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Particle stability of the isotopes ^{26}O and ^{32}Ne in the reaction 44 MeV/nucleon ^{48}Ca+Ta

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An attempt has been made to synthesize the extremely neutron-rich isotope ^{26}O in the nuclear reaction 44 MeV/nucleon ^{48}Ca+Ta. Use was made of magnetic separation and identification methods including time-of-flight and $\Delta E, E$ measurements. The ^{26}O nucleus appears to be unstable against particle emission since no events attributable to the ^{26}O nucleus were observed at a level one order of magnitude lower than that predicted from the extrapolated yields. The previously unobserved isotope ^{32}Ne was found to be particle stable and the isotope ^{31}Ne particle unstable. Neutron-separation energies calculated with different models are tabulated.

INTRODUCTION

The synthesis and investigation of the properties of the extremely neutron-rich nuclei for the light elements present considerable interest both for the localization of the neutron drip line and for the test of theories describing the exotic nuclei.[1–4] In the region of the extremely neutron-rich nuclei of the light elements new types of decay[5–14] and a new region of deformation are predicted; the latter may lead to an enhanced stability in these loosely bound nuclei and to the formation of new shells.[15–18]

At this time all the neutron-rich isotopes of the light elements up to nitrogen ($Z=7$), which are predicted to be particle-stable, have been synthesized.[19,20] In most of the theoretical work[21] nuclear stability is expected for the heavy isotope ^{26}O of the next element oxygen with the closed proton shell $Z=8$, whereas the stability of the doubly magic isotope ^{28}O is only predicted in work of Möller-Nix[21] (Table I).

Experimental[22,23] and calculated[20] two-neutron separation energies S_{2n} can be compared for the heavy isotopes ^{23,24}O for which the masses are known. It shows an underestimation by theories, with the difference $\Delta S_{2n} = S_{2n}(\text{expt}) - S_{2n}(\text{theor})$ up to 2 MeV. If this trend would persist for the heavier isotopes, then the isotope ^{26}O and, possibly, ^{28}O may well be stable.

In this work an attempt was made to synthesize the isotope ^{26}O in order to verify experimentally its nuclear stability. For this purpose an intermediate energy ^{48}Ca beam that had been found to be very efficient for the production of neutron-rich nuclei with $6 \leq Z \leq 18$ (Ref. 23) was used.

EXPERIMENTAL PROCEDURE

A ^{48}Ca beam at an energy of 44 MeV/nucleon was made using the Electron Cyclotron Resonance (ECR) Minimafios source of Grand Accelerateur National d'Ions Lourds (GANIL) as described in Ref. 24. The projectile-like fragments were collected at 0° by the triple-focusing magnetic analyzer Ligne d'Ions Super Epluchés (LISE).[25]

The search for the exotic nucleus ^{26}O, which is expected to have a very low production yield, was carried out using a four-stage semiconductor telescope consisting of two 300 μm and one 1-mm silicon detectors, and a 5.5-mm Si(Li) residual energy detector. These detectors were mounted inside a small vacuum chamber connected to the exit of LISE. The time of flight of the fragments between the initial (at the target) and final (telescope position) foci of LISE was measured.

The fragments were identified in a redundant way as

TABLE I. Two-neutron separation energy $S_{2n} = -M(A,Z) + M(A-2,Z) + 2\text{Mn}$ in MeV of the neutron-rich isotopes of oxygen predicted by different mass formulas (Ref. 21); MN, Möller-Nix; CKZ, Comay-Kelson-Zidon; SN, Satpathy-Nayak; T, Tachibana *et al*; JM, Jänecke-Masson; and comparison with experiments. An asterisk indicates an undetermined value.

Nuclide	MN	CKZ	SN	T	JM	Experimental S_{2n}	
	S_{2n}	S_{2n}	S_{2n}	S_{2n}	S_{2n}	Ref. 23	Ref. 22
^{23}O	7.15	9.22	8.0	7.45	9.19	9.59	9.67
^{24}O	4.91	6.16	6.78	4.20	5.96	6.98	5.79
^{26}O	0.67	0.87	5.32	1.26	0.96	*	*
^{28}O	0.7	−2.08		−0.13	−1.61	*	*

described in Ref. 24: The two first detectors allowed two independent Z determinations, the mass was derived from the total energy and the time of flight, or from the magnetic rigidity and the time of flight. This method provides a clear identification in atomic number and mass.

RESULTS AND DISCUSSION

It was shown[26] that the production yield of the neutron-rich isotopes at an intermediate energy is strongly dependent on the N/Z ratio of the target. In this experiment the choice of the target was properly studied in order to optimize the production of light isotopes at the neutron drip line.

This is shown in Fig. 1, where production counting rates of carbon to fluor isotope are displayed for targets of ^{9}Be, ^{64}Ni, ^{181}Ta whose thickness resulted in an equivalent energy-loss for the beam.

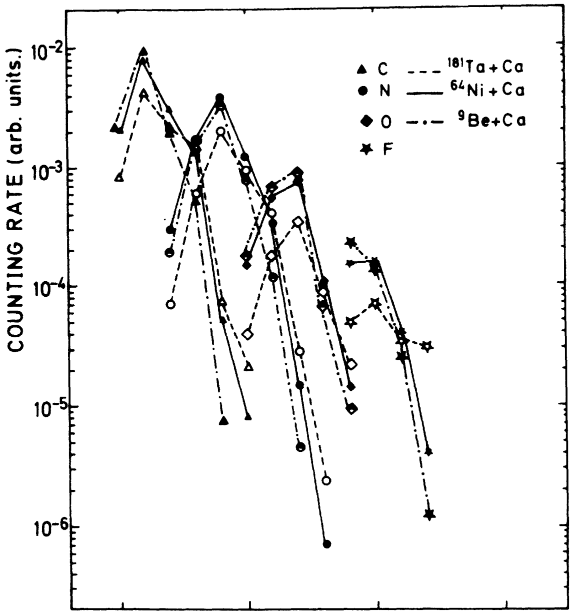

FIG. 1. Production rate for the isotopes of C,N,O,F, in arbitrary units, obtained with targets of ^{9}Be, ^{64}Ni, ^{181}Ta in interactions with a ^{48}Ca beam at 44 MeV/nucleon. The targets have the same equivalent thickness relative to the energy loss of the incident beam in order to keep the same set of the magnetic rigidity of the spectrometer optimized around ^{24}O.

It is clearly visible that for very neutron-rich isotopes the tantalum target is the most powerful target. For more stable isotopes the beryllium one is the best. This can be understood by the greater number of atoms per cm^2 available in the beryllium target as compared to nickel or tantalum.

From this study a 173 mg/cm^2 Ta target corresponding to about 10% of energy loss for the ^{48}Ca (44 MeV/nucleon) incident beam was chosen. The spectrometer was set to the magnetic rigidity $B\rho = 2.88$ T m, which optimizes the transmission for isotopes with $A/Z = 3.25$.

Figure 2 represents the two-dimensional plot (Z versus time of flight) obtained under these conditions after a 40-h measurement with an average beam intensity of 160 enA. The heaviest known isotopes ^{19}B, ^{22}C, ^{29}F, and the previously unknown isotope ^{32}Ne (four events) are clearly visible. The ^{31}Ne is particle unstable since no counts of this isotope are observed. The ^{25}O isotope, which is

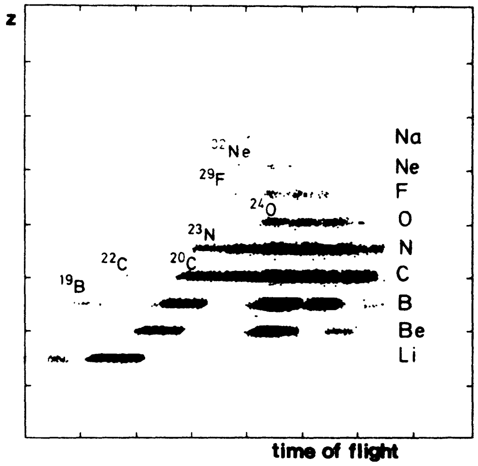

FIG. 2. Two-dimensional plot Z vs time of flight obtained in the fragmentation of the ^{48}Ca beam at 44 MeV/nucleon on a 173 mg/cm^2 tantalum target during a 40-h run at a magnetic rigidity $B\rho = 2.88$ T m of the LISE spectrometer. The ^{32}Ne isotope is clearly visible (four counts). A total of 220 events of ^{24}O has been recorded. No counts of ^{26}O are observed.

TABLE II. One-neutron and two-neutron separation energies in MeV of the neutron-rich isotopes of neon predicted by different mass formulas (see Table I).

Nuclide	MN		CKZ		SN		T		JM	
	S_{1n}	S_{2n}	S_{1n}	S_{2n}	S_{1n}	S_{2n}	S_{1n}	S_{2n}	S_{1n}	S_{2n}
^{31}Ne	−1.48	2.80	−2.61	0.17	1.24	6.39	−1.46	2.34	−2.25	0.76
^{32}Ne	1.58	0.10	1.09	−1.52	5.91	7.15	2.35	0.89	1.23	−1.02
^{33}Ne	0.36	1.94	−2.17	−1.08	2.95	8.86	−1.21	1.14	−2.35	−1.12
^{34}Ne	−0.02	0.34	1.20	−0.97	6.15	9.10	2.19	0.98	1.13	−1.22

known to be unstable, is clearly absent. No events corresponding to ^{26}O are seen.

Figure 3 shows the isotopic production along lines which proceed parallel to the drip line with neutron numbers $N=2Z-1$ (a), $N=2Z$ (b), $N=2Z+2$ (c) (note that the $N=2Z+1$ line essentially consists of isotopes known to be particle unbound). A smooth monotonous drop is observed along these lines. From this trend one may expect a production rate of about 30 counts for ^{26}O. Since it is almost impossible to explain the absence of 30 counts by statistical fluctuations, this experiment gives strong evidence for concluding that ^{26}O is particle unstable.

Table II gives the one-neutron and two-neutron separation energies for the isotopes of neon calculated with different mass prediction (see Table I). The result of the experiment for ^{31}Ne is in agreement with most predictions. For ^{32}Ne some of the calculations obviously underestimate the two-neutron separation energy by at least 1 MeV.

An analysis of particle stability for the neutron-rich isotopes of oxygen and neon within the framework of the quasiparticle Lagrangian method (QLM) (Refs. 27–30) has been carried out. This method proved[27,29] to be effective in describing the properties of the isotopes lying near the line of stability both for magic and ordinary nuclei. In previous work[28] it was shown that the QLM also ensures sufficient reliability in the prediction of the properties of nuclei far from the line of stability. In these calculations we applied the same parametrization of the Lagrangian, as that used in Refs. 27–30. Nucleon pairing with the parameter of the renormalized amplitude C_p equal to 1.4 MeV was also taken into account. This choice of the parameters provides the best agreement between the theoretical and experimental values of the one-neutron and two-neutron separation energies of the even-mass isotopes of oxygen with $A=18-24$ (Table III). The rms errors calculated by the standard method are relatively small, namely $\langle \delta S_{1n} \rangle = 0.54$ MeV and $\langle \delta S_{2n} \rangle = 1.15$ MeV.

In our calculations the isotope ^{26}O is found stable against one-neutron emission $S_{1n}(^{26}\text{O})=0.69$ MeV while two-neutron separation energy is approximately zero: $S_{2n}(^{26}\text{O})=-0.01$ MeV. If by any chance S_{2n} is indeed slightly negative, the presence of the centrifugal barrier for the two outer neutrons in the $d_{5/2}$ subshell would delay considerably two-neutron emission. This could lead to the formation of the quasistationary states of the system $^{24}\text{O}+2n$. The possibility of two-neutron emission from the ground state was discussed earlier[31] and two-

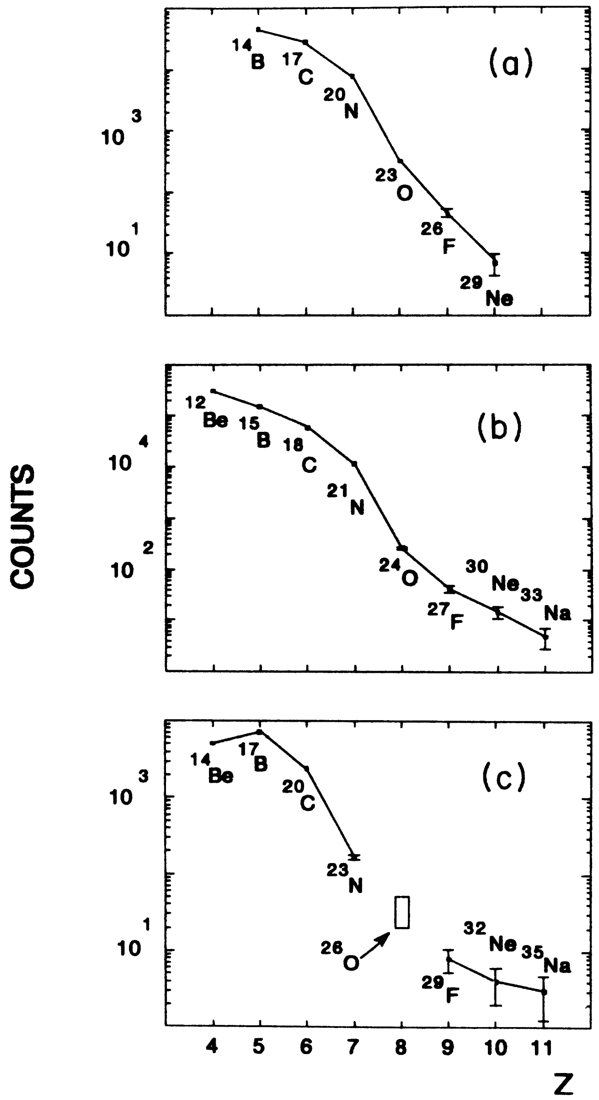

FIG. 3. Isotopic production along lines with neutron numbers $N=2Z-1$ (a), $N=2Z$ (b), $N=2Z+2$ (c). The error bars correspond to one-sigma statistical errors. From the smooth monotonous drop along these lines and the absence of any ^{26}O event, one can conclude to the particle-unbound character of ^{26}O (see the text).

TABLE III. The QLM calculations for the one-neutron S_{1n} and two-neutron S_{2n} separation energies of the even isotopes ^{18,20,22,24}O.

Nuclide	S_{1n} (MeV)		S_{2n} (MeV)	
	QLM	Expt. Refs. 22 and 23	QLM	Expt. Refs. 22 and 23
^{18}O	7.92	8.04	12.67	12.19
^{20}O	6.87	7.61	10.61	11.56
^{22}O	6.09	6.70	8.79	10.50
^{24}O	3.59	4.09	5.85	6.98

TABLE IV. The QLM calculations for the one-neutron and two-neutron separation energies of the $^{31-34}$Ne isotopes.

Nuclide	S_{1n} (MeV)	S_{2n} (MeV)
^{31}Ne	-1.04	1.84
^{32}Ne	1.74	0.70
^{33}Ne	-1.26	0.48
^{34}Ne	0.24	-1.02

neutron emission from excited states in ^{6}He isotopes was observed.[32]

The ^{28}O isotope is also predicted to be relatively stable against one-neutron emission, $S_{1n}(^{28}\mathrm{O})=0.51$ MeV, whereas two-neutron separation energy has a rather large negative value, $S_{2n}(^{28}\mathrm{O})=-0.8$ MeV in line with the calculations of Table I. Thus, the isotope ^{28}O seems to be unstable against two-neutron emission.

For neon isotopes, QLM calculations for one-neutron and two-neutron separation energies are given in Table IV. Odd neon isotopes with $A>29$ are unbound; ^{32}Ne is found to be the last particle-stable neon isotope. The calculations are in agreement with our experimental results.

The problem of the possible existence of deformation for neutron-rich nuclei arising in Na isotopes with $N \geq 20$ was first discussed in Refs. 15–18. However, the problem of a possible occurrence of deformation in the oxygen nuclei with stable proton structure and the possible influence of the deformation effects on the particle stability of ^{26,28}O could not be solved until recently. The study of neutron separation energy for oxygen isotopes has been performed both in spherical and deformed QLM calculations. Our analysis indicates spherical equilibrium shapes for all even oxygen nuclei.

The particle stability of ^{26}O and ^{28}O was also recently investigated[33] based on deformed Hartree Fock calculations using Skyrme III force and BCS pairing. It was shown that the ^{26}O isotope was very loosely bound and the ^{28}O isotope was particle unstable. Hence, it will be very interesting to check experimentally for the existence of ^{28}O. This may become possible in the near future when the intensities of the GANIL accelerator for metallic beams are upgraded by a factor 10.

CONCLUSION

This experiment used a high-intensity ^{48}Ca beam with an energy of 44 MeV/nucleon in the nuclear reaction ^{48}Ca+Ta. A total of 220 ^{24}O nuclei were detected. No events due to ^{26}O were recorded whereas, had it been particle stable, the extrapolated rate indicates more than some 30 ^{26}O nuclei should have been observed. This experimental result provides strong evidence that the neutron-rich isotope ^{26}O is particle unstable.

The calculations of the neutron-separation energy for ^{26,28}O performed within the framework of the QLM method including the potentials of both spherical and deformed nuclei have shown that the extremely neutron-rich isotope ^{28}O is unstable against two-neutron emission in its ground state and ^{26}O slightly unbound against two-neutron emission.

The particle unstability of ^{31}Ne is clearly demonstrated. A new extremely neutron-rich isotope ^{32}Ne (four events) is observed for the first time.

One may note that this work is a major step forward in mapping the neutron drip line which historically, has been a rather difficult experimental undertaking. Furthermore, the huge discrepancy between theoretical predictions and experimental result for ^{26}O underlines the importance of even basic identification experiment for putting constraints on nuclear models.

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