Alpha-Particle Bombardment of Neon, Calcium and Argon and Masses of Light Nuclei

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Under bombardment by ThC′ alpha-particles neon and calcium have been found to emit protons while argon does not. The maximum energies of the protons have been measured: the nuclear energy changes are for the neon reaction -2.6_4 Mev and for calcium -4.2_3 Mev. In each case only one group was found. Using Aston's recent value for the mass of Ne^{20} we deduce that the mass of Na^{23} is 22.9972. Data from a number of transmutations are used together with mass spectrographic values to give a table of isotopic masses from Ne^{20} to A^{40} with four exceptions.

IN two recent papers[1, 2] we have described experiments on the protons ejected from the elements sulphur, phosphorus, chlorine and potassium under bombardment by ThC′ alpha-particles. In this paper we give the results of similar work on neon, calcium and argon. These elements are of interest as the preponderant isotopes are of the type $4n$ and might be expected to give groups similar to those from the elements Mg^{24}, Si^{28}, S^{32} studied by Haxel.[3] Argon and calcium are of added interest as they are isobars differing in charge by two and the properties of any emitted proton groups might have significance in a theoretical interpretation. The transmutation of neon, and those of the elements previously investigated enable use to be made of Aston's recent mass determinations and several independently studied reactions to give values for the isotopic masses from Ne^{20} to A^{40} with the exceptions of Ne^{21}, Mg^{25}, S^{33} and K^{39}.

None of these elements has been investigated in this way since the early work of Rutherford and Chadwick[4] who reported particles were emitted from neon and argon but not from calcium.

EXPERIMENTAL ARRANGEMENT AND RESULTS

For the two gaseous elements neon and argon we used "source boxes" n which the bombardment was carried on as illustrated in Fig. 1. The design (a) was intended to test the presence or absence of a yield and no care was taken to limit the geometrical conditions to favor resolution. It happens that a fair estimate of the nuclear energy change (or Q value) can be made from the maximum range of any protons observed since an error of 20° in the angle chosen as the least effective angle between proton- and alpha-ray introduces a relatively small change in the Q value. This arrangement is very bad for the separation of groups. The design (b) in which an annular space of gas is bombarded has better geometrical conditions and was intended for a subsequent analysis into groups. In both cases the effective range of the alpha-particles depends on the gas pressure. We checked our estimate of the alpha-particle range and maximum angle between proton and alpha-ray by preliminary experiments on nitrogen in each case. Taking this angle for the design (a) to be 43°, for design (b) 37°, the calculated Q values for nitrogen were found to be -1.48 and -1.40 Mev, in agreement with the accepted value -1.4 ± 0.2 Mev. With design (b) we found two groups, ranges 22 and 48 cm of roughly equal yield: the short range group is probably a composite of protons due to the 4.9 cm particles present in the source and a second Q value discovered by

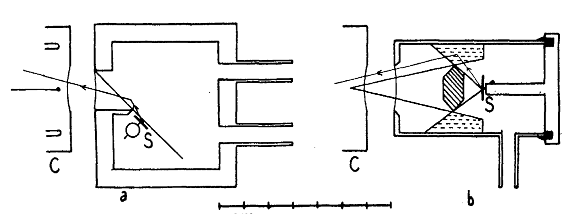

FIG. 1. The two arrangements for bombarding gases. (a) is intended to detect protons, (b) to resolve them into groups. In (b) diagonal shading indicates the lead screen and horizontal shading the annular volume of gas which is bombarded. S is the source, C the counter.

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[2] E. Pollard and C. J. Brasefield, Phys. Rev. **50**, 890 (1936).

[3] O. Haxel, Phys. Zeits. **36**, 804 (1935).

[4] Rutherford and J. Chadwick, Proc. Phys. Soc. London **36**, 417 (1924).

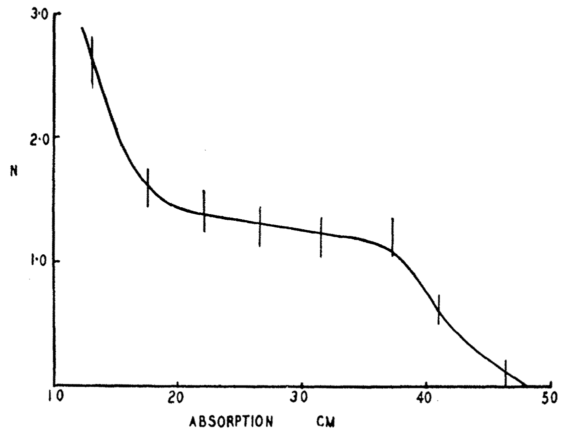

FIG. 2. Absorption curve for protons from nitrogen using arrangement (b). N is the number of protons counted per minute per millicurie, the absorption is in centimeters air equivalent.

Fischer Colbie.[5] The curve we obtain (Fig. 2) in which the number per minute per millicurie (N) is plotted against absorption, is very similar to that reported by Haxel.[6]

For calcium, bombarded as $Ca(OH)_2$, we used the arrangements described in our previous papers,[1,2] one a large yield arrangement with poorly defined angles, another giving a low yield but having better geometrical conditions.

Experimental Results

Neon

With the (a) design this gas gave a yield which was roughly two-thirds that from nitrogen. An absorption curve was plotted which appears in Fig. 3(a). The maximum range is estimated to be 32 cm for a bombarding alpha-particle range of 7.9 cm. No attempt was made to resolve the curve into several groups as the geometrical conditions render this impossible. The (b) design was then used with gas at an average pressure of 60 cm: the absorption curve found is shown in Fig. 3(b). The maximum range is 32 cm, for an effective alpha-particle range 7.5 cm. It will be seen that it is uncertain whether more than one group occurs, there being a possibility that a short range group is present. We therefore repeated the curve at a lower average pressure (38 cm) which should reduce the spread due to

[5] E. Fischer Colbie: see G. Stetter, Zeits. f. Physik **100**, 652 (1936).
[6] O. Haxel, Zeits. f. Physik **93**, 400 (1935).

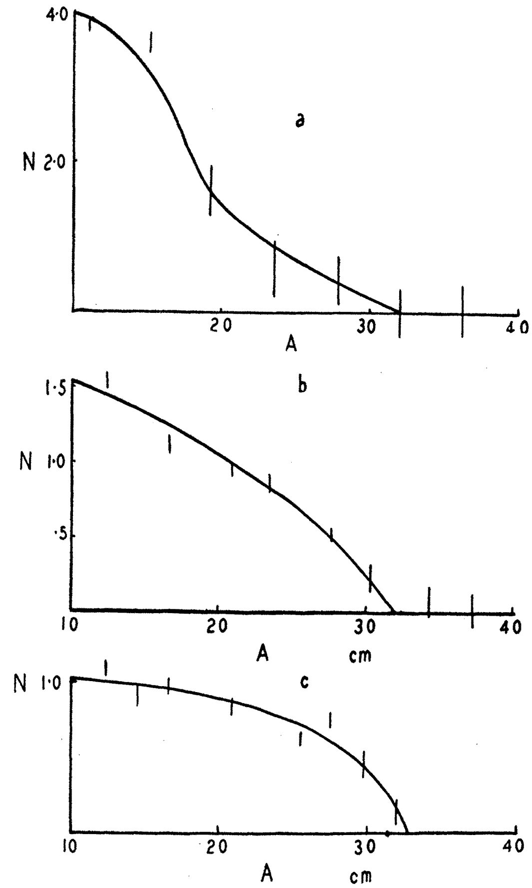

FIG. 3. Absorption curves for protons from neon using arrangements (a) and (b), the latter at two pressures. N is the number of protons counter per minute per millicurie and A is the absorption in centimeters air equivalent.

the absorption in the neon and so sharpen up the discontinuities if any. This curve appears as in Fig. 3(c). It will be seen that any rise at small absorptions is less prominent than before and we conclude that neon gives only one group of protons with a range beyond 10 cm. The maximum range for curve 3(c) is 32.5 cm for an effective alpha-particle range of 7.9 cm. Since calculation shows that protons should just be detectable beyond the natural protons from the source if emitted in the same direction as the alpha-particles (forward direction) we used a box similar to design (b) but with no central lead screen, closed by gold and aluminum foils. The yield from neon was just picked up beyond the natural protons and had a range of 41 cm which was checked by comparison with the

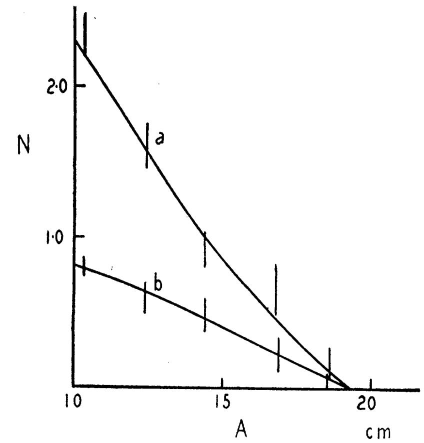

FIG. 4. Absorption curve for protons from calcium using high yield (a) and low yield (b) arrangement. *N* and *A* are as in the previous figure.

protons projected forward from methane at a pressure arranged to give the same absorption as the neon. Some yield was found of range about 50 cm but this was ascribed to nitrogen—an impurity of 3 percent would suffice to explain it.

Argon

Using the large yield design (a) we made several runs in which the box was alternately filled with argon and evacuated. With argon present we found a very small increase over the vacuum at low absorptions, amounting to less than 0.05 per minute per millicurie. Nitrogen gave 3.0 per minute per millicurie under identical conditions in counts interspersed with the argon runs. The yield we found is almost small enough to be explainable by the A^{36} isotope though we consider it more likely that it is due to either neon or nitrogen impurity. We conclude that A^{40} gives no yield of protons.

Calcium

Curves (a) and (b) of Fig. 4 show the results obtained with calcium in the large yield and low yield arrangements respectively. Both show definite yields with a maximum range of 19 cm. We made careful tests to find a group of greater range than this without success. We do not think it likely that any analysis of the observed protons into more than one group can be made.

In all the curves the lengths of the lines at each point are intended to give some idea of the precision in N. If n is the number of particles counted at a point, the line extends a distance $1/\sqrt{n}$ of the plotted value on each side. This is not a limit of error but enables the numbers counted to be inferred and a judgment of the validity of the line drawn through the points to be made accordingly.

The average strength of our sources was 2 millicuries.

Discussion

We ascribe the protons we find to the two reactions:

$$Ne^{20}+He^{4}\rightarrow Na^{23}+H^{1}(+Q), \tag{1}$$

$$Ca^{40}+He^{4}\rightarrow Sc^{43}+H^{1}(+Q). \tag{2}$$

The greatness of the yield from neon and the fact that only one group is found render it likely that the most abundant isotope is responsible for the emitted particles. The same reasoning applies to calcium where the fact that Ca^{40} has an abundance of 97 percent renders it nearly certain that the above reaction is right.

We deduce the following values for the nuclear energy change in Mev:

Reaction (1)—Neon

Design (*a*)	Design (*b*)	Forward	Recommended Value
−2.64	−2.56; −2.67	−2.51	$-2.6_4 \pm 0.20$

Reaction (2)—Calcium
From both curves $-4.2_3 \pm .20$.

The result we get for neon is in good agreement with Rutherford and Chadwick's early experiments.[4] They found a range of 16 cm in the right angle direction using Ra (B+C) alpha-particles. Calling the effective alpha-particle range 6.4 cm (i.e. allowing 0.5 cm for absorption in the gas) this gives a nuclear energy change value of −2.8 Mev which is in agreement within the errors of experiment.

Our results for argon and calcium differ from their conclusions as we do not observe protons from argon and do from calcium. Their negative result from calcium would be expected since the yield is undoubtedly very small or zero if the less energetic particles from Ra C′ are used and so would not have been detected in their experiments. If the argon they used contained neon or nitrogen their positive result could be explained. It is of some interest that this is the only case in which their early experiments, made with a method of detection that taxes the observer's freedom from bias very seriously, have not been verified substantially by later work.

Both neon and calcium appear to give only one group of protons. Since both elements contain an equal number of neutrons and protons they are similar to the elements Mg^{24}, Si^{28}, S^{32} for which three groups spaced by roughly a million volts are found. Such a spacing might occur for Ca^{40} but be undetected in our experiments as our minimum detected range is 10 cm. This is not the case for Ne^{20} where a group lying just short of our minimum would have a Q value of -4.8 Mev so that the least spacing between the ground and first excited state of Na^{23} must exceed 2.2 Mev. It therefore appears that neon does not fit in to the scheme of Mg^{24}, Si^{28} and S^{32}.

The lack of emission from argon is not surprising. A^{40} already contains four neutrons in excess of its proton content. A transmutation of the type here studied would give a product nucleus containing five excess neutrons. Since there is an increase of mass proportional to the square of this surplus[7] (the isotopic number) there will be an addition of mass which is considerable and which renders the energy required to cause proton emission much greater. The greater the isotopic number the more energy is required to achieve the transmutation. It seems likely that this factor, and not the difficulty of penetration through the barrier, is effective in preventing alpha-particle disintegration of elements beyond calcium.

Masses of Elements from Neon to Calcium

When subjected to alpha-particle bombardment all the nuclei from F^{19} to Ca^{40} of the type either $4n$ (e.g. Mg^{24}) or $4n+3$ (e.g. Al^{27}) with the exception of A^{36} have been observed to emit protons whose maximum energies have been measured. Aston[8] has recently given figures for the masses of Ne^{20}, Al^{27}, Si^{28}, Si^{29} and A^{40} while Bainbridge[9] had previously determined Cl^{35} and Cl^{37}. These data, together with the transmutation energies, permit the deduction of all the masses from Ne^{20} to A^{40} with the exception of Ne^{21}, Mg^{25}, S^{33}, A^{36} and K^{39}. For A^{36} there is an old value of Aston's[10] so that we have information about all but four mass numbers. In a letter to "Nature"[11] we used all the then available figures to derive most of these masses: the present work enables two more to be added by reason of the neon reaction giving Na^{23} and

$$Na^{23}+He^4 \rightarrow Mg^{26}+H^1(+Q)^{12}$$

studied by König giving Mg^{26}. We give below the list of reactions used and the resulting masses derived. (Energies are given in mass units $\times 10^3$.)

$$F^{19}+He^4 \rightarrow Ne^{22}+H^1+1.5^{13}$$
$$Ne^{20}+He^4 \rightarrow Na^{23}+H^1-2.8$$
$$Na^{23}+He^4 \rightarrow Mg^{26}+H^1+2.2^{12}$$
$$Mg^{24}+He^4 \rightarrow Al^{27}+H^1-1.2^{3,\,14}$$
$$Al^{27}+He^4 \rightarrow Si^{30}+H^1+2.3^{14}$$
$$Si^{28}+He^4 \rightarrow P^{31}+H^1-2.6^{3}$$
$$P^{31}+He^4 \rightarrow S^{34}+H^1+0.0^{13,\,15,\,2}$$
$$S^{32}+He^4 \rightarrow Cl^{35}+H^1-2.6^{3,\,1}$$
$$Cl^{35}+He^4 \rightarrow A^{38}+H^1=0.1^{2}$$

Ne^{20}	19.9986 (A)	P^{31}	30.9844
Ne^{21}	———	S^{32}	31.9812
Ne^{22}	21.9989	S^{33}	———
Na^{23}	22.9972*	S^{34}	33.9802
Mg^{24}	23.9939	Cl^{35}	34.9796 (B)
Mg^{25}	———	A^{36}	35.976 (A')
Mg^{26}	25.9908*	Cl^{37}	36.9777 (B)
Al^{27}	26.9909 (A)	A^{38}	37.9753
Si^{28}	27.9860 (A)	K^{39}	———
Si^{29}	28.9864 (A)	A^{40}	39.9754 (A)
Si^{30}	29.9844	Ca^{40}	———

Aston's early value is indicated by (A'), his recent values by (A), Bainbridge's by (B) while the remainder are derived from transmutations.

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* New values.