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Study of the Exotic Decay Mode of ^{20}Na with an Intense ISOL Beam

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Abstract: Beijing Radioactive Ion-beam Facility(BRIF) has been commissioned as the national Radioactive Ion Beam(RIB) facility based on the Isotope Separator On Line(ISOL) technique since 2016. At BRIF, the radioactive nuclides are produced by the proton beam of 100 MeV bombarding a thick-target, the reaction products diffusing out of the target are ionized by an ion source and delivered to the online mass separator. In addition to the post-accelerated radioactive ion beams, BRIF can provide low-energy ISOL beams of 100 to 300 keV with a mass resolution of 20 000. A general-purpose decay station has been built including the ISOL beam transport line, a conventional reaction chamber, charge-particle and γ detectors with integrated electronics and data acquisition system. An intense ^{20}Na ISOL beam up to 1×10^5 pps was produced by using the 100 MeV proton beam bombarding a MgO thick target. With high-efficiency measurements of β, γ and α simultaneously, very rare β-γ-α decay mode in ^{20}Na has been directly observed for the first time in the present work.

Key words: Beijing radioactive ion beam facility; isotope separator on line; ^{20}Na radioactivity; exotic decay mode

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1 Introduction of BRIF

Beijing Radioactive Ion-beam Facility (BRIF) is an upgrade project aiming to provide post-accelerated radioactive ion beams at the HI-13 heavy-ion Tandem accelerator laboratory. The project includes a newly-built 100 MeV, 200 μA proton cyclotron as the driving accelerator[1], an isotope separator on line with the target-ion source assembly[2], a superconducting linac booster[3] and the HI-13 tandem as the post accelerator. The layout of the facility is shown in Fig. 1. The proton cyclotron (CYCIAE-100) adopts a compact magnet and H^- acceleration with stripping extraction. The magnet is 2.31 m high and 6.16 m in diameter with a pole radius of 2.0 m. Two cavities are installed in the valleys of the magnet to accelerate the H^- beam 4 times per turn. The on-line mass separator consists of pre-separation and main separation stages situated at different potentials. The pre-separation stage with $M/\Delta M$=2 000 includes two 90° bending magnets and electrostatic quadrupoles placed on a 300 kV platform, which keeps the unwanted radioactivities at the heavily-shielded front end; the main separation stage with $M/\Delta M$=20 000 is therefore accessible for low-energy experiments. The need of negative ion injection to the HI-13 tandem accelerator for post acceleration is fulfilled by a charge exchange cell, which is also situated at the pre-separation stage.

At BRIF, proton-rich isotopes can be produced

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mainly by the proton induced fusion-evaporation reaction with various targets; for neutron-rich isotopes the proton induced fission with uranium carbide will be routinely applied. Since there is a strong neutron flux when the 100 MeV proton beam bombarding a metal target, neutron-induced reactions can also be employed for the production of light neutron-rich isotopes. In addition to the post-accelerated radioactive ion beams, the ISOL part of BRIF can deliver intense low-energy beams of 100~300 keV for β-decay study, radioactive ion implantation *etc*. For this purpose, a general-purpose decay station has been built including the ISOL beam transport line, a conventional reaction chamber, charge-particle and γ detectors with integrated electronics and data acquisition system. Before the present work, no radioactive ion beam was produced in online mode at BRIF, only a test case of ^{38}K($t_{1/2}$ =7.636 m) was run in 2015, in which a CaO thick target was bombarded by 100 MeV proton beam for a few minutes, the ^{38}K ISOL beam was delivered in batch mode in the absence of the proton beam.

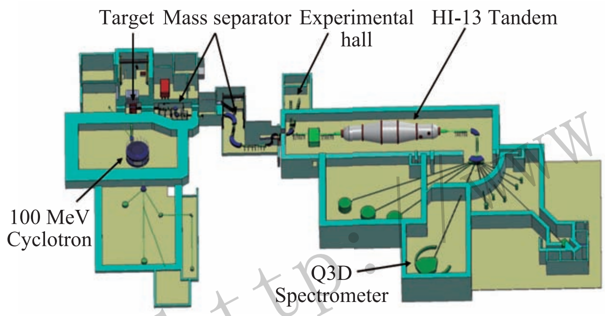

Fig. 1 (color online) The layout of the BRIF project.

2 Decay of ^{20}Na

2.1 Motivation of the present work

^{20}Na decays with a half life of 447.9(23) ms and a decay energy of 13892.5(11) keV[4], to the daughter nucleus ^{20}Ne. The spin and parity of the ground state of ^{20}Na is 2^+ and the isospin T=1, its decay mainly proceeds through the transitions to the 1^+, 2^+ and 3^+ states in ^{20}Ne with T=0 or 1. Many experimental investigations have been carried out for the decay of ^{20}Na since 1960's. Macfarlane and Siivola first observed four groups of β-delayed α's from the ^{20}Na source produced by the charge-exchange reaction[5]. Pearson pointed out in the same year the probable existence of α groups lower than 1 MeV[6], which attracted several further investigations[7−10] but the low-energy α groups were not directly discovered. Recently, Laursen *et al.*[11] made a high-statistics measurement of the β-delayed α spectrum of ^{20}Na at the IGISOL facility. By applying the α and ^{16}O coincidence, two groups of α's below 1 MeV were successfully observed. These investigations have resulted in very detailed decay scheme of ^{20}Na, however, it is interesting to notice that these are mostly β-delayed single α or single γ measurements and important information may be therefore missing as is discussed below.

The α resonance states in ^{20}Ne close to the threshold have been the focus in recent works for the astrophysical Helium-burning reaction ^{16}O(α, γ)^{20}Ne[13−14]. For this purpose, the resonance width and the detailed γ transition strengths of ^{20}Ne α-cluster states are needed. Since the decay energy of ^{20}Na is well above the α threshold of ^{20}Ne($S_\alpha = 4.730$ MeV), many α cluster states in ^{20}Ne can be populated in the decay of ^{20}Na with a total α-emission probability of about 20%[12]. According to the selection rule of allowed β transitions, the 1^+, 2^+ and 3^+ states in ^{20}Ne are directly populated in the ^{20}Na decay. However, only the ^{20}Ne resonance states with natural parity can decay directly to the ground state of ^{16}O, therefore the high-lying 1^+ and 3^+ states in ^{20}Ne cannot decay to the ground state of ^{16}O via α emission because of the violation of isospin conservation. Instead, these 1^+ and 3^+ states in ^{20}Ne must de-excite via γ rays. Important information may be missing for the high-lying 1^+ and 3^+ states in ^{20}Ne if only β-delayed α's are measured in the ^{20}Na decay experiment. Moreover, exotic β-γ-α decay mode may exist in ^{20}Na, *i.e.* the high-lying 1^+ and 3^+ states in ^{20}Ne de-excite by γ rays to resonance states with natural parity, and then emit α's to the ground state of ^{16}O. If so, neither single α nor single γ measurements can correctly extract the decay sequence, and only high-efficiency measurement of β, γ and α simultaneously can restore the right branching ratios. Similar exotic β-γ-p decay mode was observed in ^{56}Zn[15] and ^{32}Ar[16], which have resulted in significant corrections to the β decay branching ratios and therefore $B(F)$ and $B(\mathrm{GT})$ values. As highlighted in a recent comprehensive review of the radioactive decay[17], exotic decay modes from highly excited states of daughter nuclei or from isotopes close to the limits of stability are the main topics pursued by the world-leading RIB facilities.

2.2 Production of the ^{20}Na ISOL beam

The exotic β-γ-α decay mode of ^{20}Na is very scarce to a branching ratio of less than 0.01%, according to the rough estimation of Laursen *et al.*[11]. To study this rare decay mode, it is obvious that one needs an intense ^{20}Na beam to fulfil the requirement of high statistics. ^{24}Mg(p, nα)^{20}Na is a frequently used reaction to produce the ^{20}Na source, the calculated cross section of different residue nuclei from 100 MeV p+^{24}Mg using the ALICE code[18] is shown in Fig. 2. With a MgO target, radioactive isotopes of Magnesium are depressed intentionally to prevent the extraction of enormous stable Mg isotopes, the radioactive isotopes of interest to produce include ^{20,21}Na, ^{23,24}Al and ^{16}N *etc*. The threshold energy of ^{20}Na channel is about $E_{\rm p}$=30 MeV, and the cross section is among 0.8 to 0.3 mb for $E_{\rm p}$=35∼100 MeV. Since the half life of ^{20}Na is very short, the yield of ^{20}Na isotope in the thick target is easily saturated after irradiation. With the cross sections shown in Fig. 2, it is estimated that the saturated ^{20}Na nuclei are about 2×10^8 when using 1 μA proton beam. Sodium is among the easiest elements to ionize, it is therefore very promising to explore the optimum efficiency of the target-ion source assembly to produce an intense ^{20}Na beam for the present work.

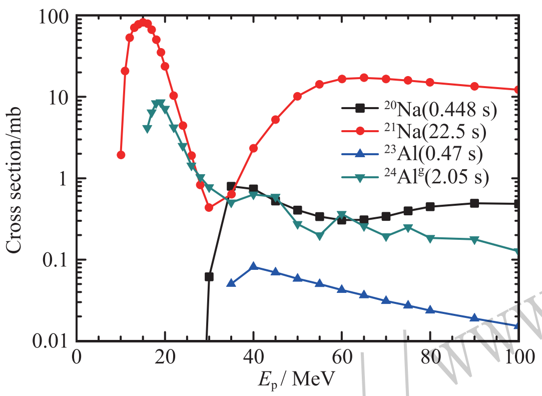

Fig. 2 (color online) The calculated cross section of different residue nuclei from p+^{24}Mg using the ALICE code.

The used MgO target is more than 10 cm thick comprising of a stack of MgO slices, each with a thickness of 2 mm. To facilitate the diffusion of neutral ^{20}Na atoms out of their production lattices, each slice of MgO is of a microporous structure. Four experiments were carried out in a period of one year for the production of intense ^{20}Na ISOL beam. Steady progresses were achieved owing to the growing knowledge of the optimum working temperature of the target-ion source system and the upgrade of the ion source. A ^{20}Na intensity of 1×10^5 pps was reached with a 5 μA proton primary beam, resulting in an overall efficiency of about 0.01%, which is comparable to the result reported from a TRIUMF-ISAC experiment[19]. Moreover, ISOL beams of $^{21,22,24-26}$Na isotopes were also produced with the MgO thick target, the intensity of ^{21}Na($t_{1/2}=22.49$ s) was at least three orders of magnitude higher than that of ^{20}Na. It is promising to make use of the ^{21}Na ISOL beam for post acceleration.

2.3 Experimental setup

When an exotic β-γ-α decay occurs, the daughter nucleus ^{20}Ne emits a 3∼6 MeV weak γ ray and a low-energy α in sequence according to the available information of ^{20}Na decay. High-efficiency measurement of the high-energy weak γ rays and the low-energy α's in coincidence is needed in the present work. The experimental setup for the decay of ^{20}Na is shown in Fig. 3. The ^{20}Na ISOL beam of 100 keV was implanted into a 3 micron thick aluminum collection foil. The Al-foil was situated in the center of a silicon box formed by five pieces of Multiguard Silicon Quadrant(MSQ) of 1 mm thick to measure the β particles. Opposite to the implantation point, two pieces of Double-sided Silicon Strip Detector(DSSD) were installed to measure the β-delayed α particles. Each DSSD was backed by an MSQ detector of the same thickness to reject the β summing events in the α spectra. The DSSD has a thickness of about 70 micron with a very thin dead-layer of only 100 nm to reduce the energy loss of α particles. The thickness of Al collection foil allows the strongest β-delayed α groups of ^{20}Na, at 2.15 and 4.43 MeV respectively, to go through and be measured by an MSQ, which can help to remove the low-energy ^{16}O recoils detected in DSSD. Two HPGe detectors with relative efficiency of 175% each were installed in the cylindric flange to measure the γ rays. As seen from Fig. 3, such a compact setup enables the simultaneous measurement of β, γ and α with high efficiencies.

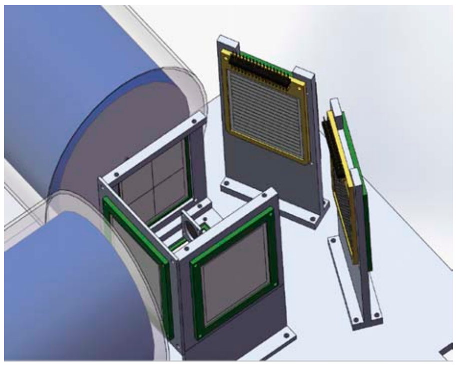

Fig. 3 (color online) Experimental setup for the decay of ^{20}Na. The top MSQ is removed to show the Al collection foil which is tilted into the center of the MSQ box from the front.

Various standard radioactive sources were used to calibrate the detectors: including ^{56}Co, ^{152}Eu for the efficiency calibration of the HPGe detectors; ^{239}Pu and ^{241}Am for the energy calibration of DSSDs; as well as ^{133}Ba for the performance check of the MSQ detectors for measuring β particles. The ^{20}Na decay experiment spread into three periods with different ^{20}Na implantation rates ranging from 1 000 to 20 000 pps, the energy and timing information triggered by either an α or a γ were taken by the data acquisition system.

3 Preliminary results

The ^{20}Na ISOL beam can be regarded as pure ^{20}Na radioactivities, since the isobaric ^{20}Mg isotope cannot be effectively produced at BRIF due to its too short half life($t_{1/2}$=95 ms) and very small cross sections. On the other hand, the stable ^{20}Ne does not contribute to the background radioactivity even it is contained in the ^{20}Na ISOL beam. High-statistics α and γ spectra are obtained in the present work. As an example, the γ spectrum from the decay of ^{20}Na is shown in Fig. 4. Five groups of known high-energy γ-transitions are seen in Fig. 4, owing to the high efficiency of the HPGe detectors used in the present work. The γ-γ coincidence spectrum gated by the 1 633.7 keV $2^+_1 \rightarrow 0^+_{\mathrm{g.s.}}$ transition of ^{20}Ne was also analyzed, which gave out no new γ lines.

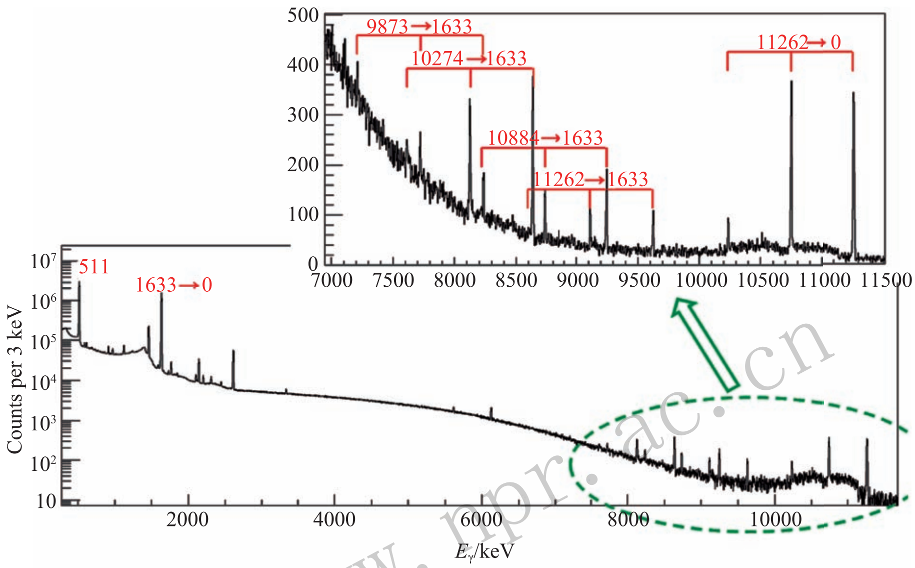

Fig. 4 (color online) The γ spectrum from the decay of ^{20}Na, the inset shows the high-energy part with labels of five groups of known γ transitions in ^{20}Ne.

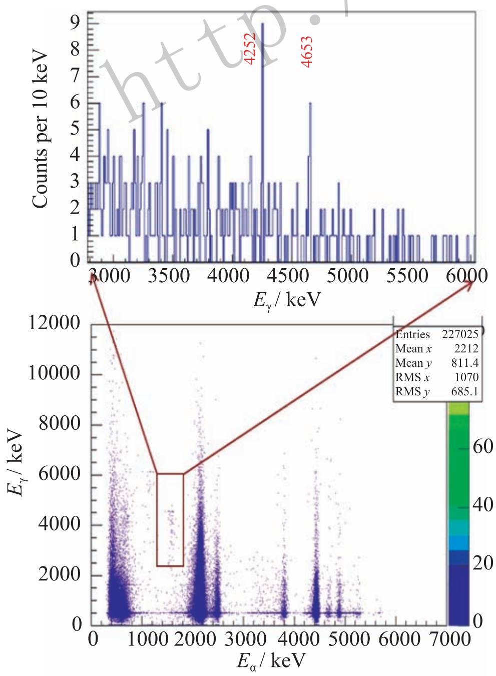

Fig. 5 (color online) The α-γ coincidence spectrum following the β decay of ^{20}Na. The inset shows the α gated γ spectrum of selected α energies.

The high-lying excited states in ^{20}Ne with $T=1$ are forbidden in the emission of α's to the ground state of ^{16}O, which results in the enhancement of high-energy γ transition strength seen in Fig. 4. The α-γ coincidence spectrum has been also analyzed, the exotic β-γ-α decay sequence in ^{20}Na is observed, as indicated by the 4 252 and 4 653 keV γ lines shown in Fig. 5. This rare decay mode was speculated to exist in a branching ratio of less than 0.01% by Laursen *et al.*[11], has been directly observed for the first time in the present work owing to the intense ^{20}Na ISOL beam and high-efficiency measurements. Further analysis of the experimental data is still in progress.

4 Summary

In summary, Beijing Radioactive Ion-beam Facility has successfully delivered its first intense on-line mass separated beam of ^{20}Na. With this ISOL beam, the β decay of ^{20}Na is re-investigated with a compact experimental setup enabling the simultaneous measurement of β,γ and α in high efficiency. The exotic β-γ-α decay mode in ^{20}Na is clearly observed with the α-γ coincidence.

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利用强流 ISOL 束研究 ^{20}Na 的奇异衰变模式

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摘要： 北京放射性离子束装置 (Beijing Radioactive Ion-beam Facility，BRIF) 是基于在线同位素分离器技术的国家大科学平台。在 BRIF 装置上利用 100 MeV 的质子束轰击较厚的反应靶产生放射性核素；反应产物经离子源电离和在线分离，在线同位素分离段可引出 100~300 keV 的放射性核束，质量分辨率达 20 000。在基金委科学仪器基础研究专项的支持下，建成了多用途的衰变实验终端，包括束流传输管道、通用靶室、带电粒子和 γ 探测器、集成电子学和数据获取系统等。利用 100 MeV 的质子束轰击 MgO 厚靶产生了流强高达 1×10^5 pps 的 ^{20}Na 放射性核束。通过高效率地同时测量 β, γ 和 α，第一次直接观测到 ^{20}Na 非常稀有的 β-γ-α 衰变模式。

关键词： 北京放射性离子束装置；在线同位素分离器；^{20}Na 放射性；奇异衰变模式

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