Study of the Neutron-Rich Nuclei with N=21, ^{35}Si and ^{33}Mg , by Beta Decay of ^{35}Al and ^{33}Na

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Abstract

The first information on the level structure of the N=21 nuclei, ^{35}Si and ^{33}Mg , has been obtained by the beta decay study of ^{35}Al and ^{33}Na , produced by fragmentation of an UC target with 1.4 GeV protons at CERN/ISOLDE. The experimental technique involved β - γ , β - γ - γ , and β -n- γ coincidences, neutron spectra being obtained by time of flight measurements. Gamma detection was made either using large Ge counters or small BaF₂ scintillators (for lifetime measurements). In the case of the ^{35}Al decay, ($T_{1/2} = 41.6(2.2)\text{ms}$), a simple structure has been found for the level scheme of ^{35}Si ($Z=14$, $N=21$) which has been interpreted with the level sequence : $7/2^-$, $3/2^-$ and $3/2^+$ corresponding respectively to the ground state and the states at 910 and 974 keV. The life-time of the 974 keV [$T_{1/2} = 5.9(6)\text{ns}$] is found consistent with the proposed level scheme and multipolarities. The investigation of the N=21, very neutron rich isotones, has been carried on with the study of ^{33}Mg resulting from the ^{33}Na decay, ($T_{1/2} = 8.0(6)\text{ms}$). In this case also, a level scheme could be obtained for the first time, with 5 bound states in ^{32}Mg and ^{31}Mg levels, populated in the 1n and 2n channels. These results are compared with sd-fp shell model calculations which give a fair account of the Gamow-Teller distribution and a reasonable explanation of the lowest levels with predominant contribution of 1p-1h and 2p-2h excitations.

1 Introduction

The beta-decay study of neutron-rich Na and Al nuclei gives access to the nuclear structure of Mg and Si isotopes in a region of particular interest. For Z between 10 and 14, it is now well established that, when neutrons are filling the sd-shell, there is an important contribution of intruder states at low energy with deformed and spherical shape coexistence. The present experiments have been performed to gain information on the effective interaction near the drip line from the observation of $1h\omega$ and $2h\omega$, as well as single particle excitations. All isotopes under study were obtained by fragmentation of a UC target with 1.4 GeV protons at CERN/ISOLDE with subsequent surface-ionization and mass separation. In these conditions, the Na isotope activities could be observed up to $A=33$ and the decay of Al isotopes for $A=34$ and $A=35$. Typical yield was 2 at/s for ^{33}Na and 8 at/s for ^{35}Al . The experimental set-up (Fig.1) was designed to detect betas, with a plastic scintillator around the collection point, gammas with two Ge counters, or a small BaF_2 counter and neutrons by time of flight, the start signal being given by the beta counter and the stop signal by eight neutron detectors located at 45 cm from the collection point. The neutron detection device has been described previously (1).

Fig. 1. Experimental setup.

As an introduction to ^{33}Na and ^{35}Al decay studies, we made a new measurement of the ^{34}Al β -decay. Improved conditions for production at 1.4 GeV enabled a more detailed description of the ^{34}Si level scheme (2) than with the 600 MeV ISOLDE/SC protons used in the first experiment (3). In particular, a careful search was made for the population of the second 0^+ state which is expected, from different calculations (4; 5) to be located below the first 2^+ state. The level scheme of ^{34}Si is then predicted with two 0^+ states, respectively with 0p-0h and 2p-2h nature, followed by two 2^+ states, respectively with 2p-2h and 0p-0h nature. This sequence, characteristic of double magic nuclei (4), is only partially established by experiments as the intruder 0^+ is still missing. From limits given by statistics, it was not possible to observe a weak decay branch of the first 2^+ state ($E_x = 3326$ keV) in the gamma-gamma coincidence spectra but in the singles-gamma ray spectra, where considering all lines assigned to ^{34}Al decay, we are left with only one transition whose properties (energy and intensity) can be compared to the predicted $2^+(2p-2h) \rightarrow 0^+(2p-2h)$ transition. This line, at 1193 keV, is then tentatively accounted for as a $3326(2^+)$ to 2133 keV (0^+) transition with an intensity of 3.2(6) % relative to the g.s. branch. The decay of the proposed 0^+ level at 2133 keV which should proceed by e^+e^- pair emission could not be observed in our experiment.

In figure 2, we have reported experimental information on 2^+ and 0^+ states in ^{34}Si with comparison to shell model predictions. In particular, if we take into

Fig. 2. ^{34}Si level structure at low energy.

account the branching ratio of the proposed $2^+(2p-2h) \rightarrow 0^+(2p-2h)$ transition and the $B(E2)$ value measured in MSU for the $0^+(0p-0h) \rightarrow 2^+(2p-2h)$ transition in ^{34}Si (5), we are led to $B(E2) = 444(210) \text{ e}^2\text{fm}^4$ for the $0^+(2p-2h) \rightarrow 2^+(2p-2h)$ transition. This value is found equivalent to the result obtained previously (7) for the corresponding $0^+(2p-2h) \rightarrow 2^+(2p-2h)$ transition in ^{32}Mg ($B(E2) = 454(78) \text{ e}^2\text{fm}^4$).

2 Investigation of the $N = 21$ isotone ^{35}Si , by beta decay of ^{35}Al

The ^{35}Al decay could be studied in detail (2) through beta-delayed gamma and neutron measurements. The average of independent beta and gamma measurements gives a weighted mean value $T_{1/2} = 38.6(4) \text{ ms}$. The P_n value ($P_n = 41(13)\%$), determined from gamma ray intensity measurements, is found larger than the highly precise value of P.L. Reeder et al. (8) measured with TOFI ($P_n = 26(4)\%$) but smaller than the very first result of A.C. Mueller et al (9) obtained at GANIL ($P_n = 87^{+37}_{-25}\%$). The large dispersion of these values may result from differences in the techniques used and in their limitations. The β -delayed neutron spectrum reveals two strong maxima (around 0.98 and 3 MeV) and negative-parity states in ^{34}Si , around 4 MeV, are found to be populated after neutron emission. The main beta branch proceeds through a level at 974 keV in ^{35}Si which decays, mainly, by a gamma cascade (64 - 910 keV). The ordering of the cascade could be deduced from the lifetime determination of the 974 keV level. The delayed coincidence measurement gives $\tau = 8.5(9) \text{ ns}$ and the decay of the 974 keV level is interpreted as an M2 ($974 \rightarrow 0 \text{ keV}$) in competition with a low energy ($974 \rightarrow 910 \text{ keV}$) E1 transition. The first levels of ^{35}Si are : a $J^\pi = 7/2^-$ ground state, a negative parity first excited state at 910 keV for which the most reasonable assignment is $J^\pi = 3/2^-$ and the strongly beta-populated state at 974 keV. This state is the first positive parity state and is interpreted as resulting from 1p-1h excitation with $J^\pi = 3/2^+$. The proposed J^π values are consistent with the observed beta intensities and the limitations for gamma multipolarities deduced from branching ratios and lifetime evaluations. The location of the $J^\pi = 3/2^-$ single particle state in ^{35}Si allows a better evaluation of the effective interaction when the neutron number is increased. The present measurement is informative on the $p_{3/2}/(s_{1/2}, d-3/2)$ neutron-proton interaction and a more precise description of the $N=21$ isotones can be made. It appears that the $f_{7/2}$ - $p_{3/2}$ gap decreases when going from ^{41}Ca to ^{35}Si . This experiment reveals also the decrease of the particle-hole energy, illustrating the global sd-fp gap, when going from ^{41}Ca to ^{35}Si .

3 Investigation of the $N = 21$ isotone ^{33}Mg , by beta decay of ^{33}Na

The study of ^{33}Mg is of particular interest, the simple structure linked to $N = 21$ being expected to be in close competition with $1h\omega$ ($2fp$) and $2h\omega$ ($3fp$) configurations. Half-life of ^{33}Na ($T_{1/2} = 8.0(3)$ ms) was found in good agreement with the previous value ($8.2(4)$ ms (10)). Using the same techniques as before, we were able to get the first decay scheme of ^{33}Na . The β -delayed neutron spectra of ^{33}Na and from its filiation (^{33}Mg and ^{32}Mg) has been disentangled on the basis of the different half-lives (see figure 3). It reveals two strong maxima at 800 and 1020 keV corresponding to peaks 4 and 3, respectively. Altogether, 19 γ -rays could be assigned to the ^{33}Na β -decay on an half life basis. These lines were attributed to the 0,1 or 2 β -delayed neutron channels belonging to ^{33}Mg , ^{32}Mg or ^{31}Mg level schemes. The level scheme of ^{33}Mg implicates 6 transitions, most already observed (11) and which, except one at 546 keV, are placed according γ - γ coincidence date or a sum of γ -ray energies. The difficulty to place the 546 keV line is tentatively explained by the existence of a coincident γ -transition outside our observation limits.

Fig. 3. Neutron time of flight spectrum for $A=33$. Peaks labelled 1 to 9, between 2.8 and 0.36 MeV, are related to ^{33}Na decay.

The ground state branch has still to be evaluated. Apart from this possible branch, two states (at 705 and 1243 keV) are strongly populated by beta decay and therefore positive parity candidates. This situation is to be compared with calculations where the first positive parity state, an intruder $1p$ - $1h$ state with $J^\pi = 5/2^+$, is predicted to lie at 811 keV. The second predicted positive parity state is a $1p$ - $1h$ state at 1997 keV, with $J^\pi = 1/2^+$, which is tentatively associated with the observed 1243 keV state. In the range of bound levels ($E_x < 2$ MeV) 6 negative parity states, of $0p$ - $0h$ or $2p$ - $2h$ nature, are predicted by the calculation. Only those located below the positive parity states are expected to be populated by gamma transitions and observed in our experiment. A definite candidate is given by the 484 keV level which can be associated with the $2p$ - $2h$ intruder predicted at 417 keV with $J^\pi = 3/2^-$. In summary, the low level structure of ^{33}Mg is found to be completely different from the one observed for the isotone ^{35}Si . The higher density of levels at low energy is understood as resulting from the close competition between fp and intruder states.

Fig. 4.

The shell model calculation successfully explains the experimental spectrum and the determination of the ground state branch has still to be evaluated to confirm the $7/2^- - 3/2^+$ crossing. The systematics of low energy levels in

$N = 21$ isotones is presented in figure 4. The general evolution of the fp-sd shell gap is a general feature with consequences far from stability. In addition, the particular case of ^{33}Mg is illustrative of an odd-even isotope in the island of inversion with the lowering of $1h\omega$ and $2h\omega$ relative to $0h\omega$. The same situation should prevail in the last bound $N = 21$ isotone : ^{31}Ne .

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