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INVESTIGATION OF THE PARTICLE STABILITY OF THE ISOTOPE ^{26}O IN THE NUCLEAR REACTIONS 44 MeV/A ^{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/A ^{48}Ca + Ta. Use was made of magnetic separation and identification methods including time-of-flight and $\Delta E, E$ measurements. With a sensitivity one order of magnitude higher than that predicted from the extrapolated yields no events attributable to the ^{26}O nucleus have been observed. Theoretical analysis of the problem of the particle stability of ^{26,28}O is being made.

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Исследование ядерной стабильности изотопа ^{26}O
в реакции 44 МэВ/А ^{48}Ca + Ta

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В ядерной реакции ^{48}Ca + Ta с энергией бомбардирующей частицы 44 МэВ/А предпринята попытка синтеза крайне нейтроноизбыточного изотопа ^{26}O. В эксперименте использовались магнитный сепарирующий канал и система идентификации на основе телескопа полупроводниковых детекторов ΔE, E и техники измерения времени пролета. С чувствительностью, на порядок более высокой по сравнению с предсказываемой, из экстраполяции выходов нуклидов в эксперименте не наблюдалось событий, относящихся к ^{26}O. Проведен теоретический анализ проблемы ядерной стабильности $^{26,28}O$.

1. Introduction

The synthesis and investigation of the properties of the extremely neutron-rich nuclei lying in the region of the light elements present considerable interest in terms of both the determination of the neutron drip-line and the choice of the most realistic theory capable of describing the exotic nuclei adequately [1-4]. In the region of the extremely neutron-rich nuclei of the light elements new types of decay [5-13] and a new region of deformation are predicted which may lead to a stability enhancement in the loosely bound nuclei and to the formation of new shells [14-17].

At the present time all the predicted neutron-rich isotopes of the lightest and light elements up to nitrogen with Z = 7 have been synthesized [18-20]. For isotopes of the next element, oxygen, with the closed proton shell Z = 8 in most of the theoretical works [21-25], nuclear stability is predicted for the heavy isotope ^{26}O, whereas the stability of the doubly magic isotope ^{28}O is predicted in the only work by Möller-Nix [21] (table 1).

The comparison of the experimental two-neutron separation energies S_{2n} (exp.) [26,27] with the calculated ones S_{2n} (theor.) [21-25] performed for the heavy isotopes $^{23,24}O$ with known masses shows a considerable underestimation by theories of the two-neutron separation energy $\Delta S_{2n} = S_{2n}(\mathrm{exp}) - S_{2n}(\mathrm{th.}) \leq 2$ MeV. If the indicated tendency in ΔS_{2n} persists for the heavier isotopes, then the nuclear stability of the isotope ^{26}O and, possibly, ^{28}O should also be expected.

Table 1. The stabilities of the neutron-rich isotopes of oxygen predicted by different mass formulae: MN – Möller-Nix [21], *CKZ – Comay-Kelson-Zidou* [22], *SN – Satpathy-Nayak* [23], *T – Tachidana et al.* [24], *JM – Janecke-Masson* [25]. *Two-neutron separation energy* $S_{2n} = -M(A,Z) + M(A-2,Z) + 2Mn$

Nuclide	MN S_{2n}	CKZ S_{2n}	SN S_{2n}	T S_{2n}	JM S_{2n}	exp. [27] S_{2n}
^{23}O	7.15	9.22	~ 8.0	7.55	9.2	9.59
^{24}O	4.91	6.16	6.78	4.2	5.96	6.98
^{26}O	~ 0.7	~ 0.8	~ 5.3	~1,3	~ 2.0	?
^{28}O	~ 0.7	unstable	unstable	unstable	unstable	?

In the present work an attempt was made to synthesize the isotope ^{26}O in order to verify its nuclear stability experimentally. For this purpose we used the reaction of an intermediate energy ^{48}Ca beam which proved to be very efficient for the production of neutron-rich nuclei with $6 \leq Z \leq 18$ [28].

2. Experimental procedure

A ^{48}Ca beam has been produced using the ECR Minimafios source of GANIL. Metallic ^{48}Ca was produced from a mixture of enriched calcium and aluminium powder. The mixture was compressed in a cylinder, and then loaded into a tantalum crucible fixed at the end of a tantalum rod. The rod was approached from outside to the hot plasma in the core of the ECR source. This procedure allowed one to produce high-intensity ^{48}Ca beams with an energy of 44 MeV/A. The projectile-like fragments were collected at 0° by the triple-focussing magnetic analyser LISE [29]. The LISE facility is a double achromatic spectrometer consisting of two dipole magnets D and the associated quadrupole focussing elements Q, as shown in fig. 1. It has two focal planes, the first F_1 being the momentum-dispersive one on which particles which different $B\rho$-values are focused at different positions, and the second F_2 — the achromatic one where all the particles are collectd into the same position. It is possible to collect all the fragments in a rather small spot and to install 4π-detectors of reasonable size for the decay studies.

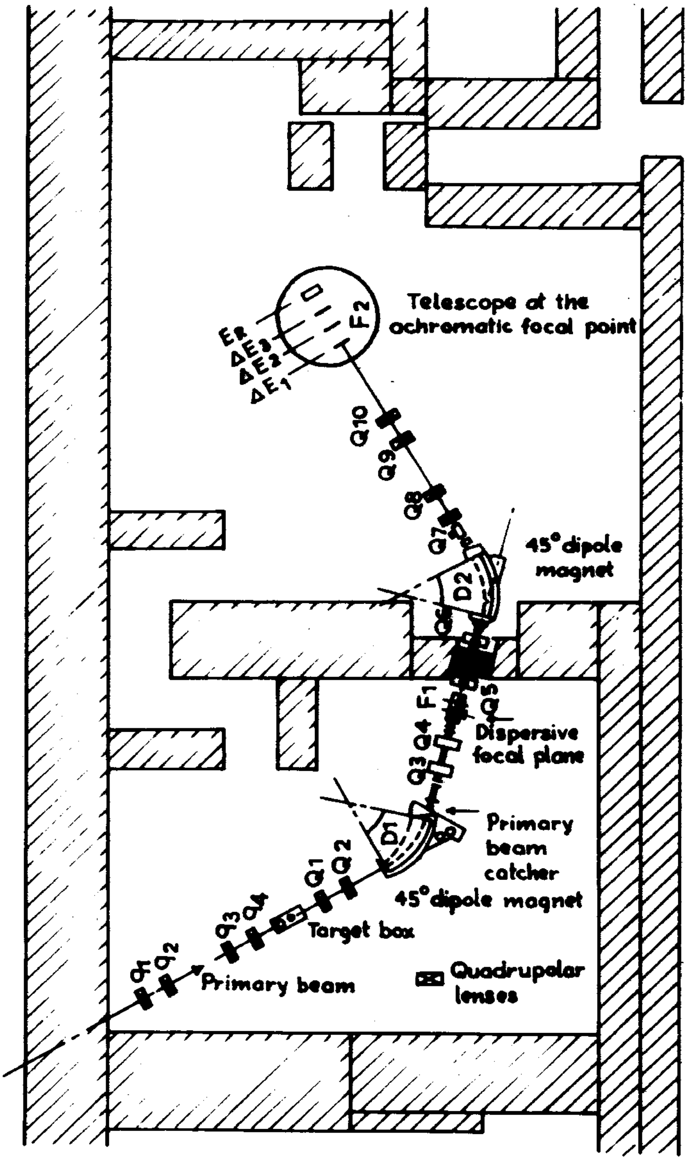

Fig. 1. Configuration of the analysing magnetic line QDQDQ (spectrometer LISE). q_1 -q_4 are quadrupole lenses of the transport channel for the ^{48}Ca projectile. Q_1 -Q_{10} are quadrupole lenses of the spectrometer LISE. D_1 and D_2 are the LISE magnetic dipoles. F_1 and F_2 are dispersive and achromatic planes. ΔE_1 , E_R are a semiconductor detector telescope.

For the detection of the exotic nucleus ^{26}O with a very low yield a four-state semiconductor telescope consisting of two 300 μm ΔE_1, ΔE_2, one 1 mm ΔE_3 and 5.5 mm Si(Li) residual energy detectors E_R is mounted inside a small vacuum chamber connected to the exit of LISE. The flight time of the fragments collected is measured between the initial (at the target) and final foci of LISE (telescope position). The time signal STOP is produced by an R.F. pulse from the last cyclotron and the time signal START comes from the E_R detector. The constancy of the correlation between the R.F. and the time of incidence on the target is monitored by a neutron detector mounted close to the primary beam catcher at the exit of the first dipole magnet. The time resolution obtained for the beam used in this experiment is better than 1 ns.

To avoid pile-up effects and ensure food energy and time resolutions the counting rate on the detectors was limited to some 10^3 events per second. This was done by limiting the momentum acceptance of the LISE spectrometer by means of movable slits in the intermediate focal plane F_1. A 5.3 mg/cm^2 Al foil was placed in order to suppress the low-intensity components of the incompletely stripped fragments. This Al foil served also as a degrader for improving isotopic separation.

The fragments were identified in a redundant way: the two first detectors independently allowed double 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 the clear identification of the atomic number and mass of exotic nuclei.

3. Results and Discussion

It was shown /30/ that the yield of the neutron-rich isotopes at an intermediate energy was strongly dependent on the N/Z ratio of the target. In the present experiment the yield of the known neutron-rich isotopes $^{22,23,24}O$ was obtained in the interaction of a 44 MeV/A ^{48}Ca beam with ^{9}Be, ^{64}Ni and ^{181}Ta targets (fig. 2). In fig. 2 it is seen that the maximum yield of the heavy isotope ^{24}O is produced on the Ta target. From an extrapolation of the yields to extremely heavy isotopes of oxygen one should expect the ratio $^{24}O/^{26}O$ to be equal to ~16. A 173 mg/cm^2 Ta target corresponding to an ~10% energy loss was chosen. The spectrometer was set to the magnetic rigidity $B\rho =$ $= 2.88$ T m optimized for heavy isotopes of the elements with $6 \leq Z \leq$ ≤ 11. Figure 3 represents the two-dimensional plot (energy loss versus time of flight) obtained under these conditions after 40-hour integra-

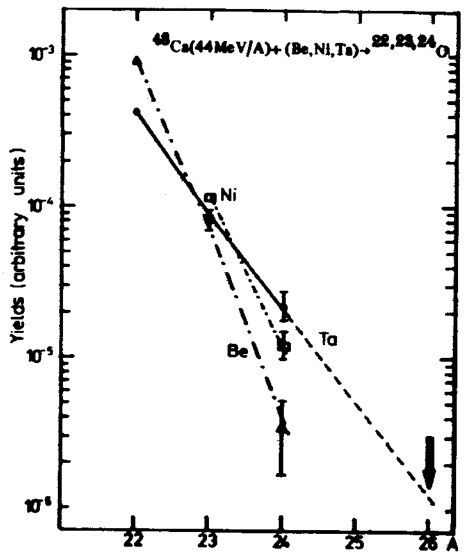

Fig. 2. Comparison of the experimental yields for the isotopes $^{22,23,24}O$ produced in the interactions of 44 MeV/A ^{48}Ca ions with ^{9}Be, ^{64}Ni and ^{181}Ta targets. The arrow indicates the extrapolation yield of ^{26}O for the most promising ^{181}Ta target.

tion with an average intensity of 150 nA. The heaviest known isotopes ^{19}B, ^{22}C, ^{29}F and the new superheavy isotope ^{32}Ne (4 events) are clearly visible. The unstable isotope ^{25}O is obviously absent but no counts due to ^{26}O are seen (broken-line rectangle).

In this run a total of 220 counts due to the isotope ^{24}O were observed and using the ratio of estimated yields, $^{24}O/^{26}O$, one should have observed more than ten events for the ^{26}O exotic nucleus. Nonobservation, in the present experiment with this sensitivity, of the ^{26}O events, can be evidence for its possible particle instability.

An analysis of particle stability for the neutron-rich isotopes of oxygen within the framework of the quasi-particle Lagrangian method (QLM) has been carried out /31-34/. This method proved /31,33/ to be efficient in describing the properties of the isotopes lying near the line of stability both for magic and ordinary nuclei. In work /32/ it was shown that the QLM method also ensures sufficient reliability in the prediction of the properties of nuclei far from the line of stability. In our calculations we applied the same parametrization of the efficient Lagrangian, as that used in work /31,34/. Nucleon pairing with the parameter of the re-normalized amplitude 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 2).

The r.m.s. errors calculated by the standard method are relatively small, namely, $<\delta S_n> = 0.54$ MeV and $<\delta S_{2n}> = 1.15$ MeV. The calculations for the one-neutron and two-neutron separation energies were carried out both for spherical and deformed shapes of the oxygen nuclei.

The problem of the possible existence of deformation shapes for neutron-rich nuclei arising at Z = 11, N ≥ 20 has first been discussed

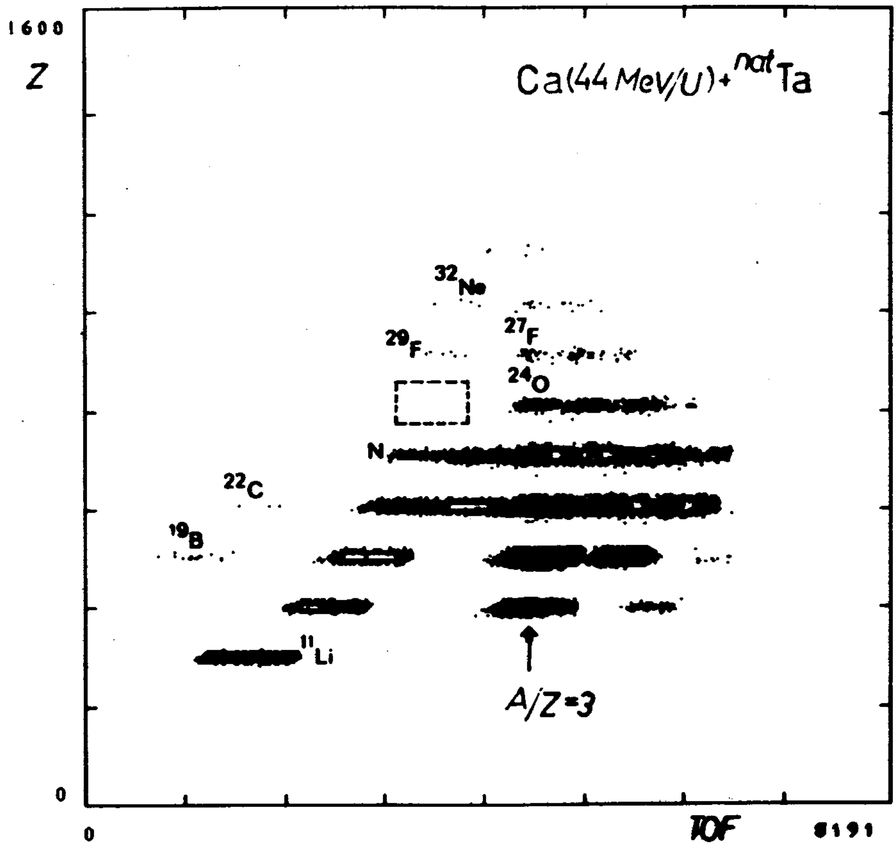

Fig. 3. Two-dimensional distribution of the events (ΔE res. TOF) due to the Li, Be, B, C, N, O, F and Be isotopes, which were detected during 40 hours of exposure at the magnetic rigidity Bρ = 2.88 T m of the spectrometer LISE. Four events due to the new ^{32}Ne isotope are observed for the first time. A total of 220 events has been recorded for ^{24}O. The place for the isotope ^{26}O is shown by a broken line.

in work[14-17]. However, the problem of the possible occurrence of deformation in the oxygen nuclei with proton structure stability (the closed proton shell Z = 8) and the possible influence of the deformation effects on the particle stability of ^{26,28}O was open until recently. In the present work we study the separation energy of one and two neutrons for the oxygen nuclei both deformed and spherical QLM calculations. The analysis showed that equilibrium shapes of all even oxygen nuclei are spherical ones. In our calculations the isotope ^{26}O is stable against one-neutron emission S_n (^{26}O) ≈ 0.69 MeV. The two-neutron separation energy was obtained to have a negative value and approxima-

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

Nuclide	S_n (MeV)		S_{2n} (MeV)	
	QLM	exp.	QLM	exp.
^{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

tely zero: $S_{2n}(^{26}O) \doteq -0.01$ MeV. Apparently the ^{26}O nucleus is unstable againts two-neutron decay. However, in the presence of the centrifugal barrier for two outer neutrons in the d-subshell with a rather small negative value of S_{2n} two-neutron emission would be delayed considerably. It can possibly lead to the formation of the quasi-stationary states of the system $^{24}O + 2n$. It is interesting to try to observe two-neutron emission from the ground state of ^{26}O. Earlier /35/ the possibility of two-neutron emission from the ground state was discussed and two-neutron emission from excited states in ^{6}He isotopes was observed /36/. The β-delayed emission of two neutrons was calculated in work /12/ . Studies of neutron emission from the ground state are now in progress.

The superheavy isotope ^{28}O is also relatively stable against one-neutron emission, $S_n(^{28}O) = 0.51$ MeV, whereas two-neutron separation energy has a rather large negative value: $S_{2n}(^{28}O) \doteq -0.8$ MeV. The isotope ^{28}O seems to be unstable against two-neutron emission.

It should be noted that the nuclear stability of the extremely neutron-rich isopotes $^{26,28}O$ was recently established in work /37/ in the deformed Hartree-Fock calculations using Skyrme 3-force and BCS pairing. It is shown that the ^{26}O isotope is very loosely bound, and the ^{28}O isotope is a particle unstable one.

4. Conclusion

In the present experiment using a high-intensity ^{48}Ca beam with an energy of 44 MeV/A in the nuclear reaction ^{48}Ca + Ta a total of 220

^{24}O nuclei have been detected. No events due to ^{26}O were recorded whereas in the case of its particle stability from the extrapolated ratio $^{24}O/^{26}O$ more than ten events attributable to the ^{26}O nuclei could be observed. This experimental result is likely to indicate the particle instability of the neutron-rich isotope ^{26}O.

The calculations of the neutron separation energy for $^{26,28}O$ performed within the framework of the QLM method in considering the potentials of both spherical and deformed nuclei have shown that the extremely neutron-rich isotopes $^{26,28}O$ are unstable against two-neutron emission in their ground states. It is possible that if the centrifugal barrier exists for two outer neutrons in the system $^{24}O + 2n$, a long-lived quasi-stationary state may be formed which would be a candidate for two-neutron decay from the ground state. In our experiment a new extremely neutron-rich isotope ^{32}Ne (four events) has been observed for the first time.

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References

1. Baz A.J. et al. — Light and Medium Mass Nuclei near the Limit of Nucleon Stability (in Russian). M.: Nauka, 1972.
2. Hamilton J.H., Hansen P.G., Zganjar E.F. — Rep. Prog. Phys., 1985, 48, p.631.
3. Detraz C. — Proc. Inter. Nucl. Phys. Conf., Harragate, UK, August 1986, IOP publishing Ltd, v.2, p.495.
4. Guerreau D. — J. Phys. C-4, 1986, 47, p.207.
5. Migdal A. — Soviet J. Nucl. Phys., 1973, 16, p.238.
6. Detraz C. et al. — Phys. Lett., 1980, 94B, p.307.
7. Azuma R.E. et al. — Phys. Lett., 1980, 96B, p.31.
8. Laugevin M. et al. — Nucl. Phys., 1987, A366, p.449.
9. Detraz C. et al. — Nucl. Phys., 1983, A402, p.301.
10. Langevin M. et al. — Phys. Lett., 1983, 130B, p.251.
11. Langevin M. et al. — Phys. Lett., 1984, 146B, p.176.
12. Lyutostansky Yu.S. et al. — Phys. Lett., 1985, 161B, p.9.
13. Borge M.J.G. et al. — Nucl. Phys., 1986, A460, p.373.
14. Thibault C. et al. — Phys. Rev., 1975, C12, p.644.
15. Campi X. et al. — Nucl. Phys., 1975, A251, p.193.

16. Detraz C. et al. — Nucl. Phys., 1983, A394, p.378.
17. Lyutostansky Yu.S. et al. — 5th Int. Conf. on Nucl. far from Stability, Rosseau-Lake, Ontario, Canada, 1987, AIP Conf. Proc. 164, I.S.Towner ed., p.727.
18. Langevin M. et al. — Phys. Lett., 1985, B150,p.205.
20. Jonson B. et al. — 5th Int. Conf. on Nuclei far from Stability, Rosseau-Lake, Ontario, Canada, 1987, AIP Conf. Proc. 164, I.S.Towner ed., p.223.
21. Moeller P., Nix J.R. — At. Data and Nucl. Tables, 1988, 39, p.213.
22. Comay E. et al. — At. Data and Nucl. Data Tables, 1988, 39, p.235.
23. Satpathy L., Nayak R.C. — At. Data and Nucl. Data Tables, 1988, 39, p.241.
24. Tachibana T. et al. — At. Data and Nucl. Data Tables, 1988, 39, p.251.
25. Janecke J., Masson P.J. — At. Data and Nucl. Data Tables, 1988, 39, p.265.
26. Wapstra A.H. et al. — At. Data and Nucl. Data Tables, 1988, 39, p.281.
27. Wouters J.M. et al. — Z. Phys., 1988, A331, p.229.
28. Guillemaund-Mueller D. et al. — GANIL Preprint 88-14, 1988.
29. Ann R. et al. — NIM, 1987, A257, p.215.
30. Barrette J. et al. — XXII Int. Winter Meeting on Nucl. Physics, Bormio, 1984.
31. Khodel V.A., Saperstein E.E. — Phys. Reports, 1982, 92, p.182.
32. Zverev M.V., Saperstein E.E. — Sov. J. Yad. Fiz., 1985, 42, p.1082.
33. Khodel V.A. et al. — Nucl. Phys., 1987, A465, p.397.
34. Migdal A.B. — Theory of Finite Fermi Systems and Properties of the Atomic Nucleus, M.: Nauka, 1983.
35. Godansky V.J. — JETP, 1960, 39, p.497.
36. Bochkarev O.V. et al. — Sov. J. Pisma in JETP, 1985, 42, p.303.
37. Nishimura M. — Report RCNP-TH 87-03, 1987.

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