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RADIOACTIVITY OF NEUTRON RICH OXYGEN, FLUORINE AND NEON ISOTOPES

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Радиоактивность нейтроноизбыточных изотопов кислорода, фтора и неона

Были зарегистрированы γ-излучение и нейтроны, испущенные после β-распада ядер ^{24}O, $^{25-27}F$ и $^{28-30}Ne$. Изотопы были получены фрагментацией пучка изотопа ^{36}S с энергией 78 МэВ/А, отселектированы спектрометром и идентифицированы по измеренным времени пролета и энергетическим потерям в детекторах. γ-излучение в совпадениях с β-распадом было измерено с использованием четырех больших Ge-детекторов, смонтированных вблизи точки имплантации. Нейтроны регистрировались с использованием сорока двух ^{3}He-счетчиков. Измеренные энергетические спектры γ-излучения были сравнены с вычислениями по оболочечной модели.

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Radioactivity of Neutron Rich Oxygen, Fluorine and Neon Isotopes

The γ-radiation and neutrons emitted following the β-decays of ^{24}O, $^{25-27}F$ and $^{28-30}Ne$ have been measured. The nuclides were produced in the quasi-fragmentation of a 78 MeV/A ^{36}S beam, separated in-flight and identified through time-of-flight and energy loss measurements. The ions were stopped in a silicon detector system, which was used to detect the β-particles emitted in their subsequent radioactive decay. The coincident γ-rays were measured using four large Ge detectors mounted close to the implantation point and the neutrons were detected using forty-two ^{3}He proportional counters. The measured γ-ray energy spectra are compared with shell model calculations and, where available, the level energies deduced from transfer reactions.

The investigation has been performed at the Flerov Laboratory of Nuclear Reactions, JINR and at the GANIL (France).

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I. INTRODUCTION

Nuclei possessing neutron/proton ratios radically larger than those of stable isotopes exhibit unexpected phenomena which have revolutionised our understanding of nuclear physics. Properties such as neutron haloes and the changing of shell closures are predicted for a wide range of extremely neutron rich nuclei, but it is only for the lightest elements that nuclei at the neutron drip line can presently be accessed experimentally and these properties investigated. Although the neutron drip line has probably been delimited for elements below neon [1,2] and atomic masses of many of these nuclei have been measured [3,4], comparatively little is known about their radioactive decay characteristics or spectroscopy [5]. Such measurements can probe important details of the underlying microscopic structures which give rise to the novel phenomena.

The energy spectra of excited levels for certain nuclei reasonably close to stability have been measured using transfer reactions [6-10], but rapidly diminishing cross-sections limit the range of nuclei which are amenable to study using this approach. A complementary tool is β-delayed γ-ray spectroscopy, which can probe a different subset of excited states and can measure level energies with a greater precision. In principle β-decay measurements can be applied to nuclei right up to the neutron drip line, provided that the nuclei of interest can be cleanly and efficiently separated and their radioactivity measured with high sensitivity. In the present work, β-delayed γ-ray and neutron emission has been studied for the first time in a range of neutron rich nuclei extending out to the A/Z=3 nuclides ^{24}O, ^{27}F and ^{30}Ne.

II. THE EXPERIMENTAL TECHNIQUE

The neutron rich nuclei of interest were produced by the quasi-fragmentation of a 0.5 μA 2.8 MeV/A beam of the rare isotope $^{36}S^{16+}$ in a range of tantalum targets mounted on carbon backings. Five different settings of the LISE3 spectrometer [11] were used to optimise the collection of different nuclei in turn, by adjusting the magnetic rigidity of the first dipole magnet of LISE3. The achromatic beryllium degrader and all subsequent elements of the spectrometer were left unchanged throughout the rest of the experiment. The selected nuclei were implanted into a stack of six silicon detectors located at the focal plane of LISE3. The first detector was 500 μm thick and provided energy loss and timing signals, which were used to obtain the unambiguous identification of the ions on an event-by-event basis. The ions subsequently passed through silicon detectors of thickness 500 μm, 300 μm and 500 μm, which provided redundant energy loss information. The final two detectors were 5 mm thick lithium drifted silicon detectors. The ions were stopped in the fifth element of the silicon detector telescope, while the sixth detector was used to veto light ions which were transmitted to the focal plane of LISE3 and passed through the fifth detector. The last three detectors were also used to detect β-particles emitted in the radioactive decay of the implanted nuclei. The efficiency for β-particle detection was determined to be 63±4%. A clock running at 10 kHz was used to time stamp all ion implantation and β-decay events in order to allow the measurement of half-lives.

The silicon detector telescope was surrounded on three sides by a total of forty-two cylindrical ^{3}He proportional counters, each encased in a polyethylene moderator, which were used to determine β-delayed neutron emission probabilities and were calibrated from known β-delayed neutron emitters produced in the experiment.

The energies of γ-rays emitted following β-decay were measured using four tapered germanium detectors, each of 70% relative efficiency [12], mounted in close proximity to the implantation point around 0° to the secondary beam direction. The germanium detectors were not housed in Compton suppression shields, in order to achieve a closer geometry, but were wrapped in lead foil to reduce cross scattering of γ-rays between the detectors. The thickness of the wall of the aluminium vacuum vessel containing the silicon detectors was reduced to 0.5 mm in order to minimise the attenuation of the γ-rays. The combined efficiency of the four germanium detectors was measured to be 2.1±0.1% at 1.33 MeV. The low energy thresholds of these detectors were set to ~100 keV

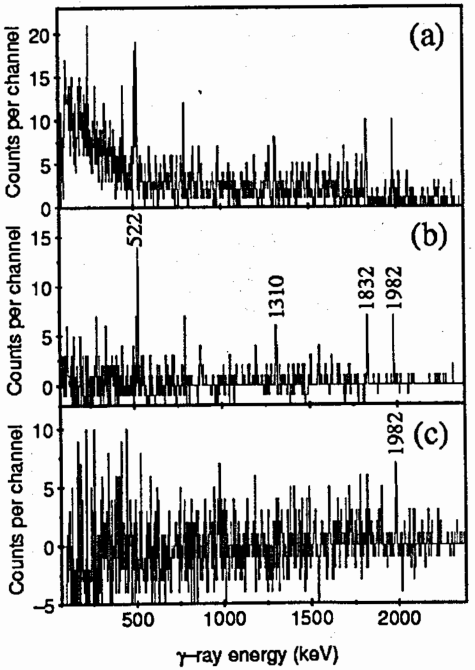

Fig.1. Energy spectra of a) all β-delayed γ-rays occuring within 200 ms of the implantation of a ^{24}O ion; b) the same spectrum following the subtraction of the background spectrum observed at this setting of the LISE3 spectrometer; and c) the background subtracted energy spectrum of β-delayed γ-rays occurring between 200 ms and 1 s after the arrival of a ^{24}O ion. γ-ray peaks associated with the β-decay of ^{24}O and its daughter ^{24}F are labelled according to their energy in keV.

III. THE DECAY OF ^{24}O

Approximately 9000 nuclei of ^{24}O, the heaviest bound oxygen isotope [1,2], were accumulated in the present experiment. The energy spectrum of all β-delayed γ-rays occuring within 200 ms of the arrival of a ^{24}O ion is shown in figure 1a and the corresponding spectrum after the subtraction of a normalised fraction of the appropriate overall background spectrum is shown in figure 1b.

Four γ-ray lines are labelled in this spectrum but the peak at 1982 keV is assigned as the known $2^+ \to 0^+$ transition energy in ^{24}Ne populated in the β-decays of the daughter nuclide

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^{24}F ($t_{1/2}$=340±80 ms [13]), rather than arising directly from the decay of ^{24}O itself. This interpretation is supported by the energy spectrum shown in figure 1c of β-delayed γ-rays which occur between 200 ms and 1 s after the arrival of a ^{24}O ion, which clearly shows a vestige of the 1982 keV line, whereas the other three lines present in the spectrum of figure 1b have decayed away.

The previous measurement of the β-delayed neutron emission probability of ^{24}O yielded a value of 58±12% [14], which raises the question of whether the remaining three γ-rays are emitted from levels in ^{24}F or from ^{23}F following neutron emission. Although no excited states are known in ^{24}F, the energy level spectrum of ^{23}F has previously been studied by Orr et al. [10]. Comparing the γ-ray energies measured in the present work with the energies of these known levels indicates that there is no correspondance between the two, suggesting that the γ-rays are emitted from levels in ^{24}F. This conclusion is supported by the lower value of 12±8% measured for the β-delayed neutron emission probability of ^{24}O using the ^3He proportional counters in the present work. Another independent estimate of the neutron emission probability was determined from the yield of the 1982 keV γ-ray, which has been measured to have a 100% emission probability in the β-decay of ^{24}F to ^{24}Ne [13]. The yield of this β-ray that indicates that 76±8% of the ^{24}O β-decays eventually feed the ^{24}F ground state, rather than leading to neutron emission, again indicating a lower emission probability than previously reported.

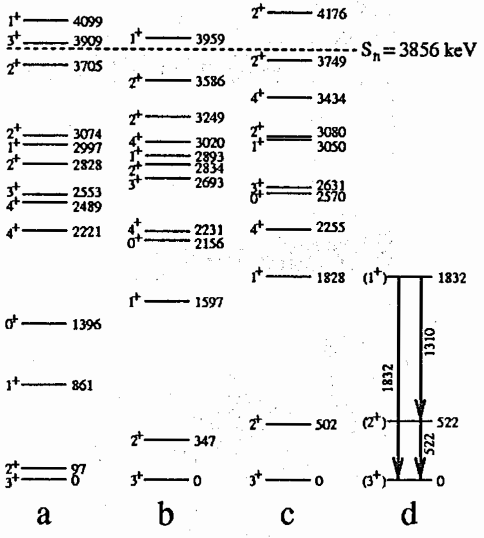

Fig.2. Energy levels of ^{24}F up to ~4 MeV calculated using the shell model code OXBASH [15] with a) the USD interaction [17]; b) the SDPOTA interaction [18] and c) the interaction of Chung and Wildenthal [16], compared with the tentative partial level scheme deduced in the present work. The energies of the levels and γ-rays are given in keV and the tentative spin and parity assignments for the deduced levels are in parentheses. The one neutron separation energy [19] is indicated by the dashed line.

The half-lives determined from the time difference between the arrival of a ^{24}O ion and the detection of a subsequent β-delayed γ-ray for each of the three γ-ray lines assigned to the decay of ^{24}O to ^{24}F are mutually consistent. Fitting the combined data yields a half-life of 65±5 ms, which compares with the previously reported value of 61^{+32}_{-19} ms [14]. By measuring half-lives using this technique, both the ion and the correlated β-decay event can be cleanly and unambiguously selected, thereby greatly reducing the problems of random correlations which can be encountered when only β-particles are detected.

The energies and intensities of the three γ-rays attributed to transitions in ^{24}F populated in the β-decay of ^{24}O are listed in table 1. It is noteworthy that the sum of the energies of the two lower energy lines equals that of the highest energy line within the uncertainties, suggesting that these transitions represent two separate decay paths between a common initial and final state. On the basis of the intensities alone, it is not possible to determine the relative ordering of the 522 keV and 1310 keV γ-rays since they are equal within the uncertainties, suggesting that there is little or no feeding of the intermediate level connecting these transitions.

The energy spectrum of excited states in ^{24}F has been calculated using the Michigan State University version of the shell model code OXBASH [15] using three different interactions proposed for *sd* shell nuclei [16-18]. The calculated level structures are shown in figure 2, from which it is evident that all three interactions predict the same sequence of lowest-lying levels although the precise energies of the levels differ. A possible partial level scheme consistent with the γ-rays identified in figure 1 is compared with these shell model calculations in figure 2. In this level scheme, a 1^+ level at 1832 keV is fed directly in the β-decay of ^{24}O and γ-decays directly both to the 3^+ ground state and to an intermediate 2^+ level at 522 keV. This tentative ordering of the 1310 keV and 522 keV transitions provides better agreement with the shell model calculations, which also predict that this lowest 1^+ level is strongly populated in the β-decay.

***Table 1.** Energies and intensities of γ-rays observed in the β-decay of ^{24}O to ^{24}F, corrected for the β-delayed γ-ray detection efficiency.*

E_γ (keV)	I_γ (relative)	I_γ (per 100 decays)
521.5±0.3	50.3±8.7	14.3±2.0
1309.5±0.5	43.2±10.6	12.0±2.6
1831.6±0.5	100.0±10.7	28.3±3.0

Within this level scheme, the absolute feeding intensity of the 1832 keV level is 40.3±4.0%. Taking the β-decay Q-value between the ground states to be 11430±315 keV [19], this corresponds to a log *ft* value of 4.30±0.13, which is consistent with an allowed transition. The β-decay to the intermediate 2^+ level cannot proceed by an allowed transition, which is compatible with the comparability of the measured intensities of the 1310 keV and 522 keV transitions. Combining the average of the β-delayed neutron emission probabilities measured in the present work and the observed β-decay strength feeding the proposed level at 1832 keV, approximately 40% of the total decay strength remains unaccounted for. Examining the shell model level schemes of figure 2 suggests that another 1^+ level could be expected at around 3 MeV, below the neutron emission threshold at 3856±103 keV [19]. If this level were mainly to decay directly to the ground state, the efficiency for detecting the emitted γ-ray in coincidence with a β-particle would be rather low (≈0.2-0.4 %), which could then provide a natural explanation for the present observations.

IV. THE DECAY OF ^{25}F

Although the β-delayed neutron emission and half-life of ^{25}F have been measured by Reeder et al. [20], the γ-rays emitted following the β-decay of this nuclide have not been previously studied. Approximately 40000 ^{25}F nuclei were collected in the present experiment and the energy spectrum of β-delayed γ-rays occurring within 200 ms of the implantation of a ^{25}F ion is shown in figure 3b. Owing to the comparatively long half-life of ^{25}F, this spectrum contains a significant contribution from the β-delayed γ-ray background observed at this setting of the LISE3 spectrometer, which is shown in figure 3a.

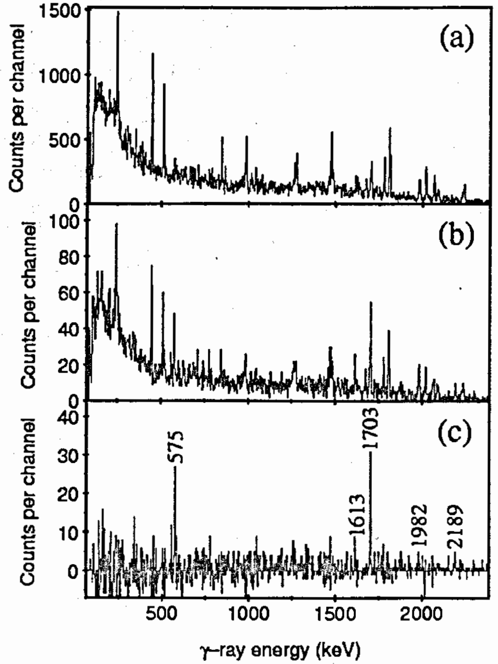

Fig.3. Energy spectra of a) all β-delayed γ-rays observed at the LISE3 spectrometer setting used to study the decay properties of ^{25,26}F; b) all β-delayed γ-rays occurring within 200 ms of the arrival of a ^{25}F ion at the focal plane of LISE3; and c) the same spectrum after the subtraction of a normalised fraction of the background spectrum, γ-rays associated with the β-decay of ^{25}F are labelled with their energy in keV.

Subtracting an appropriate fraction of this background spectrum gives the spectrum of figure 3c in which four γ-ray lines can be identified, in addition to the 1982 keV $2^+ \rightarrow 0^+$ transition in ^{24}Ne known from the β-decay of ^{24}F [13] and populated in this case following the emission of a neutron. (The 1982 keV γ-ray line in this spectrum is significantly broader than other lines in this energy region (9±1 keV FWHM compared with 4±1 keV FWHM), which is compatible with the Doppler broadening expected for γ-rays emitted following the emission of a neutron with an energy of around 1.4 MeV). None of these γ-ray energies correspond to transitions in the granddaughter nuclide ^{25}Na [21], so they are attributed to γ-rays emitted from levels in ^{25}Ne which are populated in the β-decay of ^{25}F. The absolute intensities of the γ-rays deduced from the spectrum of figure 3b are presented in table II. The half-lives extracted from the time difference between the arrival of a ^{25}F ion and the detection of a subsequent β-delayed γ-ray for each of the three most intense γ-ray lines are mutually consistent. They are also consistent with the value of 59±40 ms measured by Reeder et al. [20], supporting the above assignment. Combining these lifetime data, a value of 50±6 ms is deduced for the half-life of ^{25}F. The β-delayed neutron emission probability of ^{25}F was determined as 14±5% from the signals observed in the neutron detectors, which is consistent with the previously measured value of 15±10% [20]. This compares with the absolute intensity of 11±3% measured for the 1982 keV transition, which can be regarded as a lower limit for the β-delayed neutron emission probability of ^{25}F.

The energy level spectrum of ^{25}Ne has previously been studied by Wilcox et al. using the reaction ^{26}Mg(^{7}Li,^{8}B)^{25}Ne [6], who obtained evidence for levels at excitation energies of 1.65±0.05 MeV, 2.03±0.05 MeV, 3.25±0.08 MeV, 4.05±0.08 MeV and 4.7±0.1 MeV, and later by Woods et al. using the reaction ^{26}Mg(^{13}C,^{14}O)^{25}Ne [9]. This latter experiment identified peaks in the energy spectrum corresponding to excited levels at 1.74±0.03 MeV, 3.33±0.03 MeV, 4.07±0.03 MeV and 6.28±0.05 MeV, with the first two of these peaks each possibly comprising two unresolved components, separated by ~110 keV and ~200 keV, respectively. No evidence was found for peaks at 2.03 MeV or 4.7 MeV and the differences between the two studies are discussed in [9]. In constructing a level scheme from the measured γ-ray spectra, it is instructive to compare the γ-rays observed in the present work with the results of these transfer reaction studies and shell model calculations using the USD interaction [17], which has provided a very successful description of *sd* shell nuclei [22,23].

TABLE II. *Energies and intensities of γ-rays observed in the β-decay of ^{25}F, corrected for the β-delayed γ-ray detection efficiency.*

E_γ (keV)	I_γ (relative)	I_γ (per 100 decays)
574.7±0.5	24.3±2.8	9.5±0.9
1613.4±1.2	29.8±5.0	11.6±1.8
1702.7±0.7	100±6.7	39.1±2.6
2188.6±1.3	18.5±4.3	7.2±1.6

The shell model calculations predict spins and parities of $J^\pi=5/2^+$ and $1/2^+$ for the ground states of ^{25}F and ^{25}Ne, respectively, so β-decays directly to the ^{25}Ne ground state could not proceed by an allowed transition. Two levels are predicted close to an excitation energy of 1.7 MeV (see figure 4), both of which could be populated directly by allowed β-decays. On the basis of reaction mechanism considerations and calculated spectroscopic factors, Woods et al. argued that the peak they observed at 1.74 MeV was probably mostly due to the $3/2^+$ level predicted at 1687 keV. The shell model calculations predict that this level should be more strongly populated in the β-decay than the predicted 1779 keV $5/2^+$ level, suggesting that the

1703 keV γ-ray, which is the most intense line observed in the present work, could represent the decay of this 3/2$^+$ level to the ground state. The energy of this level would be consistent with those observed in both transfer reaction studies.

In principle, the γ-ray observed at an energy of 1613 keV could represent the decay of the second level predicted near 1.7 MeV to the ground state of 25Ne. However, the 1613 keV and 575 keV transitions sum to 2188 keV, suggesting that the three remaining γ-rays form two different decay paths between common states but no shell model states are predicted near 2.2 MeV.

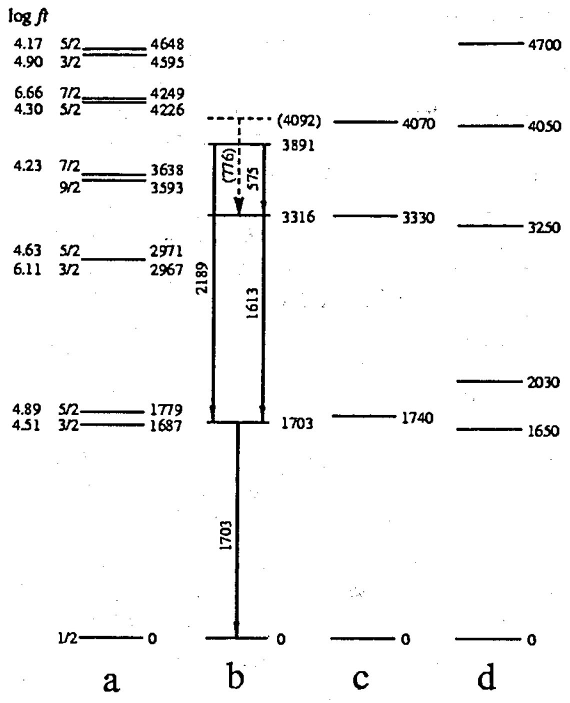

Fig.4. Comparison of a) energy levels of ^{25}Ne predicted using the shell model with the USD interaction [17], including calculated log ft values; b) the partial level scheme deduced in the present work; c) the energy levels identified by Woods et al. [9]; and d) the energy levels measured by Wilcox et al. [6]. The dashed lines and values in parentheses indicate tentative levels and transitions. The excitation energies of the levels and γ-ray transition energies are given to the nearest keV. See text for details of the widths of the levels measured in the transfer reactions.

An alternative possibility is that the 1613 keV transition represents the decay of a level at 3316 keV to the 1703 keV level. The energy of this level would also be entirely consistent with the energies observed in the transfer measurements. One difference is that Woods *et at.* argue that the level they observed is more likely to correspond to the 3/2$^+$ level predicted at 2967 keV than the 5/2+ level at 2971 keV, whereas the calculated log *ft* values suggest that the 5/2$^+$ level would be much more strongly populated in the β-decay of ^{25}F.

If the 575 keV γ-ray feeds this 3316 keV state, this would imply a level at an excitation energy of 3891 keV, which would be inconsistent with the energy of 4.07 ± 0.03 MeV measured by Woods *et al.* However, the shell model predicts a 7/2$^+$ level at 3638 keV and a 5/2$^+$ level at 4226 keV, both of which are expected to be strongly populated in the β-decay, although the latter level may lie above the neutron emission threshold of 4183±46 keV [19]. Furthermore, the 2189 keV γ-ray would fit naturally with this sequence as representing the decay of the 3891 keV level directly to the 1703 keV level. On the basis of these arguments, we tentatively interpret the four γ-rays observed in the present work as illustrated in figure 4. The level energies and feeding intensities are summarised in table III, together with the log *ft* values deduced from these values assuming the level scheme shown in figure 4. Each of these log *ft* values is consistent with an allowed β-decay.

A fifth γ-ray line which could only be tentatively assigned to a transition in ^{25}Ne was identified at an energy of 776.3±0.3 keV, with an intensity of 1.7±0.6 γ-rays per 100 ^{25}F β-decays. If this γ-ray were to feed the 3316 keV level it would imply a state at 4092 keV, which would be consistent with a level observed in both of the transfer measurements and the shell model predictions. However, this could create a potential disagreement with the shell model predictions since it would suggest there is little or no observed direct β-decay feeding of the 3316 keV level.

TABLE III. Energies and feeding intensities of energy levels in ^{25}Ne tentatively deduced from the β-decay of ^{25}F, corrected for the β-delayed γ-ray detection efficiency. The Q_β value between ground states has been taken as 13325±89 keV [19].

E_{level} (keV)	Feeding intensity (%)	log *ft*
3890.8±1.5	16.9±1.8	4.54±0.11
3316.1±1.4	2.2±2.0	5.55±1.15
1702.7±0.7	20.0±3.5	4.92±0.13
0	45.9±9.1	4.86±0.13

One possible explanation for this apparent discrepancy could be that there is another β-decay path from the 3316 keV level which could not be identified in the present experiment, presumably proceeding through the expected 5/2$^+$ level near 1.7 MeV, which the shell model calculations predict to be fed less strongly than the nearby 3/2$^+$ level. The large width measured for the 1.74 MeV level by Woods *et al.* [9] would also be consistent with this hypothesis. Another important possibility is that the 3316 keV level could decay directly to the ground state and the detection efficiency for such a high energy γ-ray would be very low (≈0.3 %) in the present experiment.

The observed γ-rays in the tentative level scheme of figure 4 and the measured β-delayed neutron emission probablity together account for only 53±8% of the total decay strength. There are several different possibilities which could account for some of this missing decay strength. The first of these could be the unobserved feeding of and through the 5/2$^+$ level expected near 1.7 MeV or the direct β-decay of the 3316 keV level to the ground state, as discussed above. Other high-lying levels which are expected and could decay directly to the ground state include the possible level at 4092 keV, for which the efficiency for detecting the γ-rays in coincidence with a β-particle would be ≈0.2 %, and a second state near 3.3 MeV, which is suggested by the transfer measurements [9] and shell model calculations. Clearly a further experiment with a greater efficiency for high energy γ-rays would be required to establish whether these are sufficient to account for the remaining decay intensity.

V. THE DECAY OF ^{26}F

The mass of ^{26}F has been measured [3,4], but its β-decay properties have not previously been investigated. Approximately 50000 ^{26}F ions were collected with the LISE3 spectrometer optimised for this nuclide, which was the same setting as for the ^{25}F data presented in the preceding section. The energy spectrum of β-delayed γ-rays occurring within 25 ms of the implantation of these ^{26}F ions into the silicon detector telescope is shown in figure 5a.

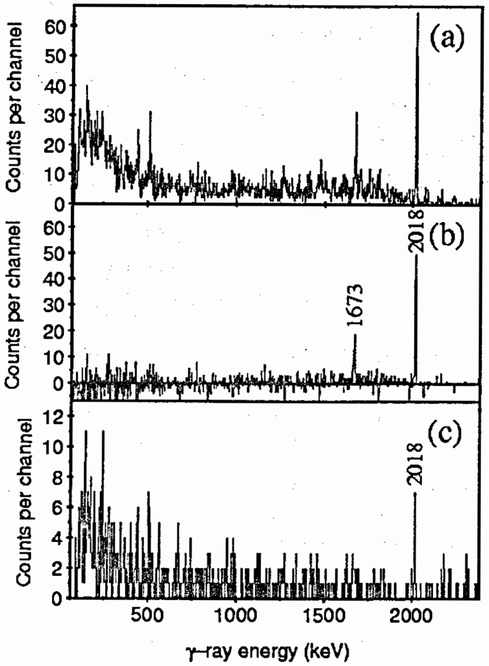

Fig.5. Energy spectra of a) all β-delayed γ-rays occurring within 25 ms of the arrival of a ^{26}F ion at the focal plane of LISE3; b) the same spectrum after the subtraction of a normalised fraction of the background spectrum of figure 3a; and c) all γ-rays observed within 50 ms of the implantation of a ^{27}F ion at the LISE3 focal plane, γ-ray lines associated with the decays of these nuclides are labelled according to their energy in keV in the lower spectra.

Comparison with the uncorrelated β-delayed γ-ray energy spectrum of figure 3a clearly shows that the observed γ-rays do not arise from random correlations. The background subtracted spectrum of figure 5b contains 2 prominent γ-ray lines at energies of 1673 keV and 2018 keV, which do not correspond to those previously measured for the β-decays of the daughter nuclides ^{25,26}Ne [13,21], or those reported above for the decay of ^{25}F to levels in ^{25}Ne. These γ-ray lines are therefore attributed to transitions in from excited states in ^{26}Ne populated in the β-decay of ^{26}F.

The half-life of ^{26}F was determined from the time differences between the arrival of ^{26}F ions at the focal plane of LISE3 and their subsequent β-delayed γ-decays. The decay curves obtained by gating on the 1673 keV and 2018 keV γ-ray transitions are shown in figure 6. The half-lives obtained from these data are mutually consistent, confirming that they originate from the decay of the same state. Combining all the data results in a first half-life measurement of 10.2±1.4 ms for ^{26}F.

The absolute intensities of the 1673 keV and 2018 keV γ-ray transitions after correcting for the energy dependent γ-ray detection efficiency are presented in table IV. Based on these intensities, the more intense line at 2018 keV is assigned as the $2^+ \rightarrow 0^+$ transition in ^{26}Ne, while the 1673 keV line is assumed to represent a β-decay to this 2^+ level (see figure 7). The relative intensities of the two lines and the absence of any other strong γ-ray lines clearly indicate that both levels are populated directly in the spherical scheme calculated in the spherical shell model using the USD interaction [17], which is compared with the experimental level scheme in figure 7. The observed higher-lying level at 3691 keV could in principle correspond to any of the 0^+, 2^+or 4^+ levels, depending on the ground state spin of ^{26}F. Shell model calculations predict that the ground state of ^{26}F has $J^\pi=1^+$, which would suggest that the 3691 keV level has $J^\pi=0^+$ or 2^+, assuming allowed β-decay transitions predominate.

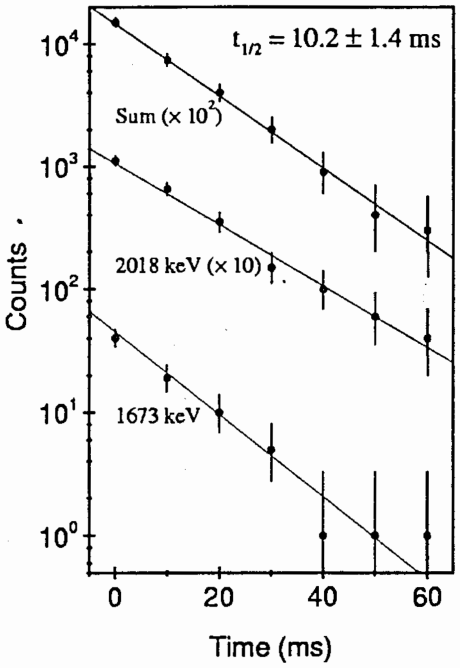

Fig.6. Decay curves for the two γ-ray transitions assigned to the β-decay of ^{26}F to levels in ^{26}Ne and the sum of these data. Each data set is plotted with the appropriate result of a maximum likelihood fit.

TABLE IV. Energies and intensities of γ-rays observed in the β-decay of ^{26}F, corrected for the β-delayed γ-ray detection efficiency.

E_γ (keV)	I_γ (relative)	I_γ (per 100 decays)
1673.0±0.3	27.7±4.1	18.7±2.2
2018.2±0.1	100.0±9.2	67.3±5.8

The daughter nuclide ^{26}Ne has previously been studied by Nann *et at.* [7] using the double charge exchange reaction ^{26}Mg(π^-,π^+)^{26}Ne. In addition to observing the ground state they obtained evidence for a peak comprising eight events at an excitation energy of ~3.75 MeV. From the kinematic constraints of their experimental technique, it was concluded that this was probably a 0^+ level. The energy of the state determined in the present work is consistent with that measured by Nann *et at.* Since

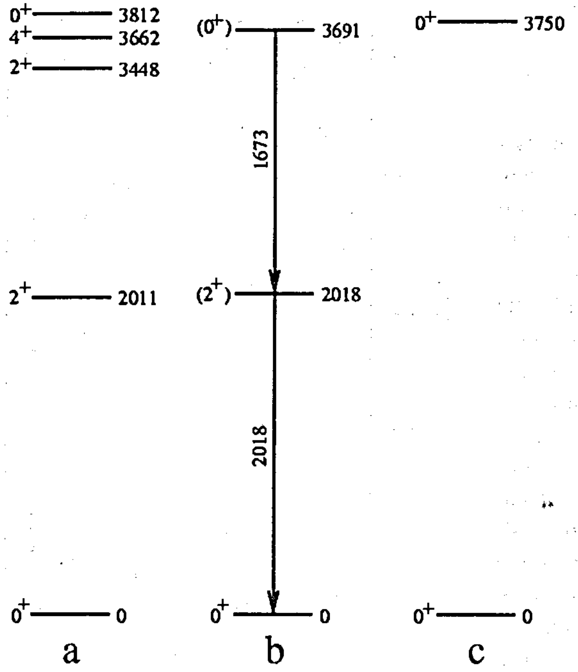

Fig.7. Comparison of a) energy levels of ^{26}Ne predicted using the shell model with the USD interaction [17]; b) the partial level scheme deduced in the present work; and c) the energy levels identified by Nann et at. [7]. The excitation energies of the levels and γ-ray transition energies are given to the nearest keV. The spin and parity values in parentheses indicate tentative assignments.

we would expect to observe this level in our measurement, assuming a $J^{\pi}=1^+$ ground state for ^{26}F, but no γ-rays attributable to other levels in this energy region are evident in our spectrum, we tentatively assign the 3691 keV level as the 0^+ level observed by Nann *et al.* This interpretation is reinforced by a comparison with the level scheme of ^{28}Mg [24], deduced from the β-decay of the $J^{\pi}=1^+$ ground state of ^{28}Na [25], in which the two most strongly populated excited levels are the first and second excited states with $J^{\pi}=2^+$ and 0^+, respectively. If the relative feeding strength of the second excited 2^+ level in the decay of ^{26}F were similar to that in the decay of its isotone ^{28}Na, the γ-ray intensity from this level to the ground state of ^{26}Ne would be below the sensitivity limits of the present experiment.

The β-delayed neutron emission probability of ^{26}F was measured for the first time in the present work as 11±4%. Combining this value with the absolute feeding intensities of the levels deduced in the above interpretation, 21.7±10.4% of the β-decay strength remains unaccounted for, the majority of which presumably feeds the ground state of ^{26}Ne directly, as suggested by shell model calculations.

From the measured absolute γ-ray intensities one can deduce the beta decay strength to each state within the above level scheme, assuming that the E2 γ-decay of the 3691 keV level predominates and that no other level is populated with significant strength in the β-decay. The feeding intensities and log *ft* values [26] deduced for each level are presented in table V, from which it can be seen that all of the decay strengths are consistent with allowed β-decay transitions.

***TABLE V.** Energies and feeding intensities of levels in ^{26}Ne deduced from the β-decay of ^{26}F, corrected for the β-delayed γ-ray detection efficiency. The Q_β value between ground states has been taken as 17858±135 keV [19] in the calculation of the log ft values.*

E_{level} (keV)	Feeding intensity (%)	log *ft*
3691.2±0.3	18.7±2.2	4.69±0.11
2018.2±0.1	48..6±6.6	4.53±0.13
0	21.7±10.4	5.15±0.35

The structure of ^{26}Ne is of particular interest since Sheline *et al.* [27] predicted that the nucleon numbers 10 and 16 both correspond to deformed shell gaps with a major to minor axis ratio of 2:1, or a β_2 deformation parameter of 0.6. Although the calculations were initially performed using an harmonic oscillator potential, more realistic potentials indicated essentially the same result [28]. In the case of ^{32}Mg, which has been shown to have a deformed ground state with $\beta_2 \approx 0.5$, the excitation energy of the lowest-lying 2^+ level is significantly lower than in neighbouring even-even magnesium isotopes. Figure 8 shows the excitation energies of even-even nuclei in this region, including the present measurement for ^{26}Ne.

It is evident that the excitation energy measured for the 2^+ level in ^{26}Ne is comparable with the known value of 1982 keV for ^{24}Ne [13], suggesting that the ground state of ^{26}Ne does not correspond to the predicted deformed configuration. This conclusion is supported by mass measurements which reveal no binding energy anomaly in the case of ^{26}Ne, in contrast to the deformed nuclide ^{32}Mg [4,7]. However, another possibility is that the 3691 keV 0^+ level could correspond to the deformed configuration, although the log *ft* value for this level does not suggest any significant reduction in β-decay strength arising as a result of a deformed shape. It is interesting to note that a recent shell model calculation predicts a value of $\beta_2 \approx 0.4$ for the first excited 2^+ state in ^{26}Ne, indicating that this state at least is highly deformed [29].

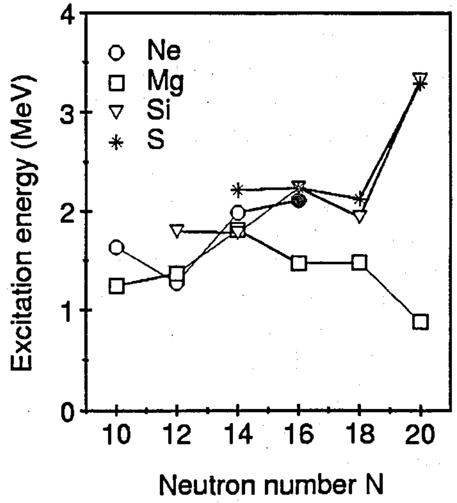

Fig.8. Excitation energies of the lowest-lying 2^+ states in even-even isotopes of neon (circles), magnesium (squares), silicon (triangles) and sulphur (stars). The energy of the 2^+ state in ^{26}Ne measured for the first time in the present work is indicated by the filled circle. The lines are drawn to guide the eye.

VI. THE DECAY OF ^{27}F

Approximately 10000 ^{27}F nuclei were produced in the present work, allowing the β-delayed neutron emission probability to be measured for the first time as 90±30%. The energy spectrum of β-delayed γ-rays occurring within 50 ms of the implantation of a ^{27}F ion into the silicon detector telescope is shown in figure 5c. Only a single γ-ray line is evident in this spectrum at an energy of 2018 keV, the energy of the $2^+\to0^+$ transition in ^{26}Ne identified above. This is compatible with the high measured neutron emission probability and the absolute intensity measured for this γ-ray line of 18.0±3.2% gives an indication of the relative population of the ground state and excited states in the neutron emission process. These measurements and the absence of any other γ-ray line in this spectrum are also consistent with the low neutron separation energy of 1408 ± 106 keV for ^{27}Ne [19] and shell model calculations, which predict that no excited levels below this threshold are strongly populated in the β-decay.

The half-life measured for ^{27}F in the present work from the time differences between the implantation of the ions and their subsequent β-decay was 6.5±1.1 ms, which compares with the value of 5.3±0.9 ms previously reported by O.Tarasov *et al.* [1]. At the same setting of the LISE3 spectrometer, approximately 650 atoms of ^{29}F were collected, from which a half-life of 2.9±0.8 ms was deduced, which is consistent with the previous measurement [1].

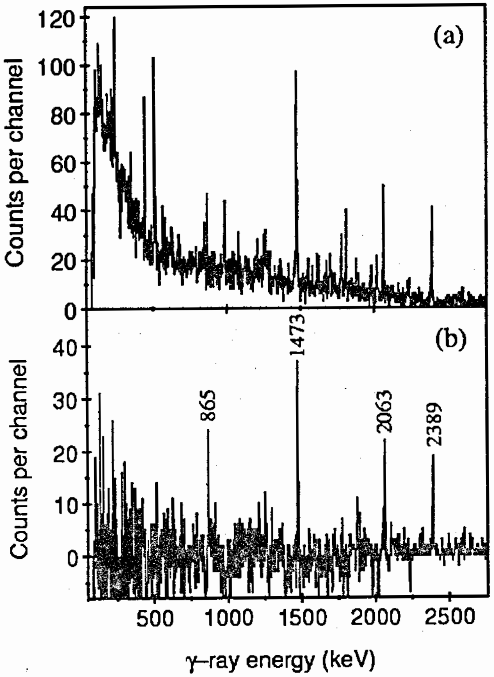

Fig.9. Energy spectra of a) all β-delayed γ-rays occurring within 50 ms of the arrival of a ^{28}Ne ion at the focal plane of LISE3; b) the same spectrum after the subtraction of a normalised fraction of the background spectrum, γ-ray peaks associated with the β-decay of ^{28}Ne and its daughter ^{28}Na are labelled according to their energy in keV.

VII. THE DECAY OF ^{28}NE

^{28}Ne was the most prolifically produced nuclide in the present work, with approximately 105000 ions being collected. The energy spectrum of β-delayed γ-rays observed within 50 ms of the arrival of a ^{28}Ne ion is shown in figure 9a and the corresponding background subtracted spectrum is shown in figure 9b.

Of the four clear lines evident in this latter spectrum, those at 1473 keV and 2389 keV are the most intense γ-rays known in the decay of ^{28}Na to ^{28}Mg ($t_{1/2}$=34.1±0.6 ms) [24]. The decay curves obtained by gating on the remaining lines at 865 keV and 2063 keV are mutually consistent and fitting these combined data yields a half-life of 18±3 ms. This value is consistent with the previously measured values for ^{28}Ne of 14±10 ms [20] and 17±4 ms [30], so these γ-rays are assigned to the decay of ^{28}Ne and their energies and intensities are summarised in table VI.

The β-delayed neutron emission probability of ^{28}Ne was determined as 11±3% in the present work, which compares with previously measured values of 16±9% [20] and 22±3 % [30]. Although these values are comparable with the intensity of the stronger 2063 keV γ-ray line, it is in principle possible that the γ-rays are emitted from levels in ^{27}Na rather than ^{28}Na. Only ~13000 ^{27}Ne ions were collected in the present work, which was insufficient to identify any β-delayed γ-ray transitions in ^{27}Na, which has not previously been studied. However, the energy level spectrum has been studied by Fifield *et al.* using the reaction ^{26}Mg(^{18}O,^{17}F)^{27}Na [8], but there is no evidence in the γ-ray spectrum of figure 9 for a line which could correspond to the decay of the first excited state in ^{27}Na at 1.72±0.04 MeV. Furthermore, the widths of the 865 keV and 2063 keV γ-ray lines show no sign of Doppler broadening, suggesting that they are not emitted following neutron emission. We therefore tentatively assign these γ-rays as emanating from ^{28}Na.

***TABLE VI.** Energies and intensities of γ-rays observed in the β-decay of ^{28}Ne, corrected for the β-delayed γ-ray detection efficiency.*

E_γ (keV)	I_γ (relative)	I_γ (per 100 decays)
864.5±0.4	17.5±2.3	3.3±0.4
2062.9±0.3	100.0±6.0	19.0±1.2

Since ^{27}Na is thie heaviest sodium isotope studied using transfer reactions, the γ-rays assigned to heavier isotopes can only be compared with shell model calculations. The level scheme calculated using the USD interaction is shown in figure 10. The ground state spin and parity of ^{28}Na has been determined to be 1^+ [24,25], rather than the 2^+ level which is predicted to lie 92 keV below the lowest 1^+ state.

Between the ground state and the one neutron separation energy of 3524±85 keV [19], the shell model calculations predict the existence of three excited 1^+ levels which could be populated by allowed β-decays of ^{28}Ne. Of these levels, the two higher-lying states at 2258 keV and 2796 keV are predicted to have lower log *ft* values than the state at 1658 keV. The γ-rays identified in the present work would therefore provide good agreement with the calculations if the 2063 keV transition were to correspond to the β-decay of the 1^+ level predicted at 2258 keV to the ground state, while the 865 keV transition could feed this excited state from a level at 2927 keV, corresponding to the predicted 1^+ level at 2796 keV. It is important to note that it is in principle possible that the observed γ-rays could feed the low-lying 2^+ state and that the β-decay of this level to the ground state is unobserved, being below the

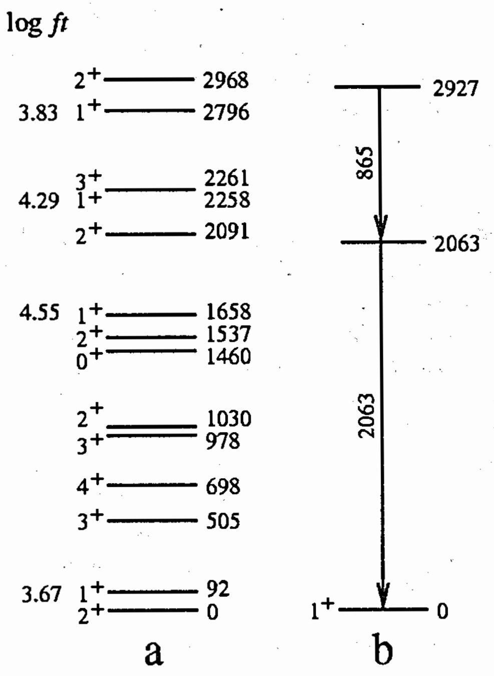

Fig.10. Comparison of a) energy levels of ^{28}Na predicted using the shell model with the USD interaction [17], including calculated log ft values, with b) the tentative partial level scheme deduced in the present work. The excitation energies of the levels and γ-ray transition energies are given to the nearest keV.

low energy threshold of ~100 keV of the germanium detectors. However, if this were the case one could expect to observe a second γ-ray line feeding the ground state just above the 2063 keV transition, but no evidence could be found for such a transition. We therefore propose the tentative partial level scheme which is compared with the shell model calculations in figure 10. No strong evidence could be found for γ-ray line at around 1.6 MeV, which could represent the decay of the predicted level at 1658 keV to the ground state.

Adopting the tentative level scheme discussed above, the feeding intensities and log *ft* values deduced are presented in table VII. The direct β-decay feeding of the ground state has been assumed to account for all of the unobserved decay strength in this table and results in a reasonable log *ft* value, although the unobserved feeding of the predicted 1658 keV level and any fragmentation of the β-decays of the higher-lying 1^+ states will serve to reduce the feeding of the ground state and hence increase the log *ft* value.

***TABLE VII.** Energies and feeding intensities of levels tentatively deduced from the -γ-rays observed in the β-decay of ^{28}Ne to ^{28}Na, corrected for the β-delayed γ-ray detection efficiency and the average β-delayed neutron emission probability of 16.4±2.1 % taken from previous measurements and the present work. The Q_β value between ground states has been taken as 12312±136 keV [19] in the calculation of the log ft values.*

E_{level} (keV)	Feeding intensity (%)	log *ft*
2927.4±0.5	3.3±0.4	4.81±0.19
2062.9±0.3	15.7±1.2	4.32±0.11
0	64.5±2.3	4.11±0.10

VIII. THE DECAY OF ^{29}NE

The energy spectrum of β-delayed γ-rays occurring within 50 ms of the arrival of a ^{29}Ne ion is shown in figure 11a and the corresponding spectrum after background subtraction is shown in figure 11b.

Although only 8600 ^{29}Ne ions were collected in the present experiment, it was possible to identify four γ-ray lines attributable to its β-decay. None of these γ-ray lines corresponds with the known γ-rays from the decay of the daughter nuclide ^{29}Na [24] or to those tentatively assigned to transitions in ^{29}Na in the previous section. These γ-rays are therefore tentatively assigned to transitions in ^{29}Na and their energies and absolute intensities are presented in table VIII.

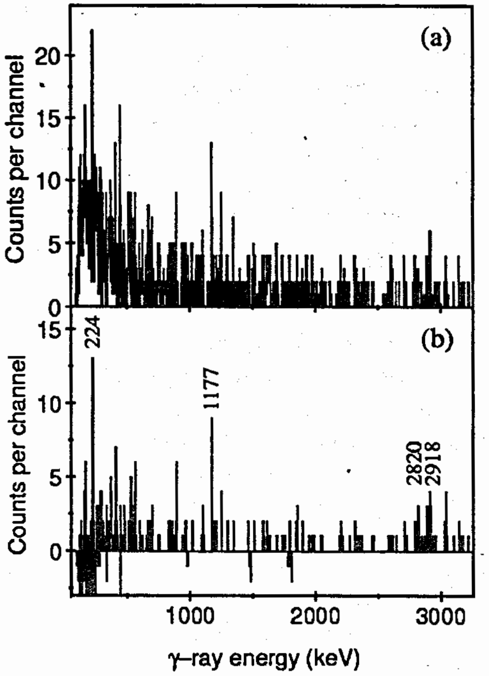

Fig.11. Energy spectra of a) all β-delayed γ-rays occurring within 50 ms of the arrival of a ^{29}Ne ion at the focal plane of LISE3; b) the same spectrum after the subtraction of a normalised fraction of the background spectrum. The γ-rays associated with the β-decay of ^{29}Ne are labelled with their energy in keV.

The 2918 keV γ-ray accounts for 55 % of the total decay strength and is significantly more intense than the other three γ-ray lines, suggesting that it perhaps represents the decay of a level directly to the ground state. However, the ground state spin of ^{29}Na has been determined as 3/2 from laser measurements [25] and has been assigned as having even parity [24], whereas shell model calculations using the USD interaction place the lowest $3/2^+$ level 137 keV above a predicted $5/2^+$ ground state. Consequently it is in principle possible that it could be this low-lying $5/2^+$ state which is fed by the γ-ray transitions and its β-decays to the true ground state are not observed because the excitation energy is below the detector threshold of ~100 keV. Alternatively, if the 2820 keV line were to represent the decay of a 2918 keV level to the $5/2^+$ state and the 2918 keV γ-ray fed the ground state directly, one would expect to see a 98 keV γ-ray line, but no evidence for this could be found. (The 96 keV γ-ray line from the β-decay of ^{20}N was clearly seen in the present experiment at a different LISE3 setting). This potential ambiguity cannot be resolved with the low level of statistics in this case and therefore prevents the construction of a level scheme for ^{29}Na.

The half-life of ^{29}Ne was determined from the time difference between the arrival the ions and their subsequent β-delayed γ-decays, gating on the three transitions identified above. Fitting the combined data yielded a value of 19±9 ms, which is consistent with the recently remeasured value of 15±3 ms [1].

TABLE VIII. Energies and intensities of γ-rays observed in the β-decay of ^{29}Ne, corrected for the β-delayed γ-ray detection efficiency.

E_γ (keV)	I_γ (relative)	I_γ (per 100 decays)
223.8±0.7	18.7±5.5	10.2±1.8
1176.5±1.0	32.8±9.4	17.2±2.9
***2820	***	***
2918.2±1.5	100.0±23.5	54.7±12.9

IX. THE DECAY OF ^{30}NE

Direct mass measurements [4] indicate that the inversion in shell model level sequences observed for the N=20 isotones ^{31}Na and ^{32}Mg may persist for ^{30}Ne. This conclusion is supported by several large scale shell model calculations [22,23,31] and has important implications for the decay properties of ^{30}Ne. The ground state of ^{30}Ne is expected to have a majority intruder (2ħω) character, whereas the ground state of ^{30}Na is mostly an *sd* shell (0ħω) configuration [32]. Consequently one would expect that the β-decays of the ground state of ^{30}Ne should mainly populate the 2ħω states in ^{30}Na.

Approximately 3000 ^{30}Ne nuclei were accumulated during the present experiment and the energy spectrum of β-delayed γ-rays occurring within 30 ms of their implantation is shown in figure 12.

A single γ-ray line at an energy of 150.6±0.2 keV is clearly evident in this spectrum. This transition accounts for 95±10% of the decay intensity but

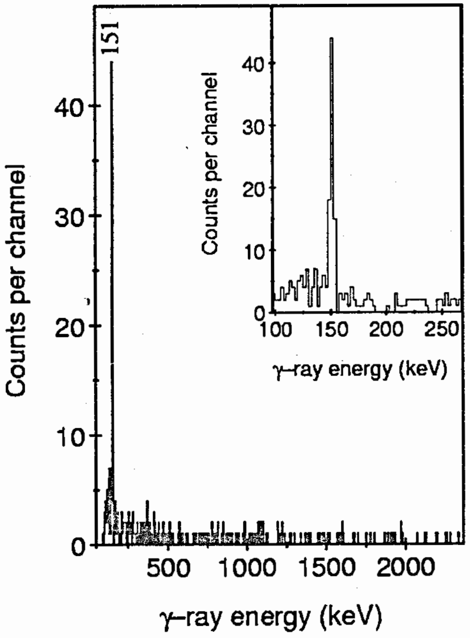

Fig.12. Energy spectrum of all β-delayed γ-rays occurring within 30 ms of the arrival of a ^{30}Ne ion at the focal plane of LISE3. The γ-ray line assigned to the decay of ^{30}Ne is labelled with its energy in keV. The inset shows a portion of the energy spectrum in the region around this γ-ray line.

is not known from the decay of ^{30}Na [24]. The β-delayed neutron emission probability of ^{30}Ne was measured for the first time in the present work as 9±17%, indicating that this γ-ray line must represent a transition in ^{30}Na. Furthermore, the half-life measured for ^{30}Ne from the time difference between the arrival of the ions and the events in the 151 keV β-delayed γ-ray line was 7±2 ms, which agrees with the previous measurement [1].

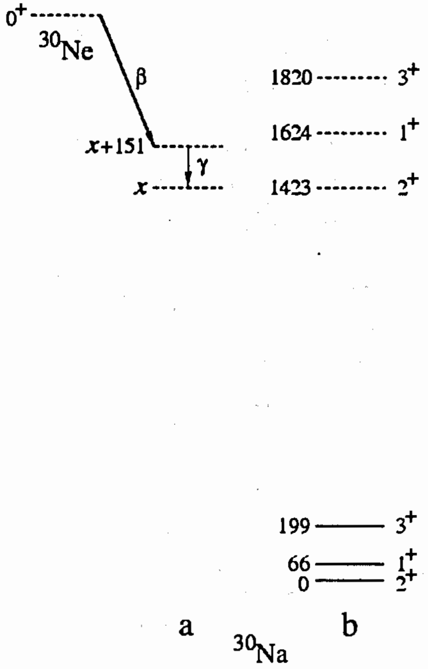

Fig.13. Comparison of a) the tentative experimental level scheme for ^{30}Na with b) shell model estimates of the lowest energy 0ħω and 2ħω levels calculated using the WBMB interaction [31]. The solid lines represent the energies of 0ħω levels, while 2ħω levels are indicated by the dashed lines. The relative energies of the lowest-lying 0ħω and 2ħω levels, denoted here by x, is unknown in ^{30}Na. See text for details of theoretical estimates of this quantity.

The lowest energy 0ħω and 2ħω levels in ^{30}Na calculated using the WBMB interaction [31] are shown in figure 13. The 1^+ level predicted to lie 201 keV above the 2^+ lowest 2^+ state is expected from the calculations to have the strongest direct feeding by an allowed β-decay from the ground state of ^{30}Ne, so we tentatively attribute the γ-ray identified in the present work to the decay of this 1^+ level to the 2^+ state.

The excitation energy of the lowest-lying 2ħω state above the 0ħω ground state in ^{30}Na is calculated to be 1423 keV in the present work, which compares with the previous estimates of ~1.9 MeV in ref. [23] and ~0.8 MeV in ref. [31]. The spin of the ground state has been determined to be 2 [25] and in principle one would expect the lowest 2ħω state eventually to decay by some path to this 0ħω ground state. However, no evidence could be found in the spectrum of figure 12 for any connect ing transition, although this may simply be a reflection of the comparatively low number of nuclei collected, the lower detection efficiency for higher energy γ-rays and a possibly fragmented decay path between the states.

Taking the average of the estimates of the excitation energy of the 2ħω state in ^{30}Na and assuming that all of the observed strength arises as a result of direct β-decay feeding of the level, the log *ft* value would be ~3.5, which is consistent with an allowed transition. Given that the one neutron separation energy of ^{30}Na is 2096±128 keV [19] and the next excited $2\hbar\omega$ 1^+ state is calculated to lie around 2 MeV above the $2\hbar\omega$ 'ground state', the conclusion that the observed transition represents essentially all of the strength not involving neutron emission is entirely consistent with the shell model calculations.

X. CONCLUSION

We have presented first β-delayed γ-ray measurements for 7 nuclides residing close to the neutron drip line and measured their half-lives and neutron emission probabilities. The γ-ray spectra have been interpreted through comparisons with shell model calculations and level schemes obtained from transfer reaction measurements, where available. Some of the nuclides investigated here are also the subject of Coulomb excitation and in-beam fragmentation γ-ray measurements [33] which potentially provide complementary information, as well as the prospect of measuring excited levels in nuclei such as ^{30}Ne where the β-decay precursors are unbound. Increases in the beam intensity and γ-ray detection efficiency soon to be available will offer new opportunities for extending the present studies, while in the more distant future it is conceivable that accelerated radioactive beams could herald the renaissance of transfer reactions being used to probe the energy level structure of extremely neutron rich nuclei.

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