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An Implantation and Detection System for Spectroscopy of ^{22,24}Si

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Abstract: A new decay detection system with high detection efficiency and low detection threshold has been developed for charged-particle decay studies, including β-delayed proton, α decay or direct proton emission from proton-rich nuclei. The detection system was tested by using the β-delayed proton emitter ^{24}Si and was commissioned in the decay study of ^{22}Si produced by projectile fragmentation at the First Radioactive Ion Beam Line in Lanzhou. Under a continuous-beam mode, the isotopes of interest were implanted into two double-sided silicon strip detectors, where the subsequent decays were measured and correlated to the preceding implantations by using position and time information. The system allows to measure protons with energies down to about 200 keV without obvious β background in the proton spectrum. Further application of the detection system can be extended to the measurements of β-delayed proton decay and the direct proton emission of other exotic proton-rich nuclei.

Key words: β-delayed proton decay; direct proton decay; double-sided silicon strip detector; continuous-beam mode; implantation-decay correlation

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1 Introduction

The study of exotic nuclei far from the stability line has been one of the frontiers of nuclear physics during the past few decades. Various exotic decay modes have been observed for proton-rich nuclei far from stability, such as β-delayed particle emission and direct particle emission. The β-delayed proton spectroscopy and proton spectroscopy have proven to be powerful tools to get information on the properties

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and structure of exotic nuclei, which become stringent tests of theoretical description of nuclear structure far from the stability line. The resonant proton capture reaction rates of interest for astrophysics can be evaluated based on information about the properties of states near the proton-separation threshold[1−4]. It is very challenging to measure β-delayed proton emissions from those states and direct proton emissions from ground states since they both require a low detection threshold of energy as well as a high detection efficiency. Various experimental setups for β-delayed proton spectroscopy and proton spectroscopy have been developed and accordingly, significant achievements have been made in the studies of exotic nuclei[5−13].

We have developed a new detection system on the basis of our previous experiments with implantation method[14] and the experiments with complete-kinematics measurements[15−17]. The implantation silicon detector was upgraded to a thin and segmented silicon detector to minimize the β pile-up effect and also to be employed under a continuous-beam mode.

2 Experimental techniques

As presented in Fig. 1, the detection setup consists of two double-sided silicon strip detectors (DSSD) and several quadrant silicon detectors (QSD)[18]. A 149 μm thick DSSD1 and a 66 μm thick DSSD2 (W1-type from Micron Semiconductor Ltd.[19]) are used to stop the isotopes of interest, which also serve as β-delayed proton decay detectors. The thinner DSSD2 is aimed at detecting low-energy protons because the β particles have a longer range in silicon, and accordingly, the β particles emitted from a thin detector make less contributions to the background of the proton spectrum. DSSD1 has a higher detection efficiency for high-energy protons, being an important supplement to the thinner DSSD2. Besides, the two DSSDs could also be used to detect the escaping protons emitted from the other one. A series of aluminum foils driven by three stepping motors are installed upstream to serve as a degrader. The thickness of the aluminum degrader can be adjusted with a small step, so the stopping range of the ^{24}Si ions in the DSSDs can be tuned accordingly. A quadrant silicon detector (QSD1) of thickness 314 μm is placed 0.7 cm downstream from DSSD2 to serve as an anticoincidence of the penetrating heavy ions and also serves for the detection of high-energy protons escaping from DSSD2. Next was a 1 546 μm thick quadrant silicon detector (QSD2) employed for β detection. Finally, two veto quadrant silicon detectors (QSD3 and QSD4), each with a thickness of ∼300 μm, are installed downstream to suppress possible disturbances from the penetrating light particles coming along with the beam. In addition, four ∼1 500 μm thick quadrant silicon detectors (QSDu, QSDd, QSDl and QSDr) are mounted upstream around the beam to detect the β particles and the protons escaping from the DSSDs. Outside the DSSD chamber, five clover-type HPGe detectors are installed to register the γ rays emitted in the decay of the implanted nuclei.

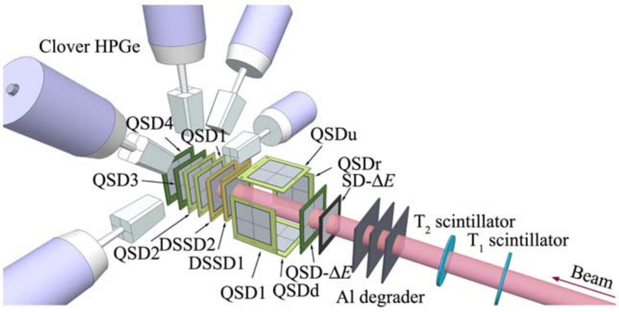

Fig. 1 (color online) Schematic layout of the detection setup.

All the silicon detectors are assembled on printed circuit plates and are equipped with the SPA02-type preamplifiers developed on our own. To achieve a better resolution and to maintain the operation stability, all the silicon detectors and the preamplifiers are cooled by using a circulating cooling alcohol system. Each output channel of the preamplifiers for the two DSSDs and QSD1 is split into two parallel electronic chains with different gains in order to measure both the high-energy implantation events with hundreds of MeV and the low-energy decay events with hundreds of keV. The implantation and decay signals measured in the two DSSDs are both used to trigger the VME data acquisition (DAQ) system, which is a revised version of 'RIBF DAQ'[20].

The performance of the detection system was evaluated in-beam using the β-delayed proton-emitter ^{24}Si. Afterwards, the system was commissioned in the spectroscopic study of ^{22}Si at the First Radioactive Ion Beam Line in Lanzhou (RIBLL1)[21]. The K450 separate sector cyclotron (SSC) provided a 75.8 MeV/u primary beam of ^{28}Si with an intensity of ∼37 enA (∼2.6 pnA). The secondary beam of ^{24}Si and ^{22}Si were produced via projectile fragmentation of a ^{28}Si beam impinging on 1 980 μm and 1 500 μm thick ^{9}Be targets, respectively. The ions of ^{22}Si in the secondary beam were identified by means of energy-loss (ΔE) and time-of-flight (TOF). The ΔE given by the SD is plotted as a function of the TOF determined with two scintillation detectors in Fig. 2. During the experiment, the average intensity and purity of ^{24}Si in the secondary beam were 1.51 particles per second (pps) and 0.31%, respectively. The average intensity and purity of ^{22}Si in the secondary beam were as low as 2.8×10^{-3} pps and 8×10^{-6}, respectively. In order to extract reliable information about the very rare decay events from disturbances, several techniques were also utilized to improve the signal-to-noise ratio of the detection system. First, the output signals of the preamplifiers were sent to the CAEN N568B amplifiers. For the 16 junction side strips of the DSSD, the 10× outputs of the N568B amplifiers of these 16 channels were inverted by a 16 channel inverter provided by Peking University and then were fed to a Philips 710 616 channel leading edge discriminator for timing. Second, a logical AND of the discriminator signals from both the junction side strips and the ohmic side strips of the DSSD, *i.e.* a front-back coincidence was applied as the trigger signal. This arrangement minimized the trigger rate caused by noises, resulting in the electronically-determined energy thresholds of DSSD1 and DSSD2 as low as ~ 80 keV and ~ 100 keV, respectively, due to the different amplification settings. Finally, both energy and time information of each channel for each detected event were recorded by the DAQ, which would facilitate the multi-constraints in the offline data selection.

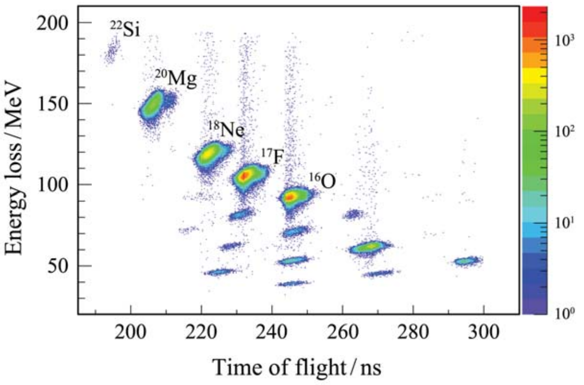

Fig. 2 (color online) Two-dimensional identification plot of ΔE and TOF.

3 Analysis and results

The time differences between every implantation event and all the subsequent decay events which occurs in the same x-y pixel of the DSSD generate the decay-time spectrum of ^{24}Si, which determines the half-life of ^{24}Si to be (143.4±2.2) ms. The error came from the fitting uncertainties. The value determined in the present work is in nice agreement with the literature values of (140±8) ms [22], (139±18) ms[23] and (140.8±1.8) ms[24].

The β-delayed proton spectra from ^{24}Si decay measured in the DSSDs are presented in Fig. 3. As can be seen from Fig. 3(b), the β-coincident spectrum has no obvious β background down to ~200 keV. The origins of each proton peak in the spectra were identified with half-life analysis. The β-delayed proton spectra from ^{24}Si decay measured by Banerjee *et al.*[23] and Ichikawa *et al.*[24] both showed two obvious undesirable proton peaks originating from ^{23}Al below 1 MeV. It is to be noted that no peak corresponding to the delayed protons of ^{23}Al are observed in Fig. 3 owing to the improved identification ability of our system. In Table 1, the energies of the β-delayed protons from ^{24}Si decay determined in the present work are compared to literature values and reasonable agreement is obtained. The energies of the β-delayed protons from

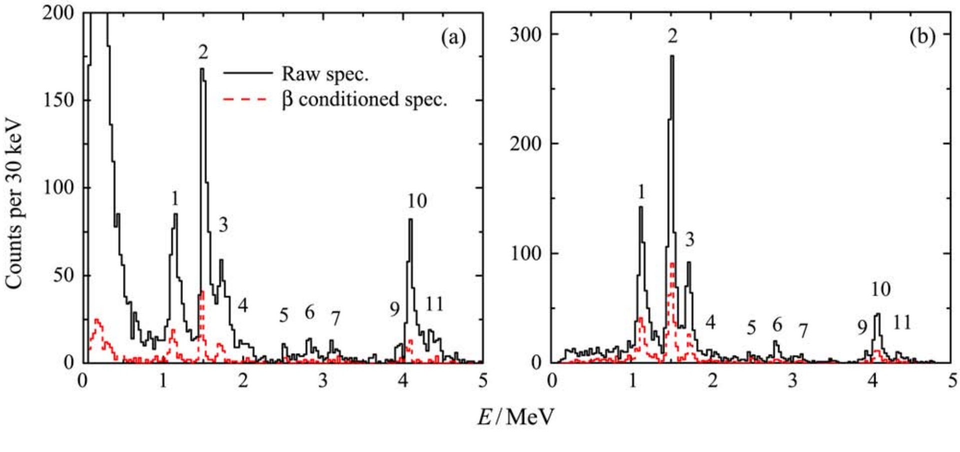

Fig. 3 (color online) β-delayed proton spectra from ^{24}Si decay measured by (a) DSSD1 and (b) DSSD2. In both cases, the raw spectrum (solid line) and the spectrum in coincidence with a β particle detected in the downstream QSD2 (dashed line) are presented.

^{24}Si decay were determined by the combined spectrum measured by the two DSSDs. The errors include the uncertainties of the calibration parameters and the peak-energy Gaussian fitting uncertainties.

Table 1　Center-of-mass energies of β-delayed protons from ^{24}Si decay.

Proton	Ref. [22] /MeV	Ref. [23] /MeV	Ref. [24] /MeV	Present work /MeV
1	1.131(30)	1.137	1.119(21)	1.127(15)
2	1.505(30)	1.503	1.492(13)	1.501(13)
3	1.731(30)	1.732	1.724(13)	1.721(14)
4	2.026(50)	2.056	2.024(10)	2.005(21)
5	2.515(50)	2.525	2.517(9)	2.505(21)
6	2.825(40)	2.797	2.828(7)	2.814(20)
7	3.104(40)	3.099	3.104(8)	3.100(27)
8		3.569	3.510(10)	
9		3.892	3.929(50)	3.940(26)
10	4.093(20)	4.090	4.081(7)	4.083(14)
11	4.388(40)	4.372	4.371(11)	4.362(19)
12		4.664	4.615(11)	
13			4.863(11)	

The proton-emission branching ratios were calculated by counting the β-delayed proton decay events in the proton spectrum, divided by the numbers of the implanted ^{24}Si ions. The background correction of the proton spectrum and the dead-time correction of the detection system were applied and it was necessary to correct the numbers of β-delayed proton decay events losses due to escaping, as well. The background correction was done by using the implantation-decay correlation time to remove the background contributed by β particles or other accidental disturbances. The dead-time correction was performed by using the trigger rate and the accepted counting rate, and the two parameters had been recorded by the scalers for monitoring in the data acquisition system itself. The proton detection efficiencies of the DSSDs for full energy protons need to be determined by a Monte Carlo simulation. The results of branching ratios are tabulated and compared with literature values in Table 2. The partial decay scheme of ^{24}Si reconstructed in the present experiment is shown in Fig. 4, and the agreement with the decay schemes proposed in Ref. [22-23, 25] is good. The deduced branching ratios (BR) to the observed proton-unbound states are denoted. The errors are attributed to the statistical errors and the uncertainties from the background correction, the dead-time correction and the detection efficiency simulation. The detailed results of β-delayed proton decay of ^{24}Si were given in Ref. [26].

Table 2　Branching ratios for the β-delayed proton decay of ^{24}Si.

Proton	Ref. [22]/%	Ref. [25]/%	Present work/%
1	5.4	5.8(7)	5.1(4)
2	11.8	11(1)	9.6(8)
3	5.8	3.7(5)	3.9(4)
4	1.3	0.8(1)	1.2(2)
5	0.9	0.49(7)	0.7(1)
6	⩾1.4	1.1(1)	1.4(2)
7	⩾1.3	0.8(1)	0.9(2)
8	0.2	0.68(10)	
9		1.0(3)	1.0(2)
10	7.0	6.1(8)	5.9(6)
11	2.5	1.4(2)	1.6(3)
12		0.26(4)	
13		0.07(2)	

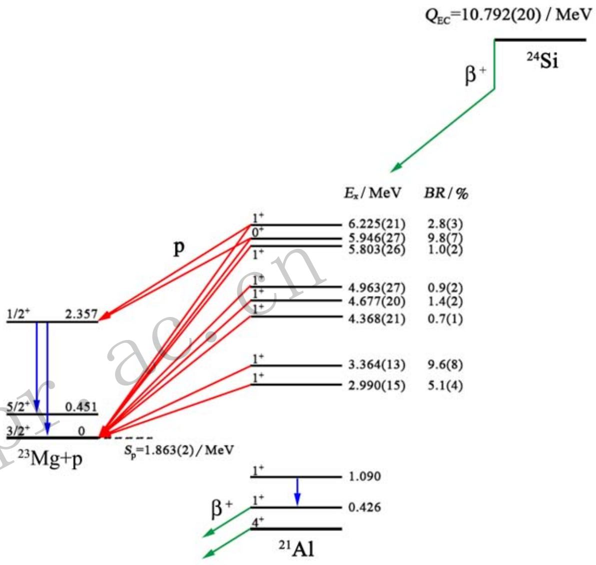

Fig. 4　(color online) Decay scheme of ^{24}Si.

4　Conclusion

A new decay detection system with an implantation method has been built and commissioned in the experiments of β-delayed proton decay of ^{22,24}Si under a continuous-beam mode. The setup makes it possible to perform an accurate identification of the implanted nuclei and the subsequent decays by means of energy, time and position measurement. Though the intensity of ^{28}Si primary beam was much lower and the collection time of our experiment were much less than those in the previous experiments of ^{24}Si, a relatively high quantity of decay events were accumulated and reliable results were obtained under this condition with our improved experimental techniques. It is desirable to extract more information by further experiments with improved statistics. The detection system of our experiment proved to be a powerful equipment to measure the β-delayed proton decay and further research can be extended to the measurements of more exotic decay modes.

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