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Mass determination of the nuclei ^{12}N, ^{16}F, ^{22}Mg and ^{26}Si using the (^3He, n) reaction

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Abstract. Fast neutron time-of-flight studies of (^3He, n) reactions have been used to obtain information on four proton-rich nuclei. The ground-state reaction Q values, and hence atomic masses, and mass excesses have been determined together with the energies of several of the low-lying levels of these nuclei. The results are consistent with other recent determinations, but the values presented here are more precise. In all cases there is disagreement with the 1964 Mass Tables.

1. Introduction

Using IBIS, the Harwell 3 MeV pulsed Van de Graaff (Ferguson 1964), a series of fast-neutron time-of-flight experiments has been conducted using singly charged ^3He ion beams in order to investigate the reactions $^{10}B(^3He, n)^{12}N$, $^{14}N(^3He, n)^{16}F$, $^{20}Ne(^3He, n)^{22}Mg$ and $^{24}Mg(^3He, n)^{26}Si$. This method affords the best means of producing the four resultant proton-rich nuclei, which are difficult, though not impossible, to form by other reactions. Conventional fast-neutron spectrometry techniques were employed using a new type of neutron–γ-ray pulse-shape discrimination system developed by White at Harwell, with a 4 in diameter × 1 in thick Nuclear Enterprises NE213 liquid phosphor (bubble-free encapsulation) coupled to a Mullard XP 1040 photomultiplier for the detection of the fast neutrons. Typical time-of-flight spectra which were used in the $^{10}B(He, n)^{12}N$ identification and analysis are shown in figure 1. Generally flight paths of 3 to 6 m were used, and

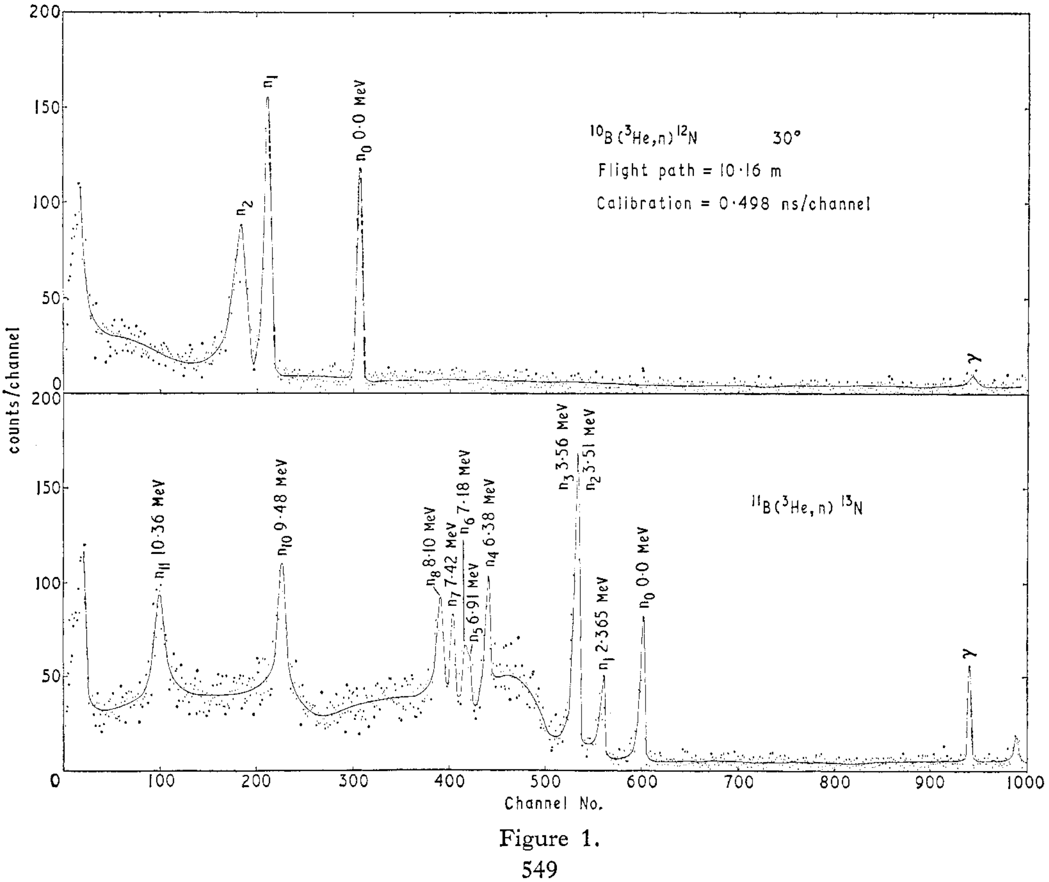

Figure 1.

Table 1. The nuclei ^{12}N, ^{16}F, ^{22}Mg and ^{26}Si

Reaction	g.s. Q value (Mev)	Residual mass ($\times 10^{-6}$ a.m.u.)	Mass excess (Mev)
	(*a*)	(*a*)	(*b*)
^{10}B(^{3}He, n)^{12}N	1·574 ±0·007	12018613 ±8	17·338 ±0·008
(*c*)	1·548 ±0·007	12018641 ±8	17·364 ±0·007
(*d*)	1·570 ±0·025	12018617 ±25	17·342 ±0·025
(*e*)	1·561 ±0·009	12018628 ±9	17·351 ±0·009
(*f*)	1·564 ±0·008	12018631 ±9	17·354 ±0·008
(*g*)		12018615 ±9	17·340 ±0·009
^{14}N(^{3}He, n)^{16}F	−0·970 ±0·015	16011480 ±15	10·693 ±0·015
(*c*)	−1·180 ±0·012	16011706 ±13	10·904 ±0·012
(*h*)	−0·963 ±0·040	16011473 ±40	10·686 ±0·040
^{20}Ne(^{3}He, n)^{22}Mg	0·197 ±0·025	21999593 ±25	−0·379 ±0·025
(*c, f*)	−0·040 ±0·08	21999850 ±80	−0·140 ±0·08
(*k*)	0·176 ±0·035	21999616 ±35	−0·358 ±0·035
(*l*)		21999567 ±36	−0·404 ±0·036
^{24}Mg(^{3}He, n)^{26}Si	0·095 ±0·015	25992305 ±15	−7·168 ±0·015
(*m*)	0·08 ±0·08	2599232 ±70	−7·15 ±0·08
(*c*)	0·059 ±0·013	25992343 ±14	−7·132 ±0·013
(*n*)	0·084 ±0·018	25992316 ±18	−7·157 ±0·018
(*p*)	0·075 ±0·030	25992326 ±30	−7·148 ±0·030

(*a*) ^{10}B, ^{14}N, ^{20}Ne, ^{24}Mg, ^{3}He and n atomic masses taken from Mattauch *et al.* 1965; (*b*) based on ^{12}C = 12·000 000 a.m.u. and a conversion factor of 1 a.m.u. = 931·476 Mev; (*c*) Mattauch *et al.* 1965; (*d*) Fisher and Whaling 1964; (*e*) Kavanagh 1964; (*f*) Zafiratos *et al.* 1966; (*g*) Bromley *et al.* 1966; (*h*) Zafiratos *et al.* 1965; (*j*) Ajzenberg-Selove *et al.* 1961; (*k*) Drysdale 1966; (*l*) Skyrme, private communication; (*m*) Ajzenberg-Selove and Dunning 1960; (*n*) Miller and Kavanagh 1965; (*p*) McMurray *et al.* 1967.

Table 2. Excitation levels of ^{12}N, ^{16}F, ^{22}Mg and ^{26}Si

Reaction	Level	This work (Mev)	Other work (Mev)	
			Kavanagh 1964	Zafiratos *et al.* 1966
^{10}B(^{3}He, n)^{12}N	g.s.	0	0	0
	1	0·969 ±0·010	0·994 ±0·020	0·959 ±0·020
	2	1·191 ±0·010	1·22 ±0·03	1·24 ±0·03
			Zafiratos *et al.* 1965	Pehl & Cerny 1965
^{14}N(^{3}He, n)^{16}F	g.s.	0	0	0
	1	0·253 ±0·035	0·20 ±0·05	0·20 ±0·05
	2	0·422 ±0·015	0·436 ±0·030	0·436 ±0·05
	3	0·711 ±0·015	0·736 ±0·040	0·736 ±0·05
			Ajzenberg-Selove *et al.* 1961	Drysdale 1966
^{20}Ne(^{3}He, n)^{22}Mg	g.s.	0	0	0
	1	1·06 ±0·04	0·995 ±0·040	1·00 ±0·06
			Ajzenberg-Selove & Dunning 1960	Miller & Kavanagh 1965
^{24}Mg(^{3}He, n)^{26}Si	g.s.	0	0	0
	1	1·809 ±0·015	1·78 ±0·06	1·79 ±0·03

flight times T_n were determined to about 0·1–0·2%. Observation at different angles θ_n gave confirmation of the initiating reaction (by kinematics). All the time-of-flight data for a given reaction were processed by computer, in which the mean Q value was calculated with the T_n and θ_n as input data for the kinematic relation.

2. The ^{10}B(^{3}He, n)^{12}N reaction

In recent years several workers (Fisher and Whaling 1964, Kavanagh 1964, Zafiratos *et al.* 1966, Bromley *et al.* 1966) have studied this reaction, but with only moderate agreement between them. We have carried out three sets of angular distribution measurements, each comprising up to 20 points, at ^{3}He energies of 2·4 Mev, 2·75 Mev and 2·94 Mev. From these, the mass of ^{12}N and the ground-state reaction Q value have been determined to be (12 018 613 ± 8) × 10^{-6} a.m.u. (^{12}C scale) and 1·574 ± 0·007 Mev, respectively, which leads to a ^{12}N mass excess of 17·338 ± 0·008 Mev. These results agree very well with those of Fisher and Whaling, Kavanagh, Zafiratos *et al.* and Bromley *et al.*, but not with the 1964 Mass Tables (Mattauch *et al.* 1965) (see table 1).

Throughout the investigations only three neutron groups, corresponding to the ground, first and second excited states of ^{12}N, were observed in the time spectra, although it was energetically possible to excite higher levels reported previously by Ajzenberg-Selove *et al.* (1957) and Zafiratos *et al.* (1966). This non-observance is most probably due to the fact that these higher levels are only weakly excited at the ^{3}He energies used and the fact that they may be obscured in our time spectra by the neutron continuum from the ^{10}B(^{3}He, pn)^{11}C reaction. Excitation values of 0·969 ± 0·010 Mev and 1·191 ± 0·010 Mev were obtained for the first and second excited states, respectively, the first agreeing well with the work of Kavanagh and Zafiratos *et al.*, but the second being somewhat lower (see table 2).

3. The ^{14}N(^{3}He, n)^{16}F reaction

One would expect the ^{16}F nucleus to have three low-lying levels above the ground state, like its mirror nucleus ^{16}N. These are predicted on a simple shell-model picture. Two independent series of angular measurements, each comprising six points, were conducted and three neutron groups corresponding to this reaction were observed at all angles. A fourth group corresponding to the first excited state of ^{16}F was seen only at backward angles, its presence at forward angles being obscured by the neutron group from the ^{12}C(^{3}He, n_0)^{14}O reaction.

The ^{16}F mass and the ground-state reaction Q values were determined to be (16 011 480 ± 15) × 10^{-6} a.m.u. and −0·970 ± 0·015 Mev, respectively, which leads to a ^{16}F mass excess of 10·693 ± 0·015 Mev. The results agree with the work of Zafiratos *et al.* (1965), but not with the 1964 Mass Tables (see table 1). The excitation values for the three low-lying levels in ^{16}F were found to be 0·253 ± 0·035 Mev, 0·422 ± 0·015 Mev and 0·711 ± 0·015 Mev respectively, which also agree with the work of Zafiratos *et al.* (1965) and Pehl and Cerny (1965) (see table 2).

4. The ^{20}Ne(^{3}He, n)^{22}Mg reaction

Only a limited study of this reaction was made since the average beam current was restricted to a maximum of 0·35 μA to avoid puncturing the 0·000 02 in Ni foil window (chosen to keep the ^{3}He energy loss small) used on the gas target. Nevertheless, measurements at eight angles were recorded, and in all cases two neutron groups from the desired reaction were observed.

The ^{22}Mg mass and the ground-state reaction Q value were determined to be (21 999 593 ± 25) × 10^{-6} a.m.u. and 0·197 ± 0·025 Mev, respectively, which leads to a ^{22}Mg mass excess of −0·379 ± 0·025 Mev. The results are consistent with those of Drysdale (1966) and Skyrme (1967, unpublished), but again not with the 1964 Mass Tables (see table 1). The first excited state was found to be at 1·06 ± 0·04 Mev, which is consistent with previous work (Drysdale 1966, Ajzenberg-Selove *et al.* 1961) (see table 2).

5. The $^{24}Mg(^{3}He, n)^{26}Si$ reaction

A complete angular distribution measurement was conducted at 3·14 MeV for this reaction, and two corresponding neutron groups were observed. The ^{26}Si mass and ground-state reaction Q value were determined to be $(25\,992\,305 \pm 15) \times 10^{-6}$ a.m.u. and $0{\cdot}095 \pm 0{\cdot}015$ MeV, respectively, leading to a ^{26}Si mass excess of $-7{\cdot}168 \pm 0{\cdot}015$ MeV. The results agree very well with the previous work of Ajzenberg-Selove and Dunning (1960), Miller and Kavanagh (1965) and McMurray *et al.* (1967), but not with the 1964 Mass Tables (see table 1). The first excited state was found to be at $1{\cdot}809 \pm 0{\cdot}015$ MeV, which is in agreement with previous work (Ajzenberg-Selove and Dunning 1960, Miller and Kavanagh 1965) (see table 2).

The discrepancies between this work and similar recent work, on the one hand, and the 1964 Mass Tables, while serious in the particular nuclides studied, do not in any way suggest that the whole of the tables are suspect since none of the 'primary' nuclides are involved. The nuclidic masses tabulated for ^{12}N, ^{16}F, ^{22}Mg and ^{26}Si, which are all 'secondary' nuclides, are based on very sparse experimental data. The inconsistencies thus do not reflect any inadequacy in the methods of computation (which have previously been described by Everling *et al.* (1961)) used in arriving at the present set of consistent nuclidic masses. Since the compilation of the 1964 Mass Tables much more powerful experimental techniques, which were not previously available, have been employed to study these proton-rich nuclei. The present set of data, as well as being more accurate, represents a self-consistent study of all four reactions under the same experimental conditions using the same accelerator and identical method of computation in all cases.

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