Search for ^{28}O and study of neutron-rich nuclei near the N=20 shell closure

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A search for ^{28}O with a 78 AMeV beam of the neutron-rich isotope ^{36}S has been performed for the first time. Evidence for the unbound character of ^{28}O was obtained. In the same experiment the half-lives of the very neutron-rich isotopes ^{27,29}F and ^{30}Ne were measured and those for ^{28,29}Ne and ^{30,31}Na reexamined. The results are compared to shell-model predictions and conclusions drawn regarding the extent of the region of deformation around N=20.

1 Introduction

The study of the extremely neutron-rich isotopes of light elements is of considerable interest both for locating the neutron drip-line and for testing models describing the properties of exotic nuclei.

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The ground state properties of the neutron-rich oxygen isotopes were studied recently in several theoretical papers. In particular, a large basis shell model[1], a Skyrme-Hartree-Fock (SHF) approach[2], and a relativistic mean-field (RMF) theory[3] have been used to calculate the properties, including a possible, neutron halo of ^{28}O. Quadrupole excitation in ^{28}O was also examined by several authors within the framework of the random phase approximation [4–6]. The β-decay of ^{28}O was studied theoretically by Poves et al.[7] and found to exhibit β-delayed deuteron emission characteristics of a neutron halo.

Most mass formulae predict ^{26}O to be bound and the doubly-magic nucleus ^{28}O to be unbound against two-neutron emission [8]. However, in the predictions of Moller and Nix[8], Moller et al.[8] and Liran and Zeldes[9], the S_{2n} value for ^{28}O is positive. In their recent shell-model calculations, Poves et al.[7] found $S_{2n}(^{28}O)=1.3$ MeV. Similar positive values were found in the SHF[2] and RMF[3] calculations. The latter results suggest that from the theoretical point of view the question of the particle stability of ^{28}O is still open.

Perhaps the most interesting aspect of the N=20 region is the transition from spherical shapes to deformed ones, resulting in the so-called "island of inversion"[10–14]. A large $B(E2;0^+ \rightarrow 2^+)$ recently measured by Motobayashi et al. for ^{32}Mg [15] confirmed the deformation of this N=20 nucleus as suggested earlier by decay studies[16]. This phenomena was interpreted in the framework of the shell-model with inclusion of fp-shell intruder states [17,18].

The lack of experimental information on the very neutron-rich isotopes in the C-Al region is mainly due to the very low production cross sections. In this context the choice of nuclear reaction used to reach the neutron drip-line is crucial. The highest production are most often found in fragmentation reactions at energies above 30 AMeV. Moreover, the highest rates for neutron-rich products have been observed in the fragmentation of a neutron-rich primary beam[19]. Some of the new neutron-rich isotopes produced in this experiment have neutron numbers larger than that of the projectile implying that the pick-up of several neutrons from the target nucleus to projectile had occurred.

The heaviest experimentally known oxygen isotope is ^{24}O, ^{26}O being unbound[19]. The latest attempt [20] to synthesize ^{26}O by fragmentation of a 92 AMeV ^{40}Ar confirmed its instability. Interestingly, however, a new isotope in the vicinity of the ^{28}O, namely ^{31}Ne, was observed in the recent experiment with a ^{50}Ti beam at RIKEN[21].

The aim of the present work was to search for the existence of a bound ^{28}O nucleus and study the β-decay of nuclei in the N=20 region. The fragmentation of an intense beam of the neutron-rich isotope ^{36}S was chosen as the tool to produce these extremely neutron-rich nuclei.

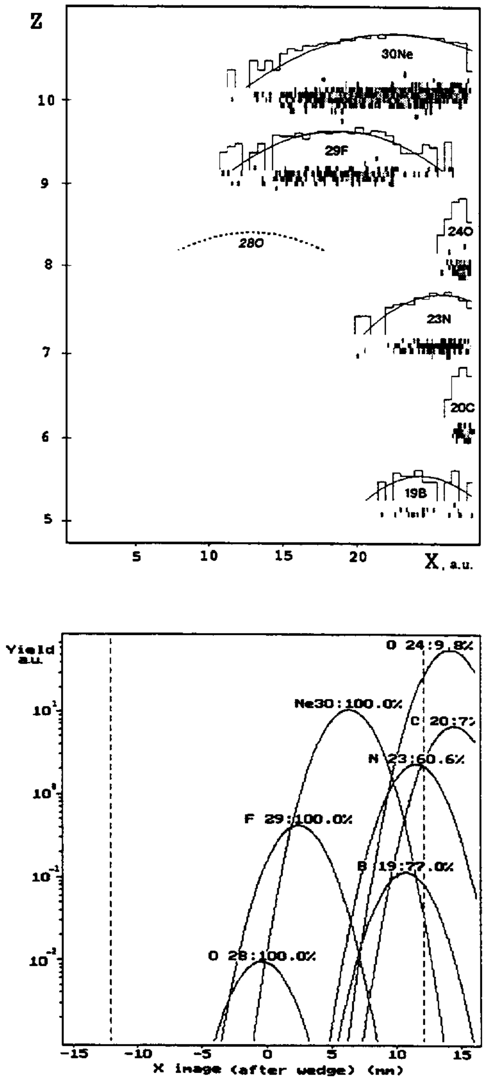

Fig. 1. Experimental (upper part) and calculated (lower part) position distributions for the isotopes transmitted through the LISE spectrometer as optimized for ^{28}O (see text).

2 Experimental procedure

The attempt to synthesize ^{28}O was carried out at GANIL with the doubly achromatic spectrometer LISE [22]. The fragmentation of a ^{36}S^{16+} (78.1 AMeV) beam with a mean intensity of 800 enA was expected to increase the production rate of the neutron-rich isotopes near N=20 with respect to the former experiments [19,20]. A further increase was obtained by the upgrading of the first dipole of the LISE spectrometer to allow rigidities up to 4.3 Tm. As a result, the yields for the neutron-rich isotopes in the region of interest (around ^{29}F) have been improved in comparison with our previous experiment[19] by a factor of 50.

The identification of the fragments was performed using the standard time-of-flight, energy loss and total kinetic energy (TKE) measurement method. A five-element semiconductor telescope, consisting of three planar surface barrier Si detectors with thicknesses of 300 μm, 300 μm, 500 μm and two 5 mm thick Si(Li) detectors, was mounted in a vacuum chamber at the achromatic focal point of LISE. The time-of-flight of the fragments was measured with respect to the radio frequency signal from the cyclotron.

The first three detectors allowed independent Z determinations to be made. The masses (A) and atomic charges (Q) of the nuclei were derived from the total energy, time-of-flight and magnetic rigidity measurements. The thickness of the telescope was chosen to stop the fragments in the region of oxygen-neon in the first 5 mm thick Si(Li) detector. One of the Si detectors was position sensitive and was used for the spatial analysis of the secondary beam. The signals from each of the Si(Li) detectors were split into two: one for residual energy measurements and another for the detection of electrons from the β-decay following the implantation of an ion. The implantation detectors were surrounded by ^{3}He neutron counters and a 70% HPGe detector for the measurement of β-n and β-γ coincidences and to search for microsecond isomeric states. The β-decay time spectra were obtained on an event-by-event basis using the time difference measured between the ion of interest and the first decay electron detected subsequently in the same detector. A Monte-Carlo simulation taking into account daughter decay and decay of other implanted ions was used to provide a background subtraction.

Measurements of the momentum distributions of all fragments with N=20 and an optimization of the target material (Be, C, Ni, Ta) and thickness were undertaken to determine the best setting of the LISE spectrometer for ^{28}O. It was found that the Ta target produced the highest rates for the neutron-rich nuclei of interest, in agreement with earlier experiments [19,21]. The detailed discussion of the momentum and yield distributions of fragments measured in the present experiment will be presented in a forthcoming publication [23].

To reduced the overall counting rate in the Si-telescope a 1047 μm thick Be achromatic degrader was placed in the intermediate dispersive plane of the spectrometer. The magnetic rigidity of the LISE spectrometer after the degrader was set to centre ^{28}O in the telescope. The position spectra for the isotopes of interest which were transmitted are shown in Fig. 1. These spectra are in good agreement with the computer simulation [24] of the horizontal images at the final focal plane thus confirming that the spectrometer was set for the optimum transmission of ^{29}F and ^{28}O. Two other settings of the spec-

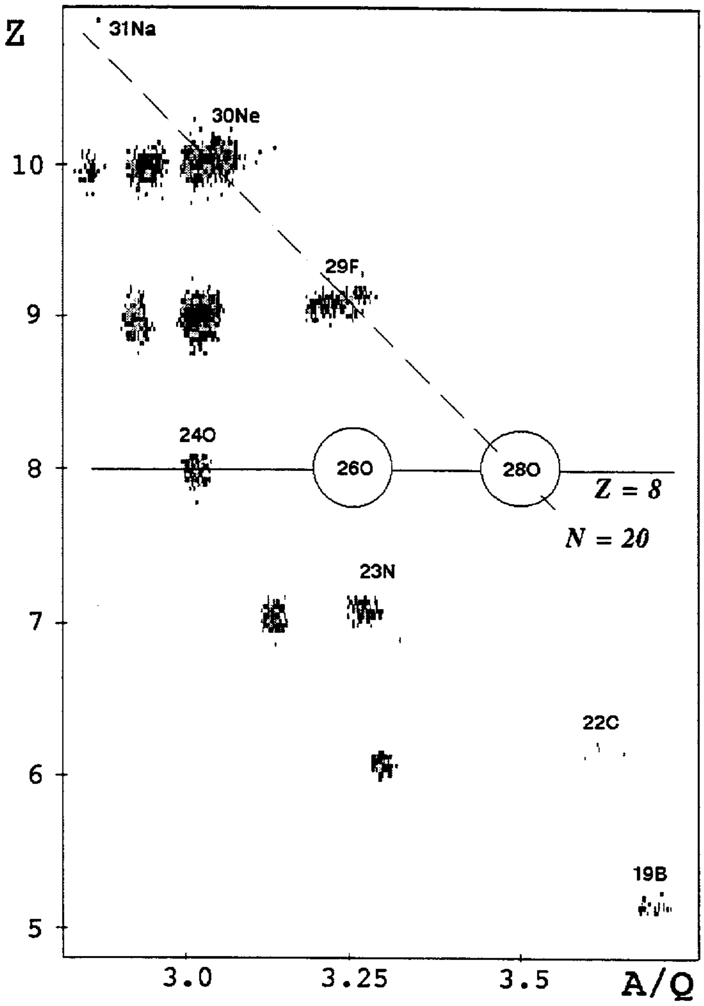

Fig. 2. Two-dimensional identification plot A/Q versus Z. No counts were observed corresponding to ^{28}O after 53 hours of irradiation of the Ta target with a 78 AMeV ^{36}S beam at 800enA (see text).

trometer optimised for the production of ^{27}F and ^{30}Ne-^{31}Na respectively were also used for the half-life measurements.

3 Results

3.1 Search for ^{28}O

The results of a 53 hour measurement with an average beam intensity of 800 enA are shown in Figure 2. A dashed line is drawn through nuclei with N=20. The heaviest known isotope of fluorine, ^{29}F, is clearly visible, for which 519

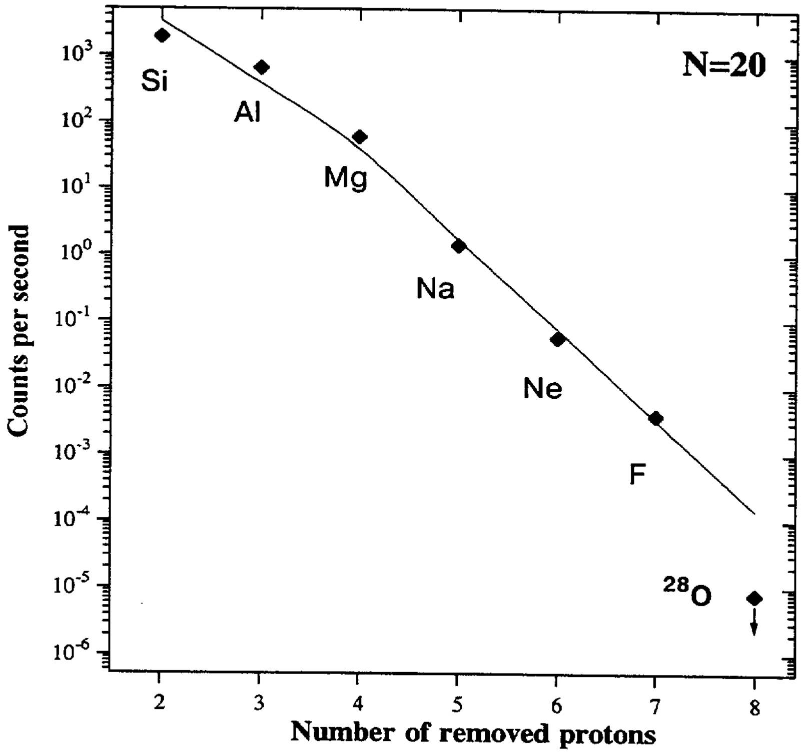

Fig. 3. Yields of the N=20 nuclei measured in the present experiment The solid represents yields calculated with the modified formula of Sümmerer et al.[24]. The point with arrow for ^{28}O corresponds to the upper limit of one event.

events were detected. In contrast no events corresponding to ^{26}O and ^{28}O were observed.

Figure 3 shows the experimentally measured yields for the N=20 isotones. According to the estimation given by the modified [24] formula of Sümmerer et al.[25] (solid curve) one would expect about 11 events in 53 hours corresponding to ^{28}O. The point with a vertical arrow is the counting rate corresponding to the observation of one event. The results of the present experiment indicate that ^{28}O is most probably particle unstable and confirms the earlier results for ^{26}O. Upper limits for the cross sections for the formation of the oxygen isotopes are estimated to be 0.7 pb and 0.2 pb for ^{26}O and ^{28}O, respectively.

3.2 β-decay of nuclei near neutron-shell closure N=20

The present experiment also provided an opportunity to study the β-decay of light neutron-rich nuclei in the vicinity of N=20. The experimental β-decay time spectra for ^{27,29}F and ^{30}Ne, shown in Fig. 4 provide the first measure-

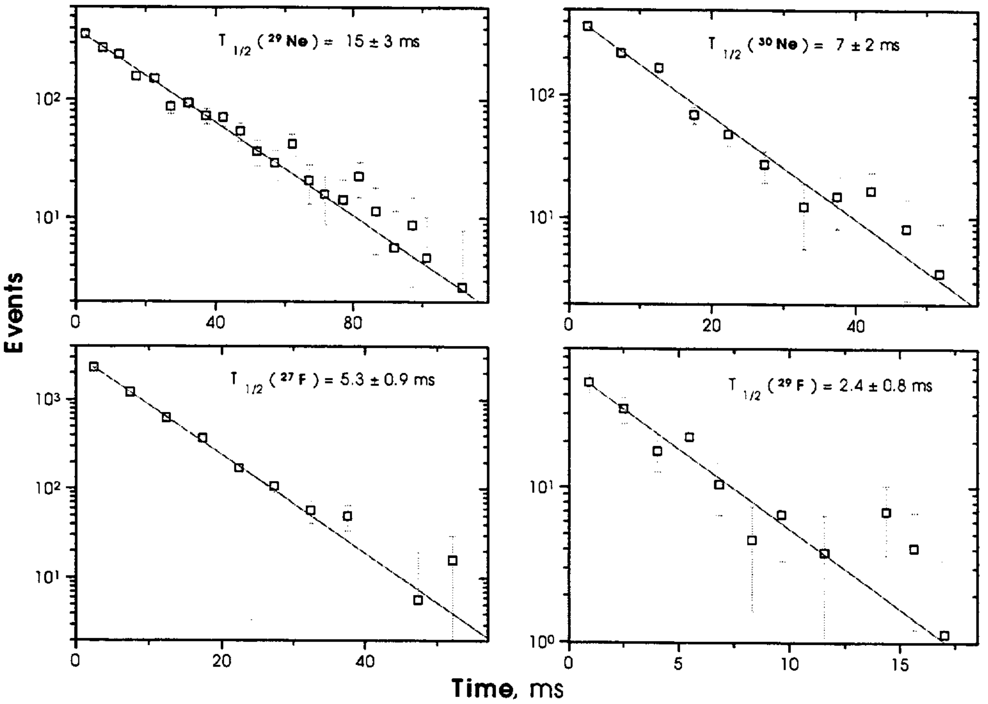

Fig. 4. The β-decay time spectra and corresponding half-lives measured for ^{27,29}F and ^{29,30}Ne.

Table 1

Experimental and shell-model(SM) half-lives in milliseconds and predicted (present work) ground state spin and parity for nuclei in vicinity of N=20

A,Z	Experiment this work	Other Experiments	SM[26]	SM this work	J$^{\pi}$
^{27}F	5.3 ± 0.9	-	7.8	4.7	5/2^{+}
^{29}F	2.4 ± 0.8	-	2.7	1.4	5/2^{+}
^{28}Ne	21 ± 5	17 ± 4[27]	16.9	12.9	0^{+}
^{29}Ne	15 ± 3	200 ± 100[27]	7.4	28.2	7/2^{-}
^{30}Ne	7 ± 2	-	3.7	17.8	0^{+}
^{30}Na	48 ± 5	50 ± 3[10]	24.7	56	2^{+}
^{31}Na	18 ± 2	17 ± 0.4[10]	11.8	16.4	3/2^{+}
^{31}Mg	-	230 ± 20[16]	27	308	7/2^{-}
^{32}Mg	-	120 ± 20[16]	11	195	0^{+}

ment of their half-lives ($T_{1/2}$). Additionally, ^{28,29}Ne and ^{30,31}Na have been remeasured. The experimental $T_{1/2}$ values are summarized in Table 1.

The measured half-lives for ^{28}Ne and ^{30,31}Na agree within the uncertainties with previous experiments[27,10]. The only important discrepancy is observed for ^{29}Ne; 15±3ms measured in this work and 200±100ms reported by Tengblad et al.[27]. The previous experiment, performed at ISOLDE, suffered from a high contamination of ^{87}Kr^{++} ions in the spectrum of the β-decay of mass 29 which, prevented an unambiguous measurement of the half-life of ^{29}Ne from being made. This problem was pointed out by the authors of ref. [27]. The present work used event-by-event correlation of the identified implanted ion in coincidence with the subsequent β-decay, thus providing a first reliable value for the half-life of ^{29}Ne.

To compare the experimental results with theoretical predictions, we have performed shell-model calculation for several isotopes in the N=20 region. Instead of including explicitly $n\hbar\omega$ mixing we determined the lowest state for fixed 0-particle 0-hole (0p0h), 1p1h and 2p2h excitations in the full sdfp space. The interaction of Retamosa et al.[30] which gives very satisfying results for $0\hbar\omega$ states around N=28 was used. In particular, use of this interaction correct reproduces a deformation occurring around ^{40}S and ^{42}S[29]. Gamow-Teller decays were computed from the lowest state predicted by the calculations. The results and comparison with experimental values and the calculations of Wildenthal et al.[26] are given in Table 1. Overall a relatively good agreement exists between our calculations and the experimental values. The results for ^{31}Mg and ^{32}Mg have been added to demonstrate the reliability of the calculations. The values for the spherical nuclei (^{27,29}F, ^{28}Ne and ^{30}Na) are slightly different from those of Wildenthal et al.[26]. This is essentially because of the values of the masses used, which were extracted from the recent compilation of Audi and Wapstra[31]. Importantly, in the calculations of ref.[26] the ground states (g.s.) are pure sd spherical states, while our deformed g.s. are sometimes 2 or 3 MeV lower than the spherical ones. For example, in the case of ^{31}Na, the half-life in the sd calculations was computed for the transition from the $3/2^+$ state instead of the deformed $5/2^+$ (g.s.) which is 1.5 MeV more bound. The calculation performed here suggests that the region of inversion where the fp-shell intruder configurations dominate the g.s. starts at Z=10 and N=19. This disagrees with the results of Poves et al.[18], where these limits were predicted at Z=9 and N=19. The disagreement may be explained by the larger model space and improved interaction used in the present calculations.

A more detailed analysis of the experimental results including the measured probabilities for the emission of delayed neutrons and observed β-γ decays will be presented in a forthcoming paper. A study of the new ^{32}Al^m isomeric state observed in the same experiment has been published elsewhere[28].

4 Summary

In summary, a dedicated search has been undertaken for ^{28}O. In a 53 hour measurement of the ^{36}S(78 AMeV) + ^{181}Ta reaction no events corresponding to the production of ^{28}O were observed. The upper limit for the production cross section was estimated to be 0.2 pb. The present experiment thus provides the first evidence for the particle instability of ^{28}O.

The half-lives measured in the present work for ^{27,29}F and ^{29,30}Ne and those measured previously for ^{30,31}Na and ^{31,32}Mg are in agreement with sd shell-model calculations which take into account the ground state mixing of the spherical sd-shell and deformed fp-shell intruder states.

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