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Surprises at the $N = 20$ Shell Closure Far from Stability by Inelastic Scattering

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(Received January 23, 2002)

Following mass-measurements in the region $N = 20$ and $N = 28$, we have studied inelastic nuclear scattering for the nuclei ^{34}Si, ^{33}Al and ^{32}Mg. No evidence for a low lying shape isomeric 0^+ state was found in ^{34}Si, and an upper limit for the population cross section could be established, rendering it's existence very unlikely. A new transition was found in ^{33}Al, that is a good candidate for a 2p-2h state and therefore a determination of the 2p-2h gap at $N = 20$. Inelastic nuclear scattering strongly excites 3^- states, as seen in ^{34}Si. A strong transition was found in ^{32}Mg that should correspond to the first 3^- in this nucleus, lying very low as compared to theory and systematics in this region.

§1. Introduction

The evolution of shell closures far from stability is a subject of much actual debate.[1),2)] Deformations, shape coexistence or variations in the spin orbit strength as a function of the neutron to proton ratio could provoke the modification of magic numbers. Such behaviour has consequences in other domains, as seen for example in nucleo-synthesis, where a quenching of shell effects, and consequently of spin orbit splitting, can provide for a better agreement between model calculations and observed abundances.[3)] A breaking of magicity has already been observed at the $N = 20$ shell closure where an island of inversion in shell ordering has been shown to exist.[4)–7)] More recently, the determination of the lifetime[8)] and of the deformation of ^{44}S[9)] has indicated the existence of a similar effect at $N = 28$.

Experimentally, nuclear binding energies are very sensitive to the existence of shells and may provide clear signatures of shell closures.[11)] In a recent measurement,[10)] the masses of 31 neutron rich nuclei in the range $A = 29$–47 have been measured. The precision of 19 masses has been significantly improved and 12 masses were measured for the first time. The neutron-rich Cl, S and P isotopes are seen to exhibit a change in shell structure around $N = 28$. Comparison with shell model and relativistic mean field calculations demonstrated that the observed effects arise

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from deformed prolate ground state configurations associated with shape coexistence. Evidence for shape coexistence is provided by the observation of an isomer in ^{43}S, by delayed γ coincidence with Ge detectors. A new run performed this year with one order of magnitude increased ^{48}Ca beam intensities should allow us to push the mass measurements one or two neutron numbers further away from stability in this region.

Most theoretical models predict shape coexistence in ^{34}Si, a $Z = 14$, $N = 20$ nucleus, with a low lying deformed 0^+ state. This state is predicted below the 2^+ state, and hence an isomeric transition by pair creation or electron conversion to the ground state should exist. We searched for this transition using nuclear inelastic scattering. Methods and results for this nucleus and other $N = 20$, ^{33}Al and ^{32}Mg nuclei with an original method will be described in some detail below.

§2. Experimental set-up

A primary beam of ^{36}S was used to produce a secondary beam at a magnetic rigidity of 2.75 Tm corresponding to about 55 MeV/nucleon provided by the Ganil facility. This beam was transported to the SPEG reaction chamber. At the target position, all the particles were stopped and detected in a telescope consisting of ΔE and E silicon detectors. This telescope was followed by a thick (3500) Si(Li)

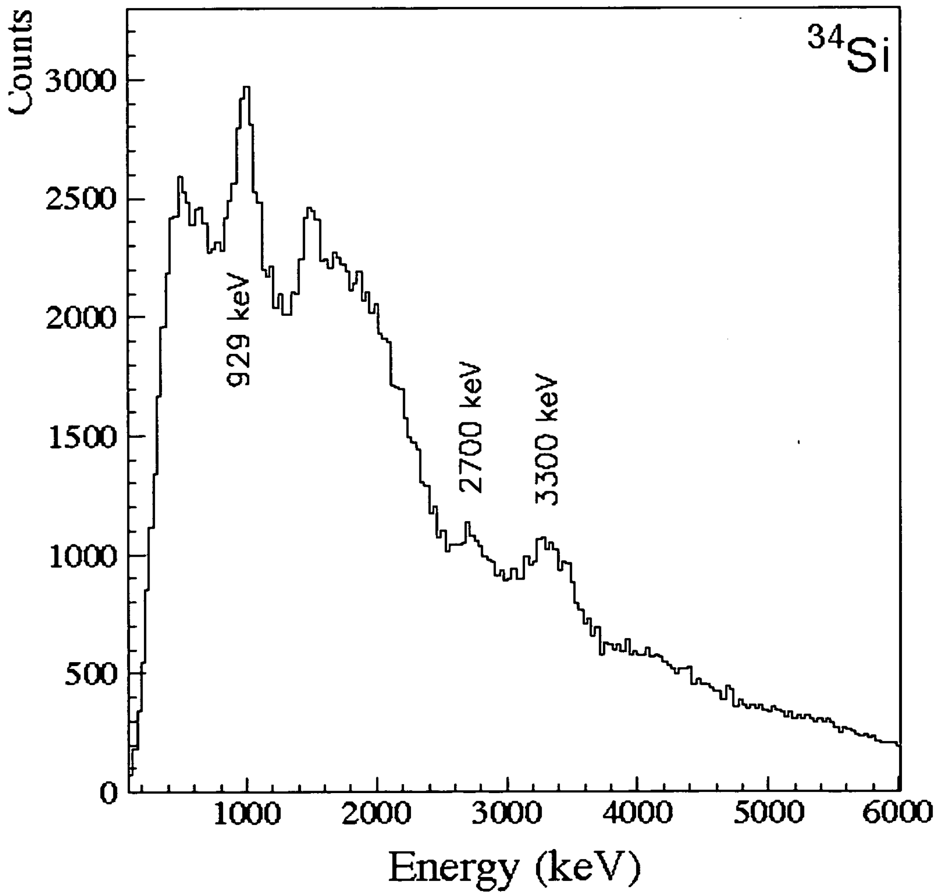

Fig. 1. Experimental γ spectra obtained after Doppler correction for inelastic scattering of ^{34}Si.

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detector to detect eventual isomeric internal conversion electrons (IC), for the case of a 0^+ state below about 1.2 MeV. The telescope was surrounded by the 4π γ-detection device "chateau de cristal" consisting of 72 BaF_2. All incident particles were stopped in the telescope which had the double function of detector and target for inelastic reactions, a new experimental method in this domain. The electronic scheme set up in the experiment allowed a good energy resolution (11 % at 1 MeV) for BaF_2 and a low energy threshold (300 keV) for the chateau de cristal. The time resolution was 2 ns FWHM.

The incident particles were identified by a time of flight measurement with 70 m between the start and the stop detector, and the ΔE signal. Quasielastic events were selected by condition on the total energy deposited in the Si-telescope. The resolution of the total energy corrected for the momentum spread by the time of flight measurement was $2.–4.10^{-3}$, at the beginning and the end of the measurements respectively, the deterioration being due to radiation damage in the detectors. It was seen that this condition nearly completely suppresses the neutrons in the BaF_2 detectors. As an example the γ spectrum obtained for inelastic scattering of ^{34}Si is shown in Fig. 1.

§3. Search for the 0_2^+ in ^{34}Si

Most theoretical models[12)–15),17)] predict shape coexistence in ^{34}Si, a $Z = 14$, $N = 20$ nucleus, with a low lying deformed 0^+ state below the 2_2^+ state. Hence an isomeric monopole transition by pair creation or electron conversion to the ground state should exist. In all recent models the ground-state 0^+ of ^{34}Si is dominated by the spherical configuration. The first 2^+ state belongs essentially to the deformed $2\hbar\omega$ configuration. A strong mixing between the spherical and the deformed configuration is necessary to explain the experimentally measured B(E2) value to this state. A recent discussion of these effects can be found in Ref. 12) and references cited. Experimentally the 2^+ state is at 3.3 MeV, and the models predict the 0^+ state between 1.7 and 2.5 MeV. From formulas given in textbooks,[20)] it is seen that for energies above about 1.2 MeV, the transition should be by electron-positron pair creation, below this energy internal conversion (IC) should be dominant. Pair creation will be followed by a 511–511 keV γ radiation from the positron decay. No significant events were found in the lifetime domain of 1ns to 100 ns. Longer lifetimes should have been seen in standard experiments with radioactive beams, for e.g. on the Ganil LISE spectrometer, where routinely there is a search for γ isomers, with lifetimes of the order of the time of flight through the spectrometer or longer. For the detection of decay by IC, a Si(Li) followed immediately the Si-telescope. For IC, lifetime with reasonable monopole transition strength should be superior to μs. A quite large background from β decay of the secondary implanted beam exists. In order to sort out events corresponding to IC, we searched for events with a prompt γ in the energy domain of 2–3 MeV, followed by isomeric IC electrons. These events would correspond of a decay of the first 2^+ at 3.3 MeV to the 0_2^+ state followed by isomeric IC. If the 0^+ state is at such a low energy that IC is dominant, one would expect a strong branch from the 2^+ state. We could set a lower limit of 1% for this

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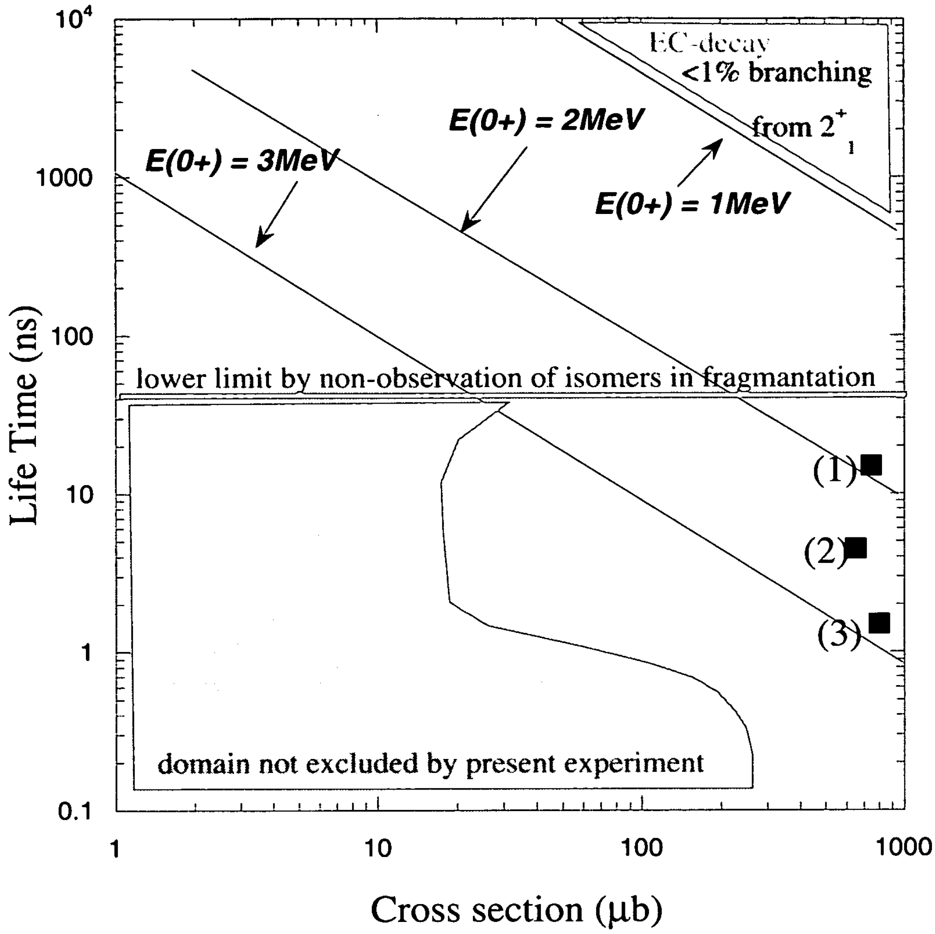

Fig. 2. Lifetime and inelastic scattering correlation for a monopole transition in ^{34}Si. Lines are labelled for different excitation energies of the 0^+ state. The lower limits obtained in the present experiment are given by the shaded area. The squares marked 1, 2, 3 correspond to values expected in the models.

transition.

Using standard relations for monopole transitions,[20] one can connect inelastic scattering cross sections, lifetime and reduced transition strength. As a result we can obtain cross section limits from the upper limits of the number of counts in the present experiment. This is shown in Fig. 2. Note however that these relations suppose equal or about equal nuclear and electric monopole strength. From the relations given in Ref. 20) and the wavefunctions published, we can calculate the expected values for the models of Refs. 17), 16) and 13). The values obtained are plotted in the figure, too. As can be seen from this figure, the existence of such a 0^+ state can likely be exluded from the present experiment. The experiment allowed us to set limits of the cross-section leading to the 0^+ state that are two orders of magnitude below the ones expected. Remember that the strong mixing necessary in the models to reproduce the quite high B(E2) value in ^{34}Si implies a strong reduced transition strength. Model predictions are shown in this figure too, and fall in a domain excluded by the present experiment. Only the model calculations of Ref. 14) would agree with the experiment, the 0^+ being in this reference above the 2^+ state. The theoretical predictions of Ref. 17) of the excitation energy of the second

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Table I. Energies and cross sections of γ rays observed in the present experiment. In parenthesis are given the experimental uncertainties. The cross section is the population cross section not corrected for feeding. When marked b, see text.

	E_γ[MeV]	$E_x[J^\pi]$	$\sigma_{\rm pop}$[mb]
^{28}Si	1.78	1.78 [2^+]	21 (5)
^{34}Si	3.33 (0.05)	3.326[2^+]	9.5 (2)
	0.94 (0.05)	4.255[3^-]	4.3 (1.5)
^{33}Al	0.73 (0.05)	[b]	5 (1)
^{32}Mg	0.86 (0.05)	0.885 [2^+]	40 (10)
	1.46 (0.05)	2.321 [b]	15 (5)

0^+ state for $N = 20$ nuclei are 2.59 and 2.52 MeV for ^{38}Ar and ^{36}S respectively, as compared to the experimental values of 3.377 and 3.346 MeV respectively. As can be seen, the theory does not well reproduce the known positions. So it might be that the postion of the 0^+ is inversed with the one of the 2^+ as compared to models. In the other theoretical predictions the positions of 0^+ states for other known $N = 20$ nuclei are not given.

Besides the search for the 0^+ state, we observed a strong γ line at E_γ=(950±50) keV after Doppler correction, that is assigned to the transition from the 3^- state at 4.255 MeV to the 2^+ state at 3.326 MeV.[16] The cross-section is given in Table I. No theoretical predictions of the transition strength are available. The cross-section to the 2^+ state is given in the table, too. When corrected for the feeding from the 3^- state (see Table I) we can calculate the ratio to the cross section to the 1.78 MeV of ^{28}Si from the detector material observed simultaneously. We find $R = 4\pm1.5$, in good agrement with the ratio of B(E2) values for ^{28}Si and the B(E2) value for ^{34}Si from Ref. 9), $R = 3.8\pm0.8$.

§4. Inelastic scattering of ^{33}Al

With the same set up we studied inelastic scattering of ^{43}Al. A new γ transition with (730±50) keV was observed. The cross section is given in Table I. It is close to the one observed for the 2^+ state of ^{34}Si, and nearly one order of magnitude lower than for the 2^+ state of ^{32}Mg (see below). In the shell model calculation of Ref. 21), a 2p-2h state of the same spin and parity as the ground state $5/2^+$, is predicted at 672 keV. The observed transition thus has the energy and the cross section that makes it an excellent candidate for this 2p-2h state, and the excitation energy is a measure of the 2p-2h energy gap.

§5. Inelastic scattering of ^{32}Mg

^{32}Mg has been the subject of many theoretical and experimental work. Mainly Coulomb excitation has been investigated. Only very recently nuclear inelastic scattering has been studied, limited to the 2^+ state at 885 keV.[23] The present experimental population cross section for this state is in good agreement with the one of Ref. 23) taking into account the difference of the target, here ^{28}Si instead of ^{12}C. In

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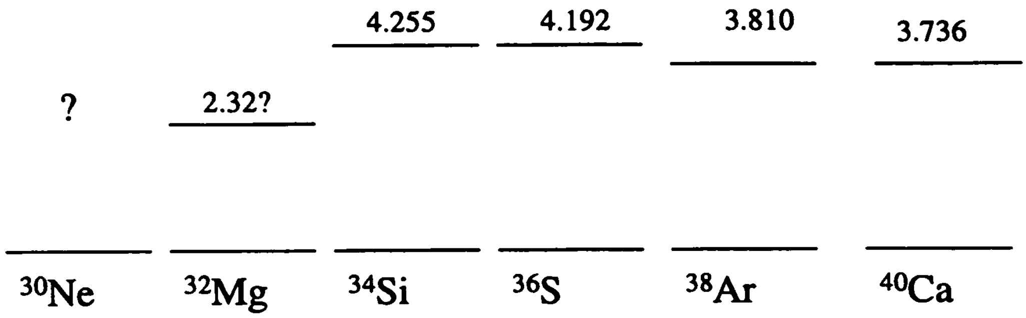

Fig. 3. The experimental position of 3^- states in MeV for $N = 20$ nuclei. The result for ^{32}Mg is from the resent work.

addition to this transition we observed a strong transition with E_γ=(1.47±0.05) MeV after Doppler correction. This transition can correspond to the decay of a state at 2.321 MeV to the 2^+ state.[22] This state is strongly populated in the β decay.[22] If the ground state of ^{32}Na is 3^- or 4^- as predicted in the shell model calculation, the parity of this state must be negative, and a 3^- is suggested in Ref. 22). The observed cross section is close to the cross sections observed for the 3^- state in ^{34}Si. For a 4^+ state that must be reached essentially in a two step process we would expect a much lower cross section. In a rotational or vibrational we obtain a ratio of about 1/20 for the 4^+ to the 2^+ cross section. It is a well known fact that in nuclear inelastic scattering the strongest transitions correspond to 2^+ and 3^- states. So this state at 2.321 MeV is an excellent candidate for a 3^- 1p-1h state. The energy is very low as compared to systematics of $N = 20$ in this region and to theoretical calculations[22],[21] that predict the first 3^- state at 2.90 MeV and 3.44 MeV respectively. This is illustrated by Fig. 3. No transition strength is given in these references.

§6. Conclusion

An upper limit of the cross-section leading to 0_2^+ below the 2_1^+ state in ^{34}Si either by direct inelastic scattering or by feeding via higher lying states could be established, rendering the existence of such a state very unlikely. This is in conflict with models that are otherwise extremely successful in this region.

Other new informations were obtained in the same inelastic scattering experiment. The transition probability in ^{34}Si to the 3^- state was measured, and a new transiton was seen in ^{33}Al. A candidate for a 3^- state was found in ^{32}Mg, that lies surprisingly low. As a general experimental conclusion we showed that inelastic nuclear scattering is a complementary tool to Coulomb excitation. Lower beam intensities may be used, and selection rules are different. 3^- states are strongly populated in this type of experiment, adding a new test for the models in this region far from stability.

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