Observation of superheavy nuclide $^{271}\text{Ds}$ based on the Gas-filled separator at IMP

Tian-Heng Huang$^{1,*}$, Zai-Guo Gan$^1$, Ming-Hui Huang$^1$, Long Ma$^1$, Zhi-Yuan Zhang$^1$, Xiao-Lei Wu$^1$, Guang-Shun Li$^1$, Zhong-Zhou Ren$^{2,5}$, Shan-Gui Zhou$^{3,5}$, Yu-Hu Zhang$^1$, Xiao-Hong Zhou$^1$, Hu-Shan Xu$^1$, Huan-Qiao Zhang$^4$ and Guo-Qing Xiao$^1$

$^1$ Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
$^2$ Department of Physics, Nanjing University, Nanjing 210093, China
$^3$ Key Laboratory of Frontiers in Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China
$^4$ China Institute of Atomic Energy, Beijing 102413, China
$^5$ Center of Theoretical Nuclear Physics, National Laboratory of Heavy-Ion Accelerator, Lanzhou 730000, China

*E-mail: Tian-Heng Huang, huangth@impcas.ac.cn

Abstract. A gas-filled recoil separator was designed and built newly at Institute of Modern Physics (IMP) in Lanzhou. With the recent commissioning of the separator, the decay properties of $^{271}\text{Ds}$ were studied via the $^{208}\text{Pb} (^{64}\text{Ni}, n)$ reaction at a beam energy of 313.3 MeV. One $\alpha$-decay chain for $^{271}\text{Ds}$ was established in total. The experimental result is consistent with the values reported in the literature.

1. Introduction
In the past half century, nuclear physicists have made their best endeavors to produce and identify the superheavy nuclei, and have achieved great progress. However, the existing experimental data show that the production cross sections of the superheavy nuclei decrease exponentially with increasing the proton number. For the heaviest region ($Z \geq 110$), the extremely small production rate of the nuclides makes their convincing identification become very difficult. It is important to reproduce the experimental results by different groups or devices.

In IMP, the 1.7 m Sector Focusing Cyclotron (SFC) has been upgraded, and heavy-ion beams are qualified to synthesize the element range to $Z=110$ combining with the super-conducting ECR source. A new gas-filled recoil separator was designed and installed for the study of heavy elements in the experimental hall recently. After a series of experiments were performed to study the performance of the gas-filled recoil separator, the decay properties of $^{271}\text{Ds}$ were investigated. In this letter, the current status of the separator and the observation of the superheavy nucleus $^{271}\text{Ds}$ based on the separator are reported.

2. Spectrometer
If a heavy ion moves in dilute gas, its electronic charge state fluctuates around a equilibrium charge state $q_{eq}$ which is related to its $Z$ number, and the ion can be filtered according to their $A/Z^{1/3}$ values by the magnetic rigidity ($B\rho$) of the dipole magnet. If an ion with a mass number $A$ and charge state $q$ was injected into a dipole magnet, the $B\rho$ value would be as following:

$$B\rho = 0.0227A(v/v_o)/q \ (\text{Tm})$$  (1)
The Bohr velocity $v_0$ is $1/137$ of the velocity of light. If the effective magnetic field is filled with gas, the charge state of the ion would fluctuate around the equilibrium charge state $q_{eq}$. Bohr has assumed that the $q_{eq}$ value is related to the velocity, and not correlated with the initial charge state of the ion while the velocity of the ion is in the region $1<v/v_0<Z^{2/3}$. The $q_{eq}$ value can thus be obtained as:

$$q_{eq} = (v/v_0)Z^{1/3}$$

(2)

Then, the $B\rho$ value is determined by

$$B\rho = 0.0227 A/Z^{1/3} \text{ (Tm)}$$

(3)

![Schematic view of the gas-filled recoil separator in Lanzhou. Typical trajectories of primary beam and evaporation residues are also indicated.](image)

Fig. 1. Schematic view of the gas-filled recoil separator in Lanzhou. Typical trajectories of primary beam and evaporation residues are also indicated.

In the ideal conditions, the Gas-filled separator could select the reaction products according to their $A/Z^{1/3}$ values, regardless of their initial charge and velocity distributions. Based on the successful experiences of the present gas-filled separators in the world, the new Gas-filled recoil separators in IMP has been designed to a $Q,D,Q_h,Q_v$ configuration, where $D$ refers to a dipole magnet and $Q$ to a quadrupole magnet, as well as the subscripts $h$ and $v$ stand for horizontally and vertically focusing, respectively. The schematic representation is shown in Fig. 1. The quadrupole magnet added in front of the dipole allows for a large solid angle of 25 msr. The large bending angle ($52^\circ$) of the dipole is designed for the better background suppression. The technical parameters of the Gas-filled separator are given in Table 1.
A differential pumping system is installed in front of the target chamber. It separates the gas-filled part from the high vacuum beam-line. The pressure at accelerator side could be reduced to 7 orders lower than the target chamber with this pumping system. A rotating target system is used for preparing the reactions with low melting point targets in the intense heavy ion beam. The maximum rotating speed of the wheel is up to 1000 rpm. The beam intensity will be monitored by detecting the elastically scattered projectiles with four Si avalanche photodiodes, which mounted at ±30° and ±45° with respect to the incident beam direction. The primary beam, having passed the target, is dumped at a copper box inside the dipole chamber.

A 300-μm thick Position Sensitive silicon Detector (PSD) is installed at the focal plane of the separator. The implantation depth was estimated to be 10 μm. The PSD with 58 × 58 mm² active area is divided into sixteen independent vertical strips. Two electronics systems were used in the experiments, one for measuring (1-20) MeV α particles and the other for measuring implantation and fission fragments with energies of 5-200 MeV. The detector was calibrated with four α sources, $^{212}$Po, $^{212}$Bi, $^{241}$Am and $^{239}$Pu. The average energy resolution of PSD was 50 keV for the 8.785 MeV α particles. Resistive charge division provided 1.5 mm vertical position resolution in each strip of the detector. The probability for observing at least two full-energy events in a five-member α-decay chain was estimated to be 81% if assuming 50% detection efficiency for α particle. A silicon surface-barrier detector with a 50 mm diameter was mounted behind the PSD to provide veto signals for light particles passing through the strip detector. When the PSD was fired, the energy, time, strip number, vertical position, and veto information were recorded.
3. $^{208}\text{Pb} (^{64}\text{Ni}, n)^{271}\text{Ds}$

The $^{271}\text{Ds}$ nuclide was produced in the $^{208}\text{Pb} (^{64}\text{Ni}, n)$ reaction. Based on the measured excitation function [1], a $^{64}\text{Ni}^{19+}$ ion beam of 317.1 MeV was chosen and extracted from SFC. The typical beam intensity on the target was $6.6 \times 10^{11}$ ions/s, and the total dose of the projectile accumulated in the experiment was about $6.4 \times 10^{17}$ ions. The targets were about 400 $\mu\text{g/cm}^2$ $^{208}\text{Pb}$ layer with a carbon backing foil of 40 $\mu\text{g/cm}^2$ thickness. A 10 $\mu\text{g/cm}^2$ thick carbon was covered on the downstream side of the target to protect the target from sputtering. The energy loss of the beam in the target was estimated to be 6.5 MeV [2]. The beam energy at the center of targets was 313.3 MeV, which corresponds to 14.4 MeV excitation energy of the compound nucleus $^{272}\text{Ds}$ [3]. Ten arc-shaped targets were mounted on a rotating wheel with a 22.4 cm diameter. The wheel was rotated during irradiation at 600 rpm. A beam chopper was used in the experiment to avoid irradiating the target frame. The chopper signal was recorded by a CAMAC system in order to distinguish between on-beam events and off-beam ones. Based on the experimental results in the commissioning of the separator, the system was filled with helium at a pressure of 0.8 mbar and the magnetic rigidity of the separator was set at 2.01 Tm during the experiment.

![Observed decay chain in the reaction $^{208}\text{Pb} (^{64}\text{Ni}, n)^{271}\text{Ds}$](image.png)

**Fig. 2.** Observed decay chain in the reaction $^{208}\text{Pb} (^{64}\text{Ni}, n)^{271}\text{Ds}$. The measured energies, positions, and decay times are indicated in the figure. Two escaped $\alpha$ particles from the decays of $^{267}\text{Hs}$ and $^{263}\text{Sg}$ were not recorded.

One correlated $\alpha$-decay chain was observed during the irradiation. This decay chain is shown in Fig. 2. Decay energies, decay position (distance below the vertical center of the strip) and decay times are indicated in the figure. The implantation energy after corrected for the
pulse-height-defect [4] corresponds approximately to the calculated kinematic energy of $^{271}\text{Ds}$. Decay energies of $\alpha_1$ and $\alpha_4$ are very close to those reported in Ref. [5]. Decay time of $\alpha_1$, 96.8 ms is consistent with the half-life (69$^{+50}_{-25}$ ms) of the isomer of $^{271}\text{Ds}$ [1]. The position deviation between the implantation and $\alpha_1$ is a little bit large, and this may be caused by the poor position resolution of the detector. The 6.63 s time interval in the chain is the sum of the lifetimes of the $^{267}\text{Hs}$, $^{263}\text{Sg}$ and $^{259}\text{Rf}$ nuclei. The escaped $\alpha$ particles from $^{267}\text{Hs}$ and $^{263}\text{Sg}$ were not recorded by the detector since the deposited energies were lower than the 1.0 MeV energy threshold. This is reasonable because the probability for escaping two succeeding $\alpha$ particles is 25%. The observed decay energy of $\alpha_5$ is at least 300 keV lower than that reported previously [1]. We might assume that the $\alpha$ particle escaped from the front of the detector, and only partial energy was deposited in the detector.

The cross section of $^{208}\text{Pb}$ ($^{64}\text{Ni, n}$) $^{271}\text{Ds}$ was calculated. The detecting efficiency at the focal plane was 81% on the condition that 2 $\alpha$ decays in the chain were detected at least. The transport efficiency of the separator was estimated to be 14%. Therefore, the cross section in the experiment was 11.8 pb, which is consistent with the previous work [5, 6].

The number of expected random decays for the experiment was estimated. The sum of the particles implanted into the focal plane detector was about $7.6\times10^6$ with the energy range from 25 to 40 MeV. In anti-coincidence with the veto signal, the rates of the $\alpha$ decay events were as follows; 10.6- 10.8 MeV: 0.11 s$^{-1}$, 8.65- 8.95 MeV: 0.27 s$^{-1}$ and 7.4- 7.7 MeV: 0.38 s$^{-1}$. With the position window of 3.0 mm, the random probabilities were determined to be $7.4\times10^{-5}$ for observing EVR-$\alpha_1$ within 207 ms and $8.7\times10^{-3}$ for observing EVR-$\alpha_4$ within 10 s. Based on the data above, the number of expected random decays for observing EVR-$\alpha_1$-$\alpha_4$ correlation chain was 0.05. For another $\alpha$ within 7.4-7.7 MeV and 9.3 min, the number of expected random decays was 0.7. Namely, the random correlation probability of observing EVR-$\alpha_1$-$\alpha_4$ followed by $\alpha_5$ within 9.3 min was 35% and the number of expected random decays for observing EVR-$\alpha_1$-$\alpha_4$-$\alpha_5$ correlation chain was 0.0175. Judging from this analysis, the decay chain shown in Fig.2 is likely assigned to the nucleus $^{271}\text{Ds}$.

4. Summary
A new Gas-filled recoil separator has been installed at IMP. In the newly commissioning of the separator, one correlated $\alpha$-decay chain was observed for the nucleus $^{271}\text{Ds}$. The measured decay properties of $^{271}\text{Ds}$ are consistent with the values reported by other groups.

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