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Study on the reaction channels in the ^{6}Li+ ^{89}Y system with multi-angular proton and deutron-γ coincidence analysis

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ABSTRACT

The ^{6}Li+ ^{89}Y experiment was conducted at the Legnaro National Laboratory in Italy to explore the influence of breakup and transfer reactions on the fusion process induced by the weakly bound projectiles. Due to the competition between neutron and proton evaporation, complete and incomplete fusion might produce identical residues, leading to the difficulties in identification of different reaction process. In this work, the High-Purity-Germanium (HPGe) detector array (GALILEO) was employed to measure γ rays, and the silicon detector array (EUCLIDES) was utilized to capture light charged particles. Exclusive measurements of prompt γ rays from residuals with various light charged particles at an energy near the Coulomb barrier are reported. In the $p-\gamma$ coincident measurements, observed ^{91}Nb, ^{92}Nb, and ^{93}Nb is considered from neutron evaporation channel in complete fusion reaction, and ^{90}Y is generated through 1n stripping reaction. A two-step, breakup followed by fusion, in case of the capture of α is inferred to be the dominant mechanism to yield the ^{92}Nb and ^{91}Nb in the deutron coincident exclusive measurement.

1. Introduction

Nuclear reactions induced by weakly bound nuclei have garnered significant attention in the past decades, especially on the coupling between different mechanisms such as fusion, elastic/inelastic scattering, breakup and transfer, etc. [1–3]. The weakly bound projectiles may break up before colliding with the target nuclei, due to the low binding energies. Compared with unstable

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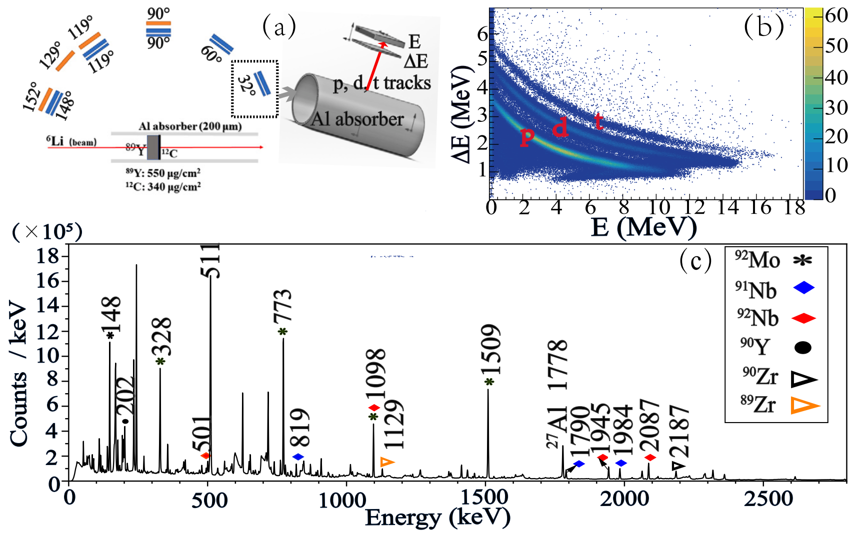

Fig. 1. (a) The schematic of the experimental setup (sectional view); (b) The two dimensional correlation plot of ΔE and E detectors for light charged particles identified in 34 MeV ^{6}Li+ ^{89}Y; (c) The single γ spectrum detected by the GALILEO array.

weakly bound nuclei, the stable weakly bound nuclei, such as ^{6}Li, ^{7}Li and ^{9}Be, were constantly chosen as projectiles due to their higher beam intensity [4–6], giving rise to much better precision in the experimental measurement. The process in which the entire projectile fuses with the target nucleus is referred as direct complete fusion (DCF). If the projectile breaks up into several fragments before fusion, different reaction processes may occur. If all the fragments fuse with the target nucleus, the process is named as sequential complete fusion (SCF). When only part of the fragments fuse with the target nucleus, the process is called incomplete fusion (ICF). Complete fusion (CF) includes the SCF and DCF, since the SCF and DCF processes cannot be separated experimentally. The sum of the CF and ICF cross sections is considered as the total fusion (TF) cross section. However, other processes such as the transfer may also compete with fusion reaction, leading to the fact that the experimental measurement or identification of fusion cross reaction becomes complicated [1,2,7–14]. In the fusion reactions induced by weakly bound nuclei, different light charged particles can be produced.

In ^{6}Li $+ ^{209}$Bi reaction, inclusive α cross sections have been measured at energies around the Coulomb barrier. The combined cross sections of non-capture α + d breakup, d-capture, and transfer reactions could successfully explain the origin of most of the experimental inclusive breakup α cross sections over the measured energy range [15]. It is shown that the dominant contribution is from d-capture reaction. On the other hand, the sum of the measured cross section for ICF, CF, breakup (α + d and α + p) and 1n pickup reactions exhausts about 80% of the total reaction cross section. The rest part could be temporarily considered to be the undetected breakup channels and other transfer channels [16]. In order to clarify all the possible origins of inclusive α cross sections, exclusive measurements have to be employed with particle-particle and pariticle-γ coincidence methods. Singles and coincidence measurements of light fragments and heavy residues in ^{7}Li $+ ^{209}$Bi reactions have been carried out [4]. Only a small fraction of ICF cross section can be explained by projectile breakup followed by fusion. Direct triton cluster transfer is dominant. The α+t breakup triggered by a 1n-pickup, was also found less important in the reactions of ^{6}Li at energies around and above the Coulomb barrier [17,18]. Due to the limited coverage of the solid angle in Refs. [17,18] for the coincidence measurement, the detailed reaction mechanism is still not clear, and a further investigation has to be taken into account. These studies with weakly bound nuclei have focused on whether the capture of one of the cluster fragments occur in projectile bound/unbound states to the colliding partner nucleus.

In the ^{6}Li+ ^{89}Y system, the published literature [19] has shown the residual cross sections measured by off-beam γ rays method. Only by measuring γ ray, the residuals from different reaction channels are shown in Table IV of Refs. [19]. However, the separation of different reaction channels cannot be done perfectly. Meanwhile, there is about a 90% difference in the cross sections of ^{90}Y from one-neutron stripping reaction between Refs. [14,19]. So more accurate information about the reaction channels is highly demanded.

In the current work, the particle-γ coincidence measurement is used in order to distinguish different reaction mechanism. This paper is organized as followed. Sec. 2 shows the experimental details. The results and experimental discussions are shown in Sec. 3. Finally, the conclusions are summarized in Sec. 4.

2. Experimental details

The ^{6}Li+ ^{89}Y experiment was performed at the Laboratori Nazionali di Legnaro, INFN, Italy. A ^{6}Li^{3+} beam with 1.0 enA intensity, was provided at 34 MeV using the XTU Tandem accelerator. The ^{89}Y target, with a thickness of 550 μg/cm^{2}, was backed by a 340 μg/cm^{2}-thick ^{12}C foil to halt all reaction products. The GALILEO array, comprised of 25 Compton-Suppressed HPGe detectors, facilitated the collection of γ-rays, with an energy resolution of approximately 2 keV at 1332 keV. For the measurement of light

Table 1
The minimum energies of particles passing through the ΔE detectors (the second column) or ^{27}Al absorber and ΔE detectors (the third column).

Particles	ΔE (MeV)	^{27}Al and ΔE (MeV)
p	3.730	6.728
d	4.910	8.970
t	5.710	10.56

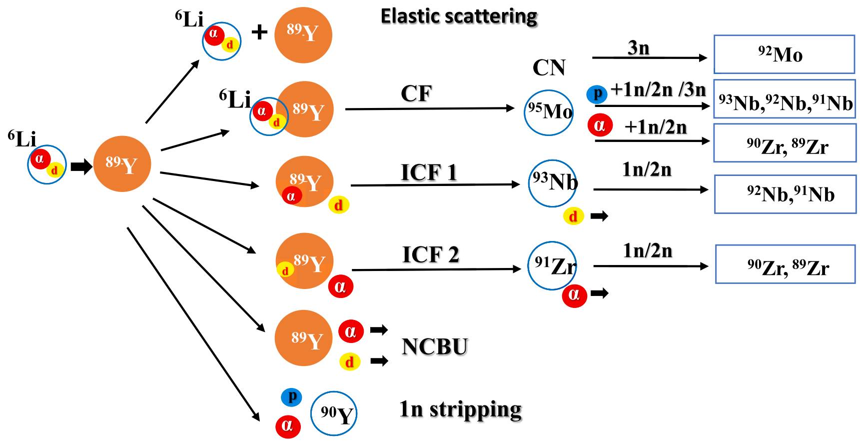

Fig. 2. The different reaction channels to produce protons and deutrons in ^{6}Li+^{89}Y system.

charged particles, a 4π Si-ball detector array known as EUCLIDES was employed, composing of 40 ΔE-E telescopes. The thickness of ΔE detector and E detector is 130 and 1000 μm, respectively. More details on the GALILEO and EUCLIDES arrays can be found in Ref. [20]. The schematic overview of the experimental setup is depicted in Fig. 1(a). Due to the sensitivity of Si detectors to radiation damage, a 200-μm-thick ^{27}Al absorber was inserted between the target and EUCLIDES array to arrest the elastically scattered ^{6}Li. The ^{27}Al-absorber shielded all Si detectors except those situated at angles greater than 148°. In this context, angles less than 148° are referred to as "covered angles," while angles more than 148° are termed as the "uncovered angle."

3. Results and discussions

The plot equivalent to the detectable in the ΔE and E detectors is shown in Fig. 1(b), the bands of the lines correspond to the particles detected for ^{6}Li+^{89}Y reaction separated by the atomic number of each particle. Notably, proton (p), deutron (d) and triton were quite remarkable. At the covered angles, all light charged particles traversed the ^{27}Al absorber and the ΔE detectors. While at the uncovered angles, particles only need to pass through the ΔE detectors. For the measured particles in ΔE-E plot, their energy losses in ^{27}Al absorber and the ΔE detectors can be calculated by physical calculator in LISE++ [21,22]. The minimum energies for proton and deutron particles to pass through the ΔE detectors and ^{27}Al absorber or only the ΔE layers are also summarized in Table 1.

The Fig. 1(c) displays the γ rays from principal residual nuclei in the individual γ spectrum detected by the GALILEO array. ^{95}Mo can be formed as compound nuclide through DCF or SCF in the ^{6}Li+^{89}Y reaction. Through neutron evaporation, the typical residuals ^{92}Mo can be produced. Additionally, the products ^{93,92,91}Nb and ^{90,89}Zr can be formed through the subsequent evaporation of protons or α particles. Since ^{6}Li can break up into α and d fragments, through ICF, ^{91,92}Nb and ^{89,90}Zr can also be produced. For ICF channel, due to the fact that the compound nuclei should have lower excitation energy since only part of projectile is captured, the evaporation of neutron would be the dominant channel. The main reaction processes are summarized in Fig. 2 for the ^{6}Li+^{89}Y system, and the detailed discussion would be shown later based on the experimental results. It should be noted here that the analysis of α-γ coincidence has been performed in Ref. [23]. In this paper, we focus on the correlation between protons/deutrons and γ rays to explore the reaction mechanisms of ^{6}Li+^{89}Y.

3.1. p-γ coincidence

In ^{6}Li+^{89}Y reaction, protons can be generated from several processes, including complete fusion, incomplete fusion and 1n transfer processes. In order to pass through the ^{27}Al foil and ΔE layer, the kinetic energy of proton has to be larger than 3.7 MeV as shown in Table 1. Assuming a two-step breakup process, the ^{6}Li itself should firstly overcome the breakup threshold and then separate into α and deuteron. With another assumption that the breakup fragments share similar velocity, the energy of E_d is about one third of ($E_{^6Li}$ - 1.47) MeV as mentioned in Ref. [16]. Accordingly, the energy of breakup proton would be half of (E_d - 2.224)

Table 2
The main energies of protons from different reaction channels.

CF (MeV)	ICF (MeV)	Transfer (MeV)
5.0 - 7.0	3.8 - 4.8	5.5 - 7

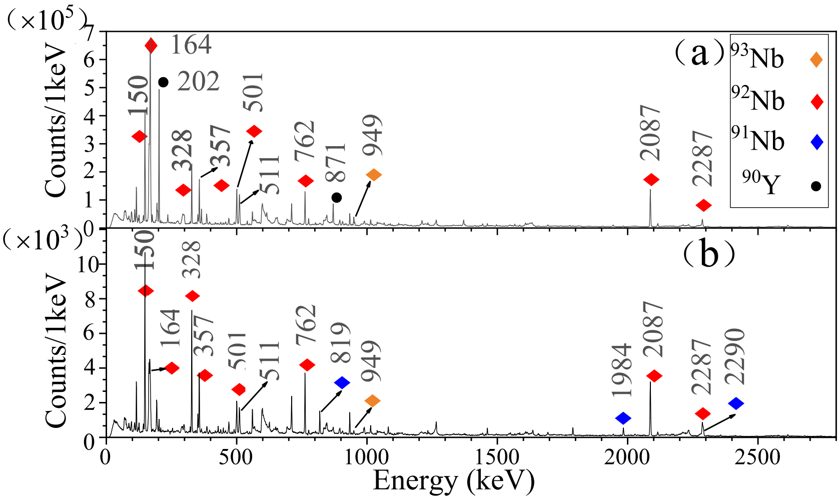

Fig. 3. In p $-\gamma$ coincidence, (a) and (b) are the γ spectra in coincidence with protons at covered angles and uncovered angles.

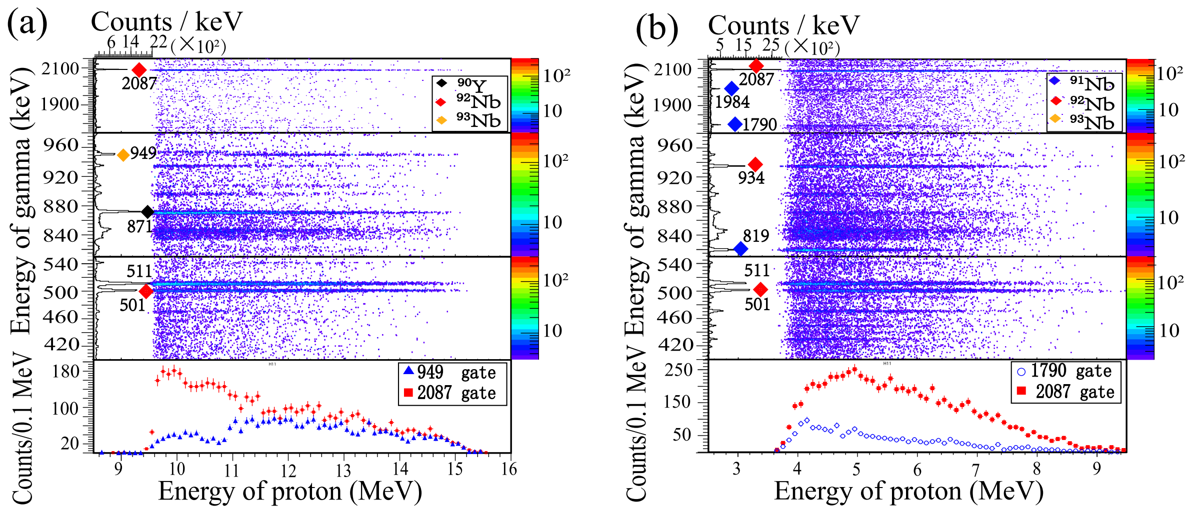

Fig. 4. The residuals at covered angle (a) and uncovered angle (b) gating on protons.

MeV, so the breakup of ^{6}Li would give proton with the kinetic energy around 4.2 MeV. On the other hand, the protons emitted from complete fusion and transfer processes are also estimated by the evaporation model and kinematics calculation, respectively. The results are shown in Table 2. Thus the protons from all the processes could pass through the ^{27}Al foil and ΔE detectors of covered angles.

By gating on the protons in the covered and uncovered (by ^{27}Al absorber) angles, γ rays emitting from various residues can be found as shown in Figs. 3 (a) and (b), respectively. The statistics of γ rays in Figs. 3 (a) and (b) represent the yield of each residual. Here ^{91,92,93}Nb can be produced by proton+neutrons evaporation from the compound nucleus ^{95}Mo as shown in Fig. 2. In both covered and uncovered angles, the γ rays peak height of ^{92}Nb is always higher than that in ^{91,93}Nb. The presence of ^{90}Y is also observed in Fig. 3. The probability of ^{90}Y originating from either the complete fusion (CF) or incomplete fusion (ICF) processes is notably low as estimated by statistical evaporation model PACE4 [24,25] as shown in Table 3. Thus, it is inferred that ^{90}Y originates from the 1n stripping reaction. Further discussion on the stripping process can be found in Ref. [14].

The main products ^{93}Nb, ^{92}Nb and ^{91}Nb are further analyzed, and the correlations between proton energies vs different γ rays are shown in Fig. 4. In Fig. 4(a), at covered angles, gating on 949-keV (^{93}Nb) γ rays, the coincident protons (the blue dots) show higher

Table 3
The PACE4 calculation results of CF (the second column) and α ICF (the third column), the transverse line means the yield is negligible.

Nuclei	Percent in CF (%)	Percent in α ICF (%)
^{92}Mo	60.6	—
^{92}Nb	15.8	44.9
^{91}Nb	1.88	47.4
^{92}Zr	—	2.49
^{90}Zr	2.36	—
^{89}Zr	11.4	—
^{89}Y	11.4	4.47

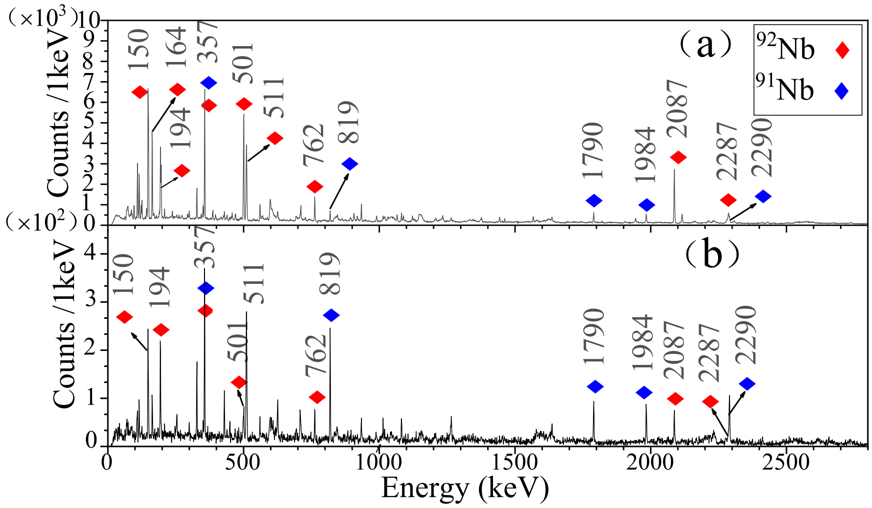

Fig. 5. In d – γ coincidence, (a) The γ spectrum at covered angles; (b) The γ spectrum at uncovered angles.

energy distribution than that in coincidence with 2087-keV (^{92}Nb) γ rays (the red dots). In the similar way, as shown in Fig. 4(b) for the uncovered angle region, the 2087-keV (^{92}Nb)γ-ray gated proton spectrum (the red dots) shows higher energy distribution than that from 1790-keV γ ray in ^{91}Nb (the blue dots). This phenomenon is well consistent with the fact that in the cases of proton/neutron competition during the evaporation, compound nuclei tend to evaporate less neutrons when the emitting proton energy increases.

3.2. d-γ coincidence

In heavy ion fusion reactions, the deutron evaporation was always not considered in the complete fusion reaction channel [25–27], thus deutron is thought to be primarily from incomplete fusion reactions. As proposed a two-step scenario, there are α and deutron clusters in ^{6}Li, the projectile ^{6}Li breaks up to α and deutron, then one of these fragments is captured by the target. Since the beam incident energy of ^{6}Li is 34 MeV, the energy of fragment deutron is about one third of (E_{6Li} - 1.47) MeV. The deuterons could pass through the ^{27}Al foil and be detected while the α fuses with ^{89}Y, which results in following reactions as shown in Fig. 2.

By gating on the deutrons at the covered and uncovered (by ^{27}Al absorber) angles, the γ rays emitting from ^{92}Nb and ^{91}Nb can be shown in Fig. 5, respectively. ^{92}Nb and ^{91}Nb can be produced by neutrons evaporation from the compound nucleus ^{93}Nb shown in Fig. 2 of the incomplete fusion reaction. Both the ^{92}Nb and ^{91}Nb are obvious at covered and uncovered angles. The ICF theoretical results are shown in Table 3, when the energy of the projectile α is about 21.86 MeV.

To further analyse the main products ^{92}Nb and ^{91}Nb, the correlations between deutron energies vs different γ rays are shown in Fig. 6. The projections of the energy of the γ rays are shown on the left side, the counts of the γ rays of ^{91}Nb are quite higher at uncovered angles. At both covered and uncovered angles shown in Fig. 6(a) and Fig. 6(b), respectively, gating on γ rays 2087-keV (^{92}Nb) and 1790-keV (^{91}Nb). The 2087-keV (^{92}Nb) γ-ray gated deutron spectrum (the red dots) shows higher energy distribution than that from 1790-keV γ ray in ^{91}Nb (the blue dots), especially at uncovered angles. It is indicated that the energies of deutron are different at the different angles, and they are much higher at the forward angles which are covered with ^{27}Al foil in Figs. 6(a). The reasons for the above phenomenon lie in the fact that the excited energy of the compound nucleus formed by α + ^{89}Y system decreases as the energy of the fragment deutron increases, resulting in a reduced capability for neutron evaporation from the compound nucleus. The ^{27}Al foil can screen deutrons with higher energies, so ^{92}Nb is obvious at covered angles. At uncovered angle 148° shown in Figs. 6(b), the energies of deutrons are lower, ^{91}Nb is dominant nuclei, which confirmed that the main residual of α + ^{89}Y in the theoretical calculation of the statistical evaporation model PACE4 [24,25] is ^{91}Nb.

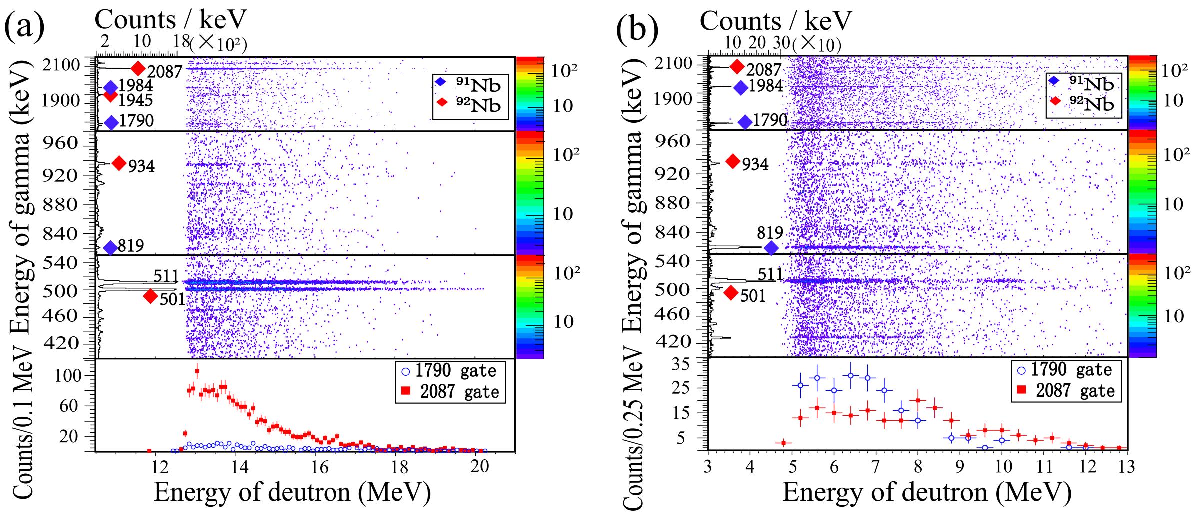

Fig. 6. The residuals at covered angle (a) and uncovered angle (b) gating on deutrons.

4. Conclusion

The ^{6}Li+^{89}Y experiment was carried out at the Laboratori Nazionali di Legnaro, INFN of Italy. Utilizing $p-\gamma$ rays and $d-\gamma$ rays coincidence measurements, various reaction channels in the ^{6}Li+^{89}Y experiment can be clearly distinguished. It provides a comprehensive understanding of the complete fusion reaction and incomplete fusion reaction. In the $p-\gamma$ coincident spectrum, the residual nuclei ^{91}Nb, ^{92}Nb, and ^{93}Nb were obvious, it is shown that the yield of ^{92}Nb is much more than that of ^{91}Nb and ^{93}Nb, and ^{90}Y is generated from 1n stripping reaction. Through $d-\gamma$ coincident measurements, by analyzing the main products ^{91}Nb and ^{92}Nb and combining with theoretical calculation, the parts of ^{91,92}Nb are considered from incomplete fusion reaction. With the development of particle detection equipments and combining particles-γ rays coincidence measurements, more reaction channels and the origins of the main products can be studied in the reactions induced by weakly bound nuclei.

CRediT authorship contribution statement

M.L. Wang: Writing – original draft. **G.X. Zhang:** Writing – review & editing, Supervision. **S.P. Hu:** Writing – review & editing. **G.L. Zhang:** Writing – review & editing, Supervision. **H.Q. Zhang:** Writing – review & editing. **H.B. Sun:** Writing – review & editing. **D. Testov:** Writing – review & editing. **P.R. John:** Writing – review & editing. **J.J. Valiente-Dobón:** Writing – review & editing. **A. Goasduff:** Writing – review & editing. **M. Siciliano:** Writing – review & editing. **F. Galtarossa:** Writing – review & editing. **F. Recchia:** Writing – review & editing. **D. Mengoni:** Writing – review & editing. **D. Bazzacco:** Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: G. L. Zhang reports financial support was provided by National Natural Science Foundation of China. S. P. Hu reports financial support was provided by Department of Science and Technology of Guangdong Province and China National Nuclear Corporation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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