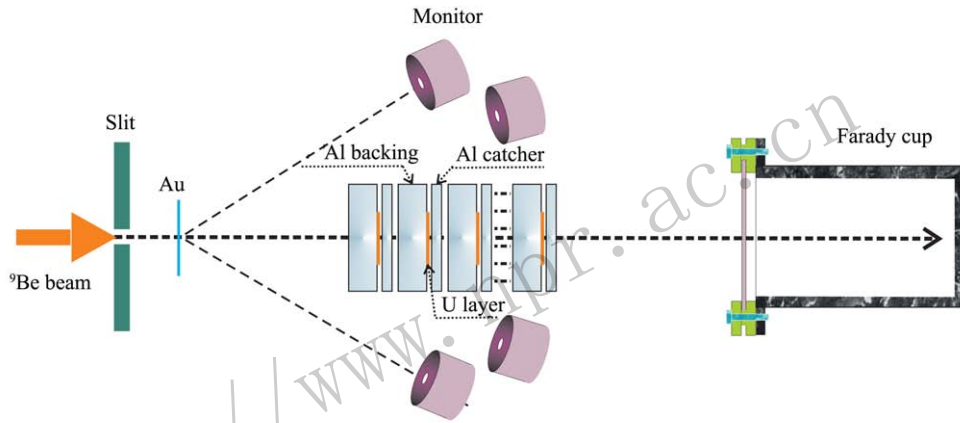


Fig. 1 (color online) Experimental setup.

Table 1 The information of the stacking targets and the experimental cross section obtained in this work.

No.	U/ $(\mu\text{g/cm}^2)$	Al/ (μm) backing	Al/ (μm) catcher	E_{Be}/MeV	Cross section/mb
1	100.3	3.00	1.43	62.78(44)	0.141(14)
2	101.2	3.04	1.24	61.83(44)	0.179(18)
3	—	—	—	—	—
4	90.6	2.92	1.41	59.98(44)	0.240(24)
5	93.7	3.08	1.31	59.02(45)	0.455(42)
6	91.5	2.94	1.27	58.04(46)	0.496(46)
7	96.5	2.84	1.25	57.07(47)	0.647(58)
8	88.0	3.02	1.22	56.13(48)	0.834(74)
9	93.7	3.07	1.20	55.14(50)	1.01(9)
10	88.6	2.99	0.75	54.12(52)	1.31(11)
11	90.8	3.07	1.17	53.22(54)	1.22(11)
12	91.0	3.03	1.16	52.18(56)	1.08(10)
13	95.2	2.87	1.25	51.14(58)	0.942(81)
14	93.9	3.19	1.20	50.10(61)	0.530(48)
15	—	—	—	—	—
16	100.3	3.13	1.21	47.81(67)	0.245(23)
17	94.5	2.90	1.36	46.66(71)	0.168(17)
18	95.0	3.05	1.27	45.51(74)	0.155(16)
19	—	—	—	—	—
20	95.2	3.10	1.03	43.16(81)	0.105(12)

The current intensity plays an important role in determining the cross section. In the center of the chamber, a $270 \mu\text{g}/\text{cm}^2$ Au foil is positioned in front of the uranium targets, as a Rutherford scattering target. The scattered beam particles will be detected using four Si(Au) monitors positioned symmetrically with respect to the beam axis. The Rutherford scattering formula will be out of validity for the monitors installed at the angle larger than the grazing angle. In this experiment, the monitors were put as near as possible with the axis, ensuring to be much smaller than the grazing angle 55° . The distance and diagram of each detector is optimized to minimize the dead time of the data acquisition but allow a high precision measurement of the beam intensity. The detectors are mounted on a shelf which could turn around the Au foil. We could rectify the angle of each monitor with respect to the beam line, taking advantage of the relatively accurate separation angle between two symmetrical ones. The geometrical information of the monitors and the average current is listed in Table. 2. Reading out the scattered particle number once per 5 min from the raw data, the current curve could be obtained. Take the result of No.1 monitor as an example, presented in Fig. 2. According to the curve's shape, we could decide the manner to calculate the average beam intensity, which is 3.494 p nA in our experiment.

Table 2 The geometrical information of each monitor and current value deduced from it. θ refers to the angle with respect to the beam line. l is the distance between the Au foil and each monitor. ϕ is the diameter of each monitor's diagram. I_i refers to the average current.

No.	$\theta/(\circ)$	l/mm	ϕ/mm	$I_i/\text{p nA}$
1	18.30	196	1.55	3.52(34)
2	19.70	196	1.52	3.71(35)
4	24.95	164	2.06	3.34(28)
5	26.05	164	2.04	3.40(29)

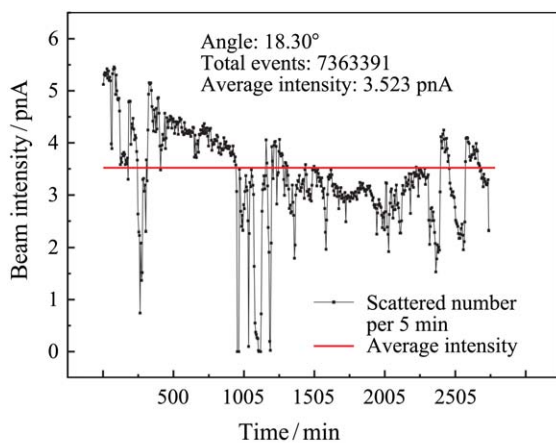


Fig. 2 (color online) Current curve of monitor No.1 as an example.

After a delaying period of more than 80 d, in order to allow the short-living activity originating from the fission products to decay out, the α radioactivity of ^{242}Cm on the catcher was measured in an off-line chamber. The size of source is about $\phi 3 \text{ mm}$, since a spot can be seen in the center of each uranium target burned by the beam. In addition, we could see that the collimation is satisfied. Put the sources several millimeters away from the Si detector. The solid angle could be simulated by a program based on the Monte Carlo method, in which a normal distribution of source is used. Subjected to the number of the detectors and the size of the off-line chamber, the catcher foils were detected group by group. The different delaying time and measuring time for each foil was taken into account carefully in the following calculation.

The decay mode of ^{242}Cm is α emission, 74.1% at 6.113 MeV and 25.9% at 6.069 MeV. Most of the contamination will come from the α radiation of ^{238}U that pollutes the catchers at high temperature, and from other neutron-evaporation channels. Since the cross section is in the order of mb, there will be large amount of ^{238}U did not react. Although the lifetime of ^{238}U is $4.468 \times 10^9 \text{ a}$, the number of α particles from ^{238}U will be 200 times larger than ^{242}Cm , when supposing all no-reacting ^{238}U were detected for 4 d. In view of its α energy at about 4 MeV, which is about 2 MeV away from the peaks concerned, we set the threshold during the off-line measurement to get clean spectra. In the beam-energy range of 43 and 62 MeV, the other residues with large probability are $^{241,243,244}\text{Cm}$. The lifetime of ^{241}Cm is only 32.8 days. And it decays 99% by electron capture. The daughter nucleus ^{241}Am decays by α with lifetime around 432 years. So its α radioactivity after 80 d could be ignored. The lifetime of $^{243,244}\text{Cm}$ is 29.1 and 18.1 years respectively. Their decaying α is all at about 5.8 MeV, which will contribute to a tail in the spectra at the lower side.

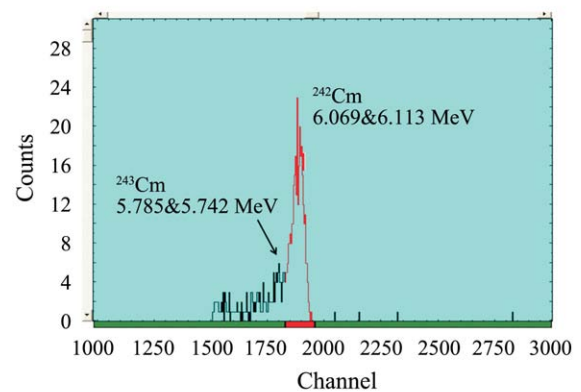


Fig. 3 (color online) An α spectrum, corresponding to $E_{\text{Be}} = 54.14 \text{ MeV}$, during off-line measurement as an example.

Since the recoil residue ^{242}Cm will penetrate into the Al catcher with a depth of 0.5 μm , the α particles will loss energy less than 100 keV when emitting from the catchers. However we still are able to get clear identification from the contamination. An α spectrum during the off-line measurement is shown in Fig. 3. Due to the drift of the peaks, the spectra were recorded section by section.

3 Data analysis and results

The cross section was obtained with following formula,

$$\sigma = \frac{\lambda n / \eta}{e^{-\lambda \times t_d} (1 - e^{-\lambda \times \Delta t}) N_0 \bar{I} (1 - e^{-\lambda \times t_r})}, \quad (1)$$

where t_r , t_d , Δt represent the time of on-line radiation, conserved and off-line measurement, respectively. n is the number of α particles detected. N_0 is the thickness of the uranium target. η is the geometry efficiency of the detector. \bar{I} denotes the beam intensity in average.

The beam-energy error is mainly deduced from FWHM versus peak position of the scattered ^9Be , which is $\sim 0.7\%$. The energy dispersion when the beam passed through the stacking targets will lead to the additional error, which is in the order of 0.01%. The cross section error could be calculated as

$$(\Delta\sigma)^2 = \left(\frac{\partial\sigma}{\partial n} \Delta n\right)^2 + \left(\frac{\partial\sigma}{\partial N_0} \Delta N_0\right)^2 + \left(\frac{\partial\sigma}{\partial \bar{I}} S(\bar{I})\right)^2 + \left(\frac{\partial\sigma}{\partial \eta} \Delta\eta\right)^2. \quad (2)$$

The first term is involved by the statistic error of the α number detected. ΔN_0 is about 5% of N_0 , which is involved mainly from the uncertainty of spectrophotometer. $S(\bar{I})$ represents the standard deviation, calculated as

$$S(\bar{I}) = \sqrt{\frac{\sum_{i=1}^n (\bar{I} - I_i)^2}{n-1}}, \quad (3)$$

where I_i is the current value deduced from each monitor. So to have,

$$(\Delta\sigma)^2 = \sigma^2 \times \left[\frac{1}{n} + 5\%^2 + \frac{\sum_{i=1}^3 (\bar{I} - I_i)^2}{3\bar{I}^2} + \left(\frac{\Delta\eta}{\eta}\right)^2 \right], \quad (4)$$

η could be expressed approximately as

$$\eta = \frac{1}{2} \left(1 - \frac{r_0}{\sqrt{r_d^2 + r_0^2}} \right), \quad (5)$$

where r_0 is the distance between the center of the source and the detector, r_d is the radius of detector.

$\Delta\eta$ could also be obtained by error recursion formula.

$$(\Delta\eta)^2 = \left(\frac{\partial\eta}{\partial r_0} \Delta r_0\right)^2 + \left(\frac{\partial\eta}{\partial r_d} \Delta r_d\right)^2. \quad (6)$$

The results of the experimental cross section is listed in Table 1. To compare with the theory results, the data were plotted together with the HIVAP results in Fig. 4. Since the Al catcher foils are very fragile, 3 pieces broke during transfer. So there are only 17 points in the plot. The maximum in the excitation function is at around 54 MeV, similar with the result from the present codes^[4, 6]. The peak value is in the magnitude of 1 mb. It gives us the preliminary conclusion that the assumptions in Ref. [4] is more reliable.

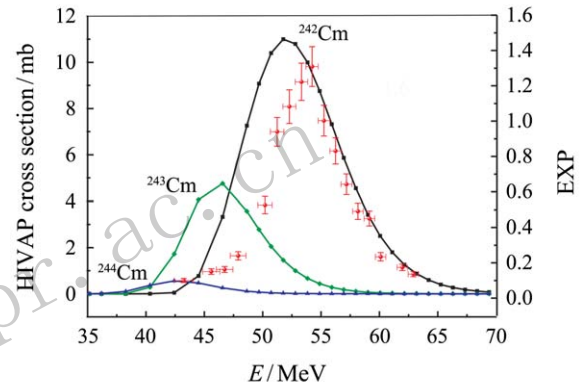


Fig. 4 (color online) The experimental results compared with the calculated ones by HIVAP code. The left ordinate is for the calculated results, which are shown by symbol+line. The right ordinate is for the experimental results shown by red points.

4 Summary

The excitation function of $^{238}\text{U}(^9\text{Be}, 5\text{n})$ is obtained in this experiment. The maximum yield happens at the incident energy at ~ 54 MeV, with the magnitude of 1 mb. This result is useful to optimise the theory models and verify the validity of their assumptions. The study on nuclear structure and reaction in the transuranium region, and the nuclear engineering research could benefit from this basic data, too. Further research on the theory work to get accurate simulation will be carried out in future.

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$^{238}\text{U}(^9\text{Be}, 5\text{n})^{242}\text{Cm}$ 熔合蒸发反应激发函数测量

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摘要: 第一次测量到 $^{238}\text{U}(^9\text{Be}, 5\text{n})^{242}\text{Cm}$ 熔合蒸发反应的激发函数。通过使用叠层靶, 在不改变束流能量的条件下, 在线获得 20 个能量点下的实验数据。利用蒸发余核 ^{242}Cm 的半衰期较长, 且衰变模式是 α 衰变的特点, 用离线测量 α 放射性的方法得到目标核产额。实验最大截面约 1 mb, 激发函数曲线的形态和峰值所在的能量位置与现有的理论模型的计算结果一致。激发函数的实验数据对选择和优化理论模型, 推动超铀核区核物理研究具有重要的意义。

关键词: 超铀核; 熔合蒸发余核; 激发函数; α 衰变; 叠层靶技术

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