First spectroscopic study of ^{22}Si

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In an experiment at the LISE3 facility of GANIL, we produced the proton-rich isotope ^{22}Si by the fragmentation of a ^{36}Ar primary beam at 95 MeV/nucleon. After implantation in a detector telescope, we studied the decay of ^{22}Si via a measurement of charged particles emitted during the decay. The most important β-delayed proton activity is observed at an energy of $E_p = (1.99 \pm 0.05)$ MeV with a branching ratio of $(20 \pm 2)\%$. The spectra allow us also to determine the half-life of ^{22}Si to be $T_{1/2} = (29 \pm 2)$ ms. These results are compared with theoretical estimates and model predictions. [S0556-2813(96)03708-9]

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The decay of nuclei in the sd shell is of particular interest due to the high quality of available shell-model calculations. Differences between experimental results and theoretical predictions can be used to extract fundamental information on the weak and strong interaction in the nuclei as well as on their shell structure.

The isotope ^{22}Si was discovered some years ago in a GANIL experiment observing fragmentation products from a ^{36}Ar primary beam at 85 MeV/nucleon [1]. This nucleus is the lightest nucleus with an isospin projection $T_z = -3$, the next heavier known ones being ^{46}Fe and ^{50}Ni. However, no spectroscopic studies have been performed on this isotope. Similar to the other very proton-rich sd-shell nuclei such as ^{31}Ar [2], it is a candidate for β-delayed proton, two-proton, and three-proton emission via the isobaric analog state (IAS), and a $\beta p \alpha$ emission is energetically also possible. While all mass models of the 1986–1987 Atomic Mass Predictions [3] find ^{22}Si to be unbound with respect to two-proton ground-state emission, the latest atomic mass evaluation [4] predicts a two-proton separation energy of only (-16 ± 202)keV, which makes ^{22}Si a very marginal candidate for two-proton ground-state emission.

In an experiment performed at the LISE3 facility [5] of GANIL, we produced ^{22}Si as projectile-fragmentation products from a ^{36}Ar primary beam at 95 MeV/nucleon. Using the LISE3 spectrometer with an intermediate degrader [6] and the velocity filter tuned to select ^{22}Si, we transmitted only ^{22}Si, ^{20}Mg, and ^{18}Ne to the final focal plane of LISE3. The isotope identification in flight has been performed by the usual technique, i.e., a ΔE-time-of-flight (TOF) measurement. The energy loss ΔE and the TOF have been measured by means of a detector telescope at the final LISE3 focus consisting of three silicon detectors and a Micro-Strip Gas Counter (MSGC) [7]. The range of the isotopes was tuned with degrader wheels to implant them in the last silicon detector and in the MSGC. After implantation of a fragment, the beam was switched off for 100 ms to observe the radioactive decay of the implanted activity. This procedure allows for a background-free correlation between implantation and decay. The contaminants transmitted in the same spectrometer setting are either well studied (^{20}Mg) or have no β-delayed proton branch (^{18}Ne). Because of the low implantation rate (3.5 ^{22}Si per minute, 10 ^{20}Mg per minute), no contamination was observed in the decay spectra correlated to implantations of the different isotopes. The decay spectra have been calibrated with the known β-delayed proton emitters ^{24}Si [8], ^{21}Mg [9], and ^{20}Mg [10,11].

Figure 1 shows the spectra registered after implantation of the ^{22}Si activity. Part (a) gives the spectrum from the MSGC showing proton groups at (1.63 ± 0.05) MeV, at (1.99 ± 0.05) MeV, at (2.10 ± 0.05) MeV, and at (2.17 ± 0.05) MeV. The experimental branching ratios are $(6 \pm 2)\%$, (20

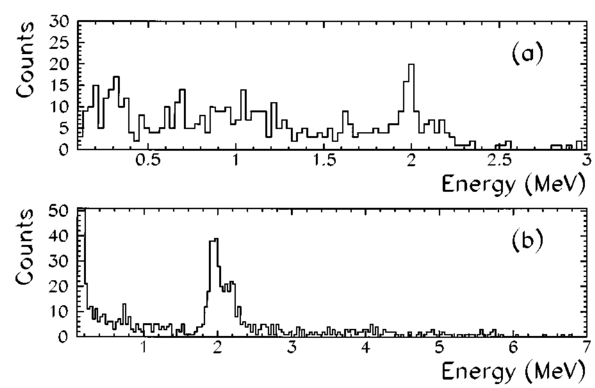

FIG. 1. Charged-particle spectra measured after implantation of a ^{22}Si isotope in the MSGC (a) and in the silicon detector (b). Energies and branching ratios are given in the text.

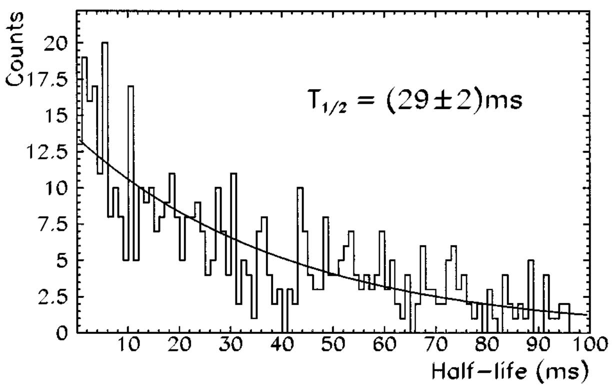

FIG. 2. Decay-time characteristics for the proton groups between 1.8 MeV and 2.4 MeV of ^{22}Si. The solid line is a maximum likelihood fit with a single decay component plus a daughter decay yielding a half-life of $T_{1/2} = (29 \pm 2)$ ms.

$\pm 2)$%, (4 ± 2)%, and (2 ± 1)%, respectively. A broad proton distribution is also visible around 1 MeV. The energies given are corrected for the pulse-height defect of the recoils [12,13] and for the energy loss of the β particles.

As this gas detector has a reasonable efficiency only up to about 2.0 MeV, we show in part (b) the spectrum registered with the last silicon detector. Because of a much higher energy loss of β particles, the resolution of this spectrum is much worse compared to the one taken with the MSGC. Nevertheless, the main proton groups between 1.8 MeV and 2.2 MeV are clearly visible. Beyond these two lines, one observes charged-particle activity up to about 6 MeV, however, no really pronounced peak. We find a charged-particle branching ratio for events above 500 keV close to 100%. The low-energy counts ($E < 500$ keV) are most probably due to β particles.

The half-life of ^{22}Si has been determined by means of the charged particles in an energy range from 1.8 MeV to 2.4 MeV, thus including the main proton groups. This part of the spectrum may contain charged particles from the decay of the daughter nucleus ^{21}Mg. However, because of the longer half-life of this nucleus, only a small contamination (<5%) is expected. Nevertheless, the daughter decay has been taken into account while determining the half-life of ^{22}Si. The decay-time spectrum is shown in Fig. 2. A maximum likelihood fit with a single decay component plus a component for the daughter decay yields a half-life for ^{22}Si of (29 ± 2) ms.

The prominent proton lines in the decay spectra of light proton-rich isotopes may be due to the decay by proton emission of the IAS of the β-decay daughter nucleus fed by a superallowed Fermi transition. In the case of even-even nuclei, this transition involves two O$^+$ levels and the transition strength is easily calculable. The logft value is linked to the Fermi matrix element by the relation $ft = k/B(F)$. Assuming pure Fermi transitions, one obtains $B(F) = 6$ for $T_z = -3$ nuclei. Using the measured half-life of (29 ± 2) ms, the Q value for the decay of ^{22}Si to the IAS in ^{22}Al of (4.1 ± 0.2) MeV [4,14], and a value of $k = (6127 \pm 9)$ [15] yields a branching ratio for the decay to the IAS of (3.6 ± 0.8)%.

The intensity of the peak at 1.99 MeV corresponds to a branching ratio of (20 ± 2)%. This excludes the possibility that this peak stems from the decay of the IAS. Instead, it belongs to the decay of a lower-lying level fed by Gamow-Teller decay. In the mirror-nucleus β decay (see Fig. 3), i.e., ^{22}O $\rightarrow$ ^{22}F, Gamow-Teller transitions to states at an excitation energy of 1.627 MeV and at 2.572 MeV with branching ratios of $\leqslant 34$% and $\geqslant 48$%, respectively, have been observed [16].

Based on the mirror decay, we attribute the proton activity at 1.99 MeV to the decay of an excited level in ^{22}Al at 2.21 MeV towards the first excited state at 0.196 MeV [17]. This level is most probably an $I^\pi = 1/2^+$ level and favors thus a transition from the $I^\pi = 1^+$ state at 2.21 MeV. The peak at 2.17 MeV is attributed to the decay of the same state to the ground state of ^{21}Mg.

Following the analogy in the mirror decay, we attribute the proton peak at 1.63 MeV to the decay of an $I^\pi = 1^+$ level at an excitation energy of 1.85 MeV in ^{22}Al to the first excited state in the daughter nucleus. Such a scheme is supported by the weak activity observable at about 1.8 MeV which could belong to the decay to the ground state.

The proton line at 2.10 MeV cannot be put in the decay scheme. However, the observed overall proton branching ratio of close to 100% is in reasonable agreement with the fact that the β-decay daughter nucleus ^{22}Al is only very slightly bound [4] and almost all excited levels can decay by proton emission.

Shell-model calculations of Brown [18] predict a strong feeding (branching ratio of 57.5%) of an $I^\pi = 1^+$ level at an excitation energy of 2.327 MeV in ^{22}Al. The decay of this level corresponds to our observed proton lines at 1.99 MeV and at 2.17 MeV. On the other hand, the calculations predict also a feeding of a state at 3.250 MeV with a branching ratio of 18.6%, however, no feeding of a level at 1.629 MeV. As already in the case of ^{22}O, this seems to be in contradiction with the experimental results. In principle, we could assign the 1.63 MeV activity to the decay of a hypothetic level at 3.29 MeV decaying to an excited state at 1.64 MeV [17] in ^{21}Mg. However, if there is no strong suppression by spectroscopic factors, there is no reason that such a level would not decay to the ground or first excited state and thus release 3.2 MeV. In such a case, it would be clearly visible in our spectra.

As mentioned above, ^{22}Si can also decay by β-delayed two-proton and three-proton emission. Under the assumption that the highest state fed with a branching ratio larger than 1%, which is comparable to the error bars of our measurement, is the IAS, it follows that the activity observed below 5.6 MeV can belong to $2p$ events and those below 3.4 MeV to $3p$ decays. However, because of the low statistics, it is not possible to distinguish these events probably spread over a wide energy range from β-delayed one-proton emission.

The half-life of ^{22}Si has been determined to be (29 ± 2) ms. This value can be compared to prediction of the gross theory [19] which gives 14.9 ms. The pnQRPA model of Hirsch *et al.* [20] predicts half-life values between 68 ms and 99 ms depending on the mass predictions used. Our value lies in between the theoretical predictions. The shell model of Brown [18] predicts a half-life of 28 ms, very well in line with our experimental result.

In Fig. 3, we summarize the spectroscopic information from this paper in a partial decay scheme and compare it to shell-model predictions.

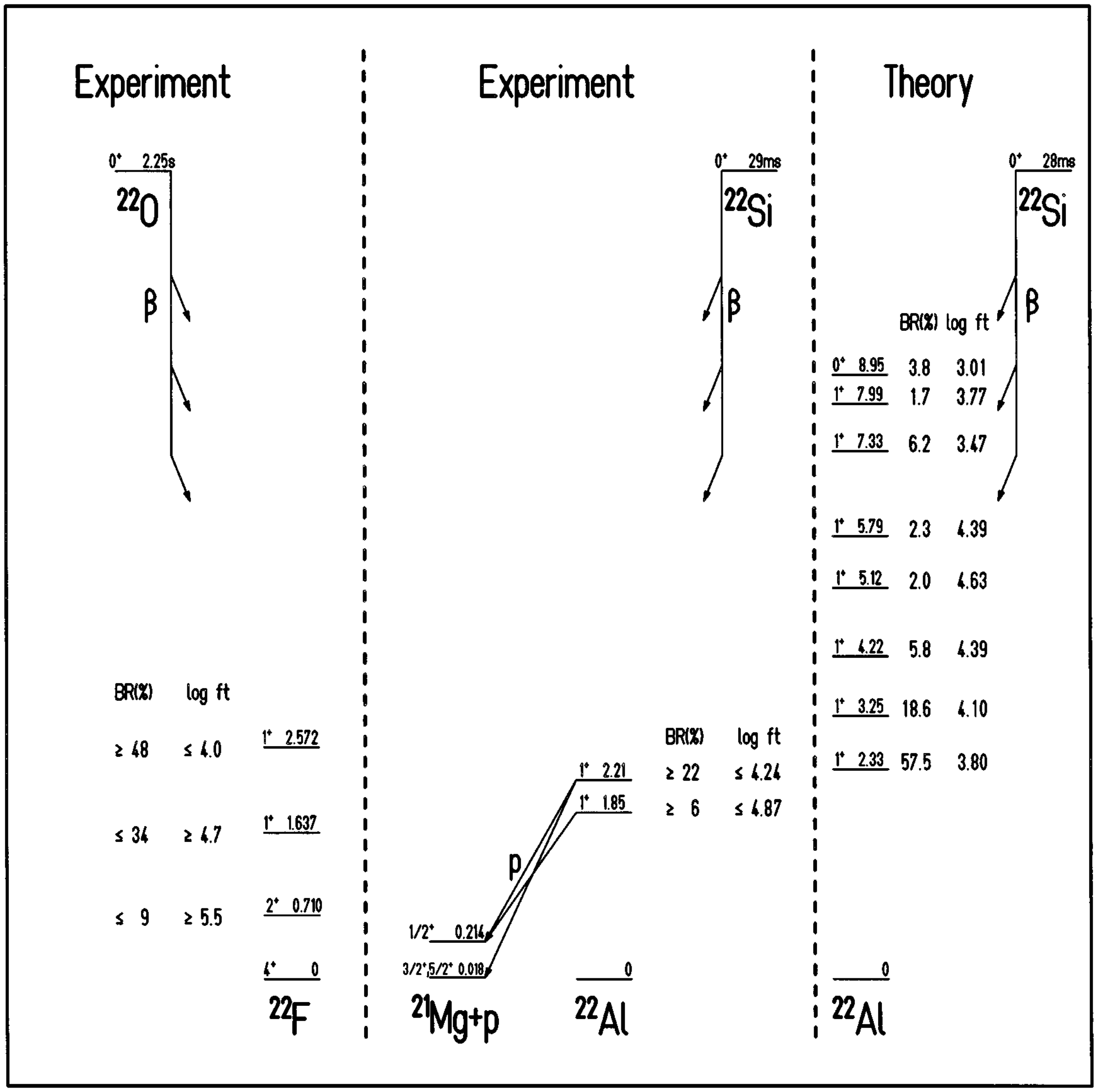

FIG. 3. Partial decay scheme for the decay of ^{22}Si. The ground-state energies are from Audi and Wapstra [4] and excitation energies in ^{21}Mg are from Endt [17]. The experimental levels in ^{22}Al are determined from our proton lines. The spins are deduced by means of the mirror nucleus and the shell-model calculations. These calculations are from Brown [18]. Given are only 0^+ and 1^+ levels with branching ratios larger than 1%. On the left-hand side of the figure, we show also the β-decay properties of the mirror nucleus [16]. All energies are given in MeV.

In summary, we performed for the first time spectroscopic studies of the decay of the $T_z = -3$ nucleus ^{22}Si produced as projectile fragments at the LISE3 spectrometer of GANIL with a counting rate of about 3.5 nuclei per minute. By comparing with the mirror decay, we can place the main transitions in a partial decay scheme. We have determined the half-life of ^{22}Si to be (29 ± 2) ms.

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