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MASS MEASUREMENTS OF ^{21}O AND ^{22}O

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1. Introduction

In recent years considerable progress in the studies of light nuclei with large neutron excess has been made. For the production of these nuclei the fragmentation reactions induced by high energy protons have been used with great success by Poskanzer et al.[1,2], Thomas et al.[3], and by Klapisch et al.[4]. In our previous papers (see for example refs.[5,6]) it was shown that also the multinucleon transfer reactions induced by heavy ions are very useful for the production of neutron-rich nuclei. The particle stability of 28 new isotopes in the region $6 \leq Z \leq 17$ has been demonstrated in this way. However, the properties of the new nuclei have not yet been investigated.

The mass of the nucleus is one of the basic characteristics of its ground state. Garvey, Kelson and coworkers[7,8] found the mass relations which may be used to predict the experimentally unknown nuclidic masses by extrapolation from the regions in which the masses are already measured. However, the masses of light nuclei are known only in the region close to the β-stability

valley, hence, the extrapolation to the extremely neutron-rich region is not reliable. For more accurate mass predictions and for reliable predictions of the limits of particle stability the measurements of nuclear masses for nuclei with large isospin T_z are required.

In the region $Z \leq 15$ only the masses of nuclei with $T_z = 2$ or less are known, while the predicted[8] limits of neutron stability comprise the nuclides with T_z -values as large as 6 for oxygen isotopes, and 9 for magnesium isotopes. Recently, Scott et al.[9] have measured the mass of ^{29}Mg ($T_z = \frac{5}{2}$) using the $^{26}Mg(^{11}B, ^{8}B)^{29}Mg$ reaction. In this paper we report the results of direct mass measurements for ^{21}O ($T_z = \frac{5}{2}$) and ^{22}O ($T_z = 3$) from the $^{232}Th(^{22}Ne, ^{21}O_{g.s.})^{233}U_{g.s.}$ and $^{232}Th(^{22}Ne, ^{22}O_{g.s.})^{232}U_{g.s.}$ reactions. The ^{21}O and ^{22}O nuclei, together with even heavier oxygen isotopes (^{23}O and ^{24}O), were previously observed with quite large cross sections as products of multinucleon transfer reactions on heavy targets[5]. Therefore, reactions of this type were chosen for the mass measurements of ^{21}O and ^{22}O.

2. Experimental Method

The $^{22}Ne(+4)$ beam with intensity $1.5\mu A$ and energy 174 MeV from the 310 cm cyclotron of JINR in Dubna was used to irradiate a 2.5 mg/cm^2 target of metallic ^{232}Th. The reaction products were detected at 40° with respect to the beam direction, i.e., near the angle corresponding to the grazing trajectory, where the angular distribu-

tion of the reaction products should reach the maximum. The reaction products passed the magnetic spectrometer and were detected in a telescope of two solid-state, surface barrier detectors: a ΔE detector of thickness 59 μm (or 37 μm) and an E detector. Pulses from both detectors were fed into a converter for two-parameter pulse-height analysis. A selected region of the two-dimensional ΔE, $E - \Delta E$ spectrum was recorded in the 4096-channel analyser, operating in the 64 x 64 channel mode. This detection method combining the magnetic analysis and the ΔE-E technique makes possible an unambiguous identification of the reaction products in a wide range of Z and A (see for example ref. /6/).

Energy spectra of the reaction products were obtained from the measurements of the product yields at different magnetic fields in the spectrometer. The yields were normalized with respect to the elastically scattered ^{22}Ne ions, detected in a monitor solid state detector, at 30°. The magnetic field in the spectrometer was measured by the nuclear resonance method. In order to obtain good energy resolution, the effective area of the telescope was limited by a slit 3 mm in width. This corresponds to 320 keV energy spread for 140 MeV ^{21}O and ^{22}O ions (the dispersion of our magnetic spectrometer amounts to 13 mm/1% of momentum).

3. Results and Discussion

The energy spectra of ^{21}O and ^{22}O from the $^{232}Th(^{22}Ne, ^{21}O)^{233}U$ and $^{232}Th(^{22}Ne, ^{22}O)^{232}U$ reactions were measured in a wide range of energies. The $^{232}Th(^{22}Ne, ^{20}O)^{234}U$ reaction was also investigated in order to test the correctness of the mass determination of ^{21}O and ^{22}O (the ground state mass of ^{20}O is known with high accuracy[10]). The energy spectra of ^{20}O, ^{21}O and ^{22}O are shown in fig. 1. In the detection system described above the reaction products of definite ionic charge Z_i are detected. The oxygen ions emitted from the target with energies of a few MeV/nucleon have most probable charge $Z_i = 8$, therefore it was this component of the charge spectrum that was measured. The yield measurements for $Z_i = 7$ and $Z_i = 6$ show that at energy 125 MeV (where the maxima in the energy spectra are located) 80% of oxygen have the charge $Z_i = 8$.

Energies of the reaction products were calculated according to the formula:

$$E = const. \frac{Z_i^2 B^2}{M} \left(1 - \frac{E}{2Mc^2}\right), \qquad (1)$$

where B is the magnetic field in the spectrometer, and M and Z_i are the rest mass and the charge of the ion, respectively. The relativistic corrections are rather small (≤ 600 keV), but for the Q-value determination they cannot be neglected. The energy of the elastically scat-

tered ^{22}Ne ions was also calculated from formula (1).In such a way,the beam energy which was not known with any great precision could be determined from the formula (1) with the same constant as for energies of ^{20}O , ^{21}O and ^{22}O . Stability of the beam energy was controlled by frequent energy measurements of the elastically scattered ^{22}Ne ions.

The energy losses of reaction products in the target were determined by comparing the energies of the ^{22}Ne ions elastically scattered from a 260 μ g/cm^2 ^{197}Au target and from the ^{232}Th target used in the experiment. Using the tables of dE/dx for heavy ions (in gold and uranium) of Nortchliffe and Schilling /11/, it was found that our ^{232}Th target is equivalent to 2.63 mg/cm^2 of uranium. This value together with the mentioned dE/dx data were then used to estimate the energy losses of oxygen ions in the target.

Figure 1 shows that energy spectra of ^{20}O , ^{21}O and ^{22}O have the form of wide maxima, located at about 125 MeV.At higher energies they fall approximately exponentially. The high energy part of these spectra with expanded energy scale is shown in Fig. 2. We assume that the rapid change of the slope, seen in each spectrum, corresponds to the reaction with formation of the products in the ground states.Indeed, these sharp ends of the spectra have a slope identical with that for ^{22}Ne elastic scattering peak. This suggests that there are no lower levels contributing with significant yields to this part of the spectrum.

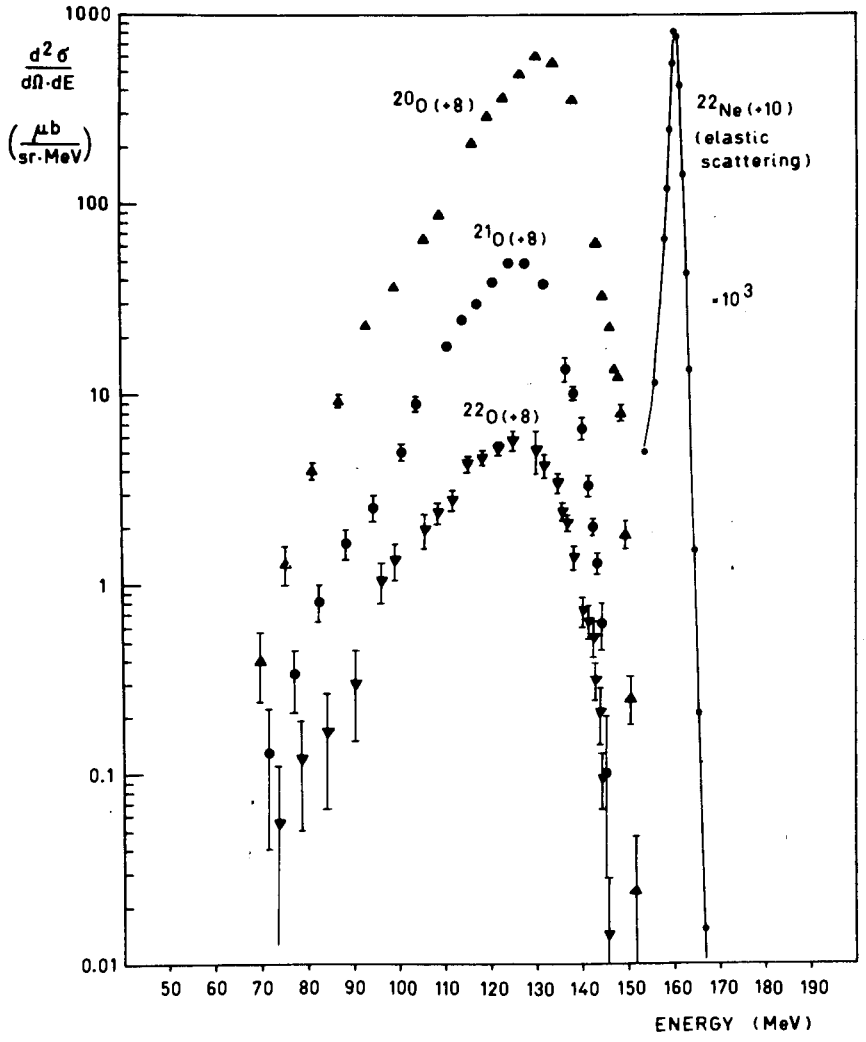

Fig. 1. Energy spectra of ^{20}O , ^{21}O and ^{22}O particles from the $^{232}Th + {}^{22}Ne$ (174 MeV) reaction at $\theta = 40^{\circ}$. Only the oxygen ions with $Z_i = 8$ were detected.

To determine the energy value corresponding to the ground state reaction channel one has to know the shape of the peak for this reaction channel. The peaks of ^{20}O, ^{21}O or ^{22}O for a single energy state should be similar to that of ^{22}Ne elastic scattering, but they should be somewhat broader, owing to the difference of the energy losses in the target. Describing the shape of the elastic scattering peak by $f(E - E_0)$, one can assume that the shape of the ground state peak for ^{20}O, ^{21}O or ^{22}O has the form:

$$\tilde{f}(E - E_0) = \text{const.} \int_{E-a}^{E+a} f(E' - E_0)\, dE' , \qquad (2)$$

where $2a$ is the difference of the energy losses between ^{22}Ne and the oxygen ion on the path equal to the target thickness. The form of the elastic scattering peak can be approximated by the Gaussian function

$$f(E - E_0) = e^{-\frac{(E - E_0)^2}{2\sigma^2}}$$

with $\sigma = 0.84$ MeV. The shapes of the ground state peaks of ^{20}O, ^{21}O and ^{22}O, calculated according to formula (2), are shown in Fig. 2. The width parameters σ are: 0.96 MeV, 0.93 MeV, and 0.92 MeV for ^{20}O, ^{21}O and ^{22}O, respectively. The centres of the ground state peaks correspond to the reaction taking place at half the thickness of the target. Therefore, the kinematics for all three reactions was calculated with respect to this point. We bear in mind that the beam energy was

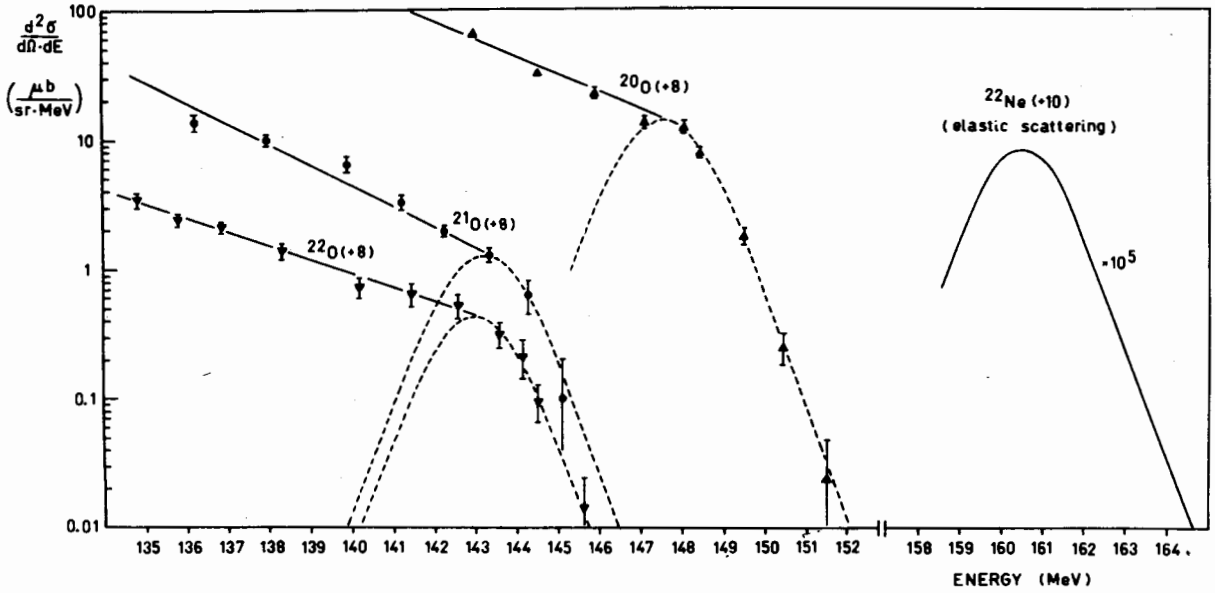

Fig. 2. High energy part of the ^{20}O , ^{21}O and ^{22}O spectra. Dashed lines show the predicted shapes of peaks corresponding to the ground state reaction channels.

calculated from the elastic scattering energy, measured with the same magnetic method as the energies of ^{20}O, ^{21}O and ^{22}O. The error in the calibration constant of the spectrometer influences very weakly the measured Q-values. For instance, in the case of the ^{232}Th (^{22}Ne, ^{22}O) ^{232}U reaction, the value of $\delta Q / \delta E_{in}$ is equal to about 0.10 (error in the calibration constant equivalent to the error of 1 MeV in the energy of the incident beam results in an error of 100 keV in the Q-value).

The $M-A$ values for ^{20}O, ^{21}O and ^{22}O measured in this experiment are shown in table 1. The agreement with the known mass of ^{20}O ($M-A = 3.802 \pm 0.010$ MeV[10]) is

Table 1

Comparison of the measured masses with theoretical predictions

nuclide	$(M-A)_{exp}$ (MeV)	$(M-A)_{theor}$ (MeV)	
		ref. [8]	ref. [14]
^{20}O	$3.8\ ^{+0.2}_{-0.4}$	-	-
^{21}O	$9.3\ ^{+0.3}_{-0.7}$	10.70	8.92
^{22}O	$11.5\ ^{+0.2}_{-0.5}$	13.73	10.14

is very good. We consider this as the best, direct verification of our mass determination method. The measured $M-A$ values for ^{21}O and ^{22}O are smaller than those predicted by Garvey et al. /8/ by 1.4 MeV and 2.2 MeV, respectively. These discrepancies are not surprising since some of the nuclear masses which have been used by Garvey and co-workers for extrapolation, namely the masses of ^{22}F and ^{26}Na were errorneous differing greatly from the values obtained in the recent measurements /12,13/. Using the same procedure as in the work of Garvey et al. /8/, but including new experimental data, Thibault-Philippe obtained quite different parametrization of nuclidic masses in the region $A < 40$ /14/. Experimental values of $M - A$ for ^{21}O and ^{22}O are slightly larger than those predicted by Thibault-Philippe.

The mass predictions based on the Garvey and Kelson relations seem to be at present the most reliable procedure. However, as any extrapolation procedure, it can accumulate errors. Therefore, the comparison with the measured masses of the nuclei with large neutron excess is extremely interesting and useful.

The cross sections for the reactions investigated here are quite large: the ^{232}Th (^{22}Ne , $^{21}O_{g.s.}$) $^{233}U_{g.s.}$ reaction (changing T_z of the nuclei by $3/2$ units) has $d\sigma/d\Omega = 3.5\,\mu b/sr$, and the ^{232}Th (^{22}Ne , $^{22}O_{g.s.}$) $^{232}U_{g.s.}$ reaction ($\Delta T_z = 2$) has $d\sigma/d\Omega = 1.2\,\mu b/sr$. The cross sections of equivalent reactions on light targets are significantly smaller (see for example ref. /15/). Therefore the multi-

nucleon transfer reactions on heavy targets will probably play an important role in the future progress of the mass determinations of light nuclei with extremely large neutron excess.

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