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Observation of β-delayed two-proton emission in the decay of ^{22}Si

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ABSTRACT

The decay of the lightest nucleus with $T_z = -3$, ^{22}Si, was studied by a silicon array. A charged-particle group at 5600 (70) keV in the decay-energy spectrum was identified experimentally as β-delayed two-proton emission from the isobaric analog state (IAS) of ^{22}Al. Experimental results of the IAS fed by a superallowed Fermi transition were compared with our large-scale shell-model calculations. The ground-state mass of ^{22}Si was obtained indirectly in the experiment for the first time. Two-proton separation energy for ^{22}Si is deduced to be -108 (125) keV, which indicates that it is a very marginal candidate for two-proton ground-state emission.

1. Introduction

Nuclei with drastic imbalance of proton-to-neutron ratios propound as a sensitive probe to validate the state-of-the-art nuclear models. Their measured ground state energies, structures, as well as decay modes can be utilized to constrain the assumptions imposed in theory and also to refine the nucleosynthesis paths close to either proton or neutron drip lines. The proton drip line heretofore is sufficiently well-known compared to the neutron one, which is not yet experimentally well constrained. Henceforth, precisely measuring ground-state masses and decay modes of these proton-rich nuclei, and identifying more energy levels permit us to have a better assessment on the understanding of nuclear forces and isospin-symmetry-breaking effects, and to extract and explore more insightful physics. Impressive progresses in nuclear decay studies near the proton drip line have been achieved over recent decades [1–3]. These exotic decay modes of proton-rich nuclei, such as latest studies of two-proton (2p) emission from ground states (e.g., ^{45}Fe [4], ^{54}Zn [5], ^{48}Ni [6] and ^{30}Ar [7]) and excited levels [8,9], and β-delayed particle emission (^{31}Ar [10,11] and ^{20}Mg [12–14]), play a significant role in studies of nuclear structure, quantum many-body systems, and nuclear astrophysics.

The lightest nucleus with an isospin projection $T_z = -3$, ^{22}Si, was discovered nearly thirty years ago in GANIL [15]. Up to now, only one experiment [16] has been performed to study its spectroscopic information, in which β-delayed proton emission was observed and the half-life of ^{22}Si was determined. The β-decay of ^{22}Si is of particular importance as high-quality shell-model calculations can be performed for 1s-0d-shell nuclei and comparisons of relevant theoretical and experimental results can be made in order to check the reliability of the shell-model near the proton drip line. ^{22}Si was postulated to be a candidate for β-delayed 2p and

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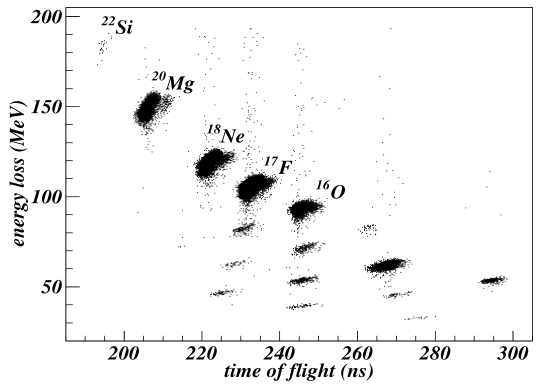

Fig. 1. Particle identification spectrum of energy loss from a large-area silicon detector versus time of flight between two plastic scintillators for secondary ions.

3p emissions via the IAS [17], as well as possible β-delayed $p\alpha$ emission [16]. However, such postulations have yet to be discovered. Moreover, ^{22}Si may be unbound with respect to 2p emission to the ground state of ^{20}Mg according to the Atomic Mass Evaluation (AME) [18,19]. Therefore, a new experiment was carried out to further investigate exotic decay properties of ^{22}Si.

2. Experiment and results

The experiment was performed at the National Laboratory of Heavy Ion Research (HIRFL) of the Institute of Modern Physics, Lanzhou, China. ^{22}Si was produced by projectile fragmentation of a primary ^{28}Si beam, accelerated to 75.8 MeV/nucleon by HIRFL cyclotrons, which impinged with an average intensity of 37 enA on a 1500 μm ^{9}Be target. The fragments were separated and purified by the first Radioactive Ion Beam Line in Lanzhou (RIBLL1) [20], then delivered to a detection system [21] for charged-particle decay studies.

In the detection system, two plastic scintillators at the second and fourth focal planes of the RIBLL1 were used for measurements of time of flight (ToF) of fragments. A silicon array [21] coupled with germanium clover detectors at the end of RIBLL1 was used to identify secondary ions on an event-by-event basis and study their decay properties with an implantation-decay correlation. In the silicon array, two silicon detectors in the front were used to measure the energy loss (ΔE) of fragments. Fig. 1 shows the two-dimensional particle identification spectrum of ΔE versus ToF for secondary ions. Implantation rates of ^{22}Si and ^{20}Mg were 0.2/minute and 30/minute, respectively.

Two thin double-sided silicon strip detectors segmented into 16 horizontal and 16 vertical strips (DSSD1 of 149 μm thickness and DSSD2 of 66 μm, respectively) in the center of the array served to measure the residual energy of the fragments and their decay characteristics. The calibrations of DSSDs for charged particles in the decay and heavy fragments were realized with the known β-delayed proton emitter ^{20}Mg [12–14] and secondary ions produced by the primary beam at several energies, respectively. A quadrant silicon detector (QSD1) was placed behind DSSD2 to achieve anticoincidence with the penetrating fragments and detect high-energy protons escaping from DSSD2. After QSD1, a 1546 μm thick quadrant silicon detector (QSD2) was installed for β measurements. Finally, two quadrant silicon detectors [22] were installed downstream to reject light particles coming along with the beam. In addition, four 1500 μm thick quadrant silicon detectors (QSDs) were mounted upstream around the beam to detect β particles and protons escaping from DSSDs. The low-energy threshold of 150 keV was determined by two-dimensional energy-correlation spectrum for protons escaping from one DSSD and deposited in the other in the decay of high statistical ^{20}Mg. Details on the detection array and implantation-decay correlation were described in Ref. [21].

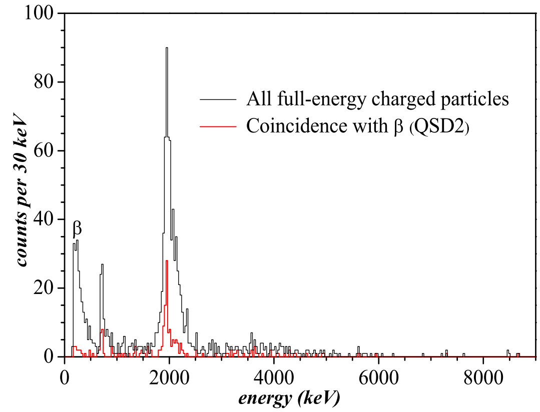

Fig. 2. Charged-particle spectrum in the decay of ^{22}Si measured by two DSSDs. Escaping protons from DSSDs can be largely rejected by surrounding detectors and only full-energy protons stopped in DSSDs are registered in spectra. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

The spectrum of a sum of charged-particle energies in the decay of ^{22}Si measured by DSSDs is shown in Fig. 2, in which black and red lines represent protons of the full energy and in coincidence with β particles detected by the downstream QSD2, respectively. The contaminants in the secondary ions either do not emit protons (^{18}Ne, ^{17}F and ^{16}O) or are well studied (^{20}Mg [12–14]). Due to low implantation rates of ^{22}Si and ^{20}Mg, no contamination was observed. The spectrum may include charged particles mainly from the decay of the daughter nucleus ^{21}Mg [23] and little from another one ^{22}Al as there are few events at 1.3 MeV which is the energy of the proton group with the largest branching ratio in the decay of ^{22}Al [24]. Several proton groups were identified with an energy resolution of 70 keV (50 keV for each DSSD). The prominent proton group at 1950 keV was recognized as the same transition as the one at 1990 (50) keV in the work of Blank et al. [16] based on its high intensity. A new proton group at 680 keV was also observed obviously. The decay time up to 200 ms after ^{22}Si implantation was fitted by a single decay component using the Maximum Likelihood Method in order to determine the half-life of ^{22}Si. Fig. 3 (a) shows the decay-time spectrum of events in the gate of the decay energy greater than 500 keV which also contains the decay of the daughter nucleus ^{21}Mg. The proton group at 680 keV should completely originate from the decay of ^{22}Si as the decay of the only contamination ^{21}Mg [23] mentioned above has no contribution at the energy region between 500 and 800 keV. The half-life of ^{22}Si thus is determined as 27.8 (35) ms by fitting the decay time of the proton group at 680 keV, shown in Fig. 3 (b), which is consistent with the previous experimental data of 29 (2) ms [16]. More details on β-delayed proton emission in the decay of ^{22}Si will be shown elsewhere [25].

^{22}Si is also a candidate for β-delayed 2p emission via the IAS in ^{22}Al. According to the predictions based on systematics [2], the expected energy for a 2p decay of the IAS to the ground state in ^{20}Na is about 5610 (220) keV. In Fig. 2, a charged-particle group at 5600 (70) keV with low statistics of only five events has been observed and two of them coincided with β particles, which is in accordance with the β detection efficiency of 43%. One β particle was detected by the downstream QSD2 (shown in Fig. 2) and the other was measured by upstream QSDs, respectively. It should be pointed out that charged particles at 5600 keV cannot originate from light particles coming along with the beam. Firstly, the co-

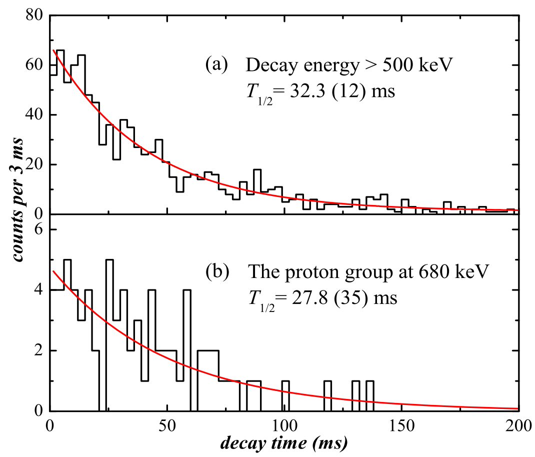

Fig. 3. Decay-time spectrum of ^{22}Si. (a) The events with the decay energy greater than 500 keV which also contain the decay of the daughter nucleus ^{21}Mg. (b) The proton group at 680 keV entirely from the decay of ^{22}Si which yields a half-life of 27.8 (35) ms.

incidence rate of random background due to secondary ions flying through the separator is very small, which means that even though the beam is continuously provided, an event of light particle penetration near 5600 keV is very unlikely to take place in any DSSD pixel after an ^{22}Si implantation event within the time window of 200 ms. Secondly, the disturbances from penetrating heavy ions and light particles can be eliminated by anticoincidence conditions with two downstream QSDs in the silicon array [21].

To provide evidence for the decay mode of β-delayed 2p emission, the decayed-light-particle identification with the energy-loss method was realized in the experiment. ^{22}Si was implanted in one of DSSDs, then decayed and emitted charged particles which may escape from the implantation DSSD and be detected by the other DSSD. In this case, the path length of the emitted particles within the implantation DSSD can be calculated based on the kinematics information including the emission angle of protons and the implantation depth of fragments. The emission angle of protons was determined by the detected position in DSSDs. The implantation depth was deduced from a SRIM calculation [26] through the residual energy of ^{22}Si measured by DSSDs.

Table 1 shows the path lengths, measured energy losses for particles at 5600 keV in the implantation detector, and calculated energy losses for one proton with the same initial energy and path length. The large errors of the path lengths mainly come from the uncertainties of proton positions in DSSDs and propagate into calculated energy losses for one proton given in column 4 of Table 1. Although their errors in calculations are also large, energy losses of detected charged particles are much larger than those of one proton indicating that the particle should be heavier. On the other hand, the range of α with the energy of 5600 keV is only 28 μm in silicon and it cannot escape from the implantation detector. Therefore, experimental results strongly suggest that the peak at 5600 keV corresponds to β-delayed 2p emission. Moreover, for the event of number 2, two protons both escaped from the implantation DSSD and were detected by two different strips of the other DSSD. For the event of number 4, one proton was detected by the adjacent strip of the implantation one of the same DSSD, and the second proton escaped from the implantation DSSD and hit the other DSSD. In other words, two protons were observed experimentally for the events of number 2 and 4. The path lengths of two protons for the event number 5 cannot be deduced as two protons were both stopped in the implantation detector. The decay time of these events shown in Table 1 yields a half-life of 22.5 (105) ms, which is consistent with the property of ^{22}Si.

The excited energy of IAS (0^+) in ^{22}Al is deduced to be 8829 (406) keV according to two-proton energy, ground-state masses of ^{22}Al and ^{20}Na based on AME2012 [19]. With the simulated detection efficiency of 70(7)% under the assumption of 2p emission in phase space, the experimental branching ratio of β2p emission from the IAS is determined to be 0.7(3)% which is in accordance with the former experimental result (less than 1%) [16].

We performed shell-model (SM) calculations based on two different Hamiltonians in the full *sd* shell to compare with experimental results. The first set Hamiltonian is named cd-USDB, which is an isospin non-conserving Hamiltonian [27] composed by an isospin conserving Hamiltonian, i.e. USDB interaction [28], a two-body Coulomb interaction adjusted with short-range-correlation scheme based on unitary correlation operator method (UCOM) [29], a phenomenological charge-dependent part describing the isospin-symmetry breaking of the effective nucleon–nucleon interaction, and isovector single particle energies. The other Hamiltonian called wb-USD [30], which is based on USD, considers the weakly bound effect of the proton $1s_{1/2}$ orbit contributed by Coulomb interaction. The monopole based universal interaction V_{MU} [31] plus M3Y spin–orbit force [32] is used to calculate the two-body matrix elements (TBME) differences between the proton–proton and neutron–neutron terms involving $1s_{1/2}$ orbit. The validity of the V_{MU} plus M3Y spin–orbit force is also examined in the neutron-rich nuclei in the *psd* region [33]. The Hamiltonian cd-USDB concentrates on the isospin asymmetry effect in the interaction, while the wb-USD focuses on the weakly bound effect on the wave function of proton $1s_{1/2}$ orbit originated from the Coulomb interaction.

Theoretical IAS energies determined by cd-USDB and wb-USD are estimated to be 9144 keV and 9020 keV with the branching ratios of 10.0% and 7.7%, respectively. The SM energies for the IAS agree with the observed data. The branching ratio of the IAS mainly corresponds to proton emissions including β-delayed p, 2p, and 3p decay as theoretical calculations show that the width of proton emission (see Refs. [34,35] for similar calculations) is much larger than the one of γ decay. Possible βp emission from the IAS was unobserved because of the low detection efficiency of single protons greater than 5 MeV and many branches of transitions

Table 1
Identification of particles at the energy of 5600 keV. Energy losses of experimental measurements and calculations for one proton with the same initial energy and path length in the implantation DSSD show that the particles cannot be one proton and should be heavier. Residual energies of escaping protons were measured by the other DSSD. The decay time of these events measured in the experiment is consistent with the half-life of ^{22}Si.

No.	Path length (μm)	Energy loss in the implantation detector (keV)		Residual energy (keV)	Decay time (ms)
		Measurement	Calculation for one proton	Measurement	
1	32.2 (50)	680 (50)	420 (70)	4950 (50)	30.6
2	35.7 (99)	1930 (50)	470 (130)	3630 (50)	19.3
3	66.1 (177)	3420 (50)	900 (260)	2190 (50)	16.3
4	49.3 (91)	4980 (50)	660 (130)	620 (50)	3.1
5	–	5600 (50)	–	–	89.6

to different excited states of ^{21}Mg. Due to the smaller decay energy (3.4 MeV) and branching ratio, possible β3p emission was also unidentified experimentally. Half-lives of ^{22}Si are deduced to be 28.1 ms and 21.0 ms by the two models, respectively, in agreement with experimental data of 27.8 (35) ms.

The mass excess of the ground state of ^{22}Si can be deduced from the equation: $\Delta(^{22}\text{Si}) = \Delta(\text{IAS}) + \Delta E_c - \Delta_{nH}$ [36], where Δ(IAS) is the mass excess of the IAS of ^{22}Al and can be determined as 27029 (70) keV with the sum of the decay energy of β2p, the mass of two hydrogen atoms and the mass of ^{20}Na [19]. ΔE_c is the Coulomb displacement energy between the ground state of ^{22}Si and the IAS of ^{22}Al, which can be deduced to be 5917 (101) keV according to the formula for the isospin $T = 3$ [36]. Δ_{nH} is the mass excess difference between a neutron and a hydrogen atom [19]. In this way, the atomic mass excess of ^{22}Si was deduced to be equal to 32163 (123) keV. Two-proton separation energy (S_{2p}) for ^{22}Si can be determined as -108 (125) keV according to the recent mass measurement of ^{20}Mg [37], which shows that ^{22}Si marginally situates beyond the two-proton drip line.

The isobaric multiplet mass equation (IMME) is also used to deduce the mass excess of ^{22}Si. It can thus be determined as 32402 and 32070 keV from the mass of its mirror nuclide ^{22}O [19] via $\Delta(^{22}\text{Si}) = \Delta(^{22}\text{O}) - 2b(A,T)T_Z$ using a standard fit of the b-coefficient [38] and a readjustment [39], respectively. Consequently, S_{2p} for ^{22}Si can be deduced to be -346 and -15 keV, respectively, which show that ^{22}Si is a very marginal candidate for two-proton radioactivity as well. Two-proton separation energy obtained experimentally also agrees well with the compilation of AME2003, -104 (201) keV [18], with the many-body perturbation theory based on three-nucleon (3N) forces in an extended $sdf_{7/2}p_{3/2}$ valence space, -120 keV [40], and with the improved Kelson–Garvey (ImKG) mass relations, -4 (57) keV [41]. However, for other compilation and mass models, such as AME2012 [19], the infinite nuclear matter (INM) model [42] and the finite-range droplet model (FRDM) [43], ^{22}Si is found to be over unbound with respect to two-proton ground-state emission.

3. Summary

In summary, the decay properties and mass of the proton-rich nucleus ^{22}Si are presented in this letter. Firstly, a new β-delayed one-proton emission has been observed, of which the half-life was determined to be 27.8 (35) ms. Secondly, β-delayed 2p emission via the IAS of ^{22}Al was experimentally identified, which is compared with shell-model calculations. Thirdly, the mass excess of the ground state of ^{22}Si estimated according to β-delayed 2p emission indicates that it is a very marginal candidate for 2p ground-state emission which agrees well with IMME and the recent results of AME2003, 3N forces and ImKG. In order to learn more about the ground-state mass of ^{22}Si, more experiments with high statistics are required to be performed in the future, such as mass measurements with the storage ring. Furthermore, the nature of β-delayed 2p decay via the IAS of ^{22}Al can be investigated by using a more advanced high-granularity and large-coverage silicon array.

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