Half-Life of the New Isotope ^{32}Na; Observation of ^{33}Na and Other New Isotopes Produced in the Reaction of High-Energy Protons on U

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With an improved on-line mass spectrometer we have discovered, by means of the reaction of 24-GeV protons on uranium, the very neutron-rich isotope ^{32}Na and measured its half-life. We have also produced in the same reaction the new isotopes ^{33}Na, $^{48-50}$K, and ^{227,228}Fr. There is evidence for shell effects in the cross sections of the new sodium isotopes.

The particle stability of neutron-rich sodium isotopes filling the *sd* shell to ^{31}Na has been shown, and their half-lives have been measured.[1] The purpose of this note is to report on evidence for ^{32}Na and ^{33}Na, belonging to the next neutron shell. This indicates that other, more neutron-rich isotopes of sodium are likely to exist, filling the $f_{7/2}$ shell as suggested by nuclidic mass calculations.[2,3]

Light nuclei with a large excess of neutrons can be produced in the reaction of high-energy protons on heavy targets,[1,4] or in complex transfer from heavy-ion-induced reactions.[5] In the case of high-energy reactions it was shown that the on-line mass spectrometric techniques[1] can sort out selectively the isotopes of alkali elements and supply information on their half-lives. This work has been further extended with the construction of an improved instrument, and we report here on the first results obtained in a recent experiment.

The technique has been described in detail elsewhere.[6] In brief, the energetic recoils from the reaction are caught in heated graphite foils from which they diffuse out very quickly. The alkali ions (Li^+, Na^+, K^+) produced by surface ionization are then mass analyzed in a Nier-type mass spectrometer. The detection of ions is achieved by an electron multiplier capable of counting single ions.

To increase the production of rare nuclei, the effective target thickness was increased to 2 g/cm^2 of U. The mass spectrometer is a magnetic sector (90°, $r = 35$ cm). It has a wide gap to accept ions from the long target (50 mm) and is slightly inhomogeneous ($n = 0.23$) to ensure high transmission by means of z focusing.[7]

The experiment was performed with 24-GeV protons in the "neutrino" fast-ejected beam of the CERN proton synchrotron. Short (2.1 μsec) and intense (1.5×10^{12} protons) bursts were directed on our 6-mm-diam target every 10 sec. A previous experiment[1] had shown the existence of a background "tail" extending many milliseconds after the beam bursts. Since this was the limiting factor in the sensitivity to low-yield, short-lived isotopes, the detector was installed in a shielded enclosure lined with a thin sheet (0.7 mm) of cadmium. A combination of electrostatic quadrupole lenses was used to refocus the ions after the exit slit of the spectrometer through a beam pipe traversing the shielding wall (40 cm iron, 80 cm concrete) onto the detector. This was extremely effective in reducing the magnitude of the background and changing its time dependence. In particular, the exponential tail disappeared completely in agreement with a conjecture[8] that it was due to thermal neutrons bouncing between the walls before undergoing (n,γ) reactions. The background was thus reduced by ~1200 at $t = 5$ msec and by ~200 at $t = 10$ msec. A residual long-lived background, which was not completely understood, appeared to be associated with neutral radioactive particulates coming from the hot ion source.

To prove the existence of a new isotope and measure its half-life, the following steps are taken (see Fig. 1):

(i) The mass spectrometer is set on a known abundant long-lived isotope (e.g., ^{22}Na). A periodic, triangular, modulation of the ion accelerating potential results in a series of peaks regularly spaced in time when the beam is in phase with the exit slit. Residual background is not affected by this modulation and will appear between the peaks.

(ii) The value of the magnetic field is then changed accurately (with an NMR probe) to the value corresponding to the new isotope. Figure 1(a) then shows that peaks do occur for ^{32}Na in

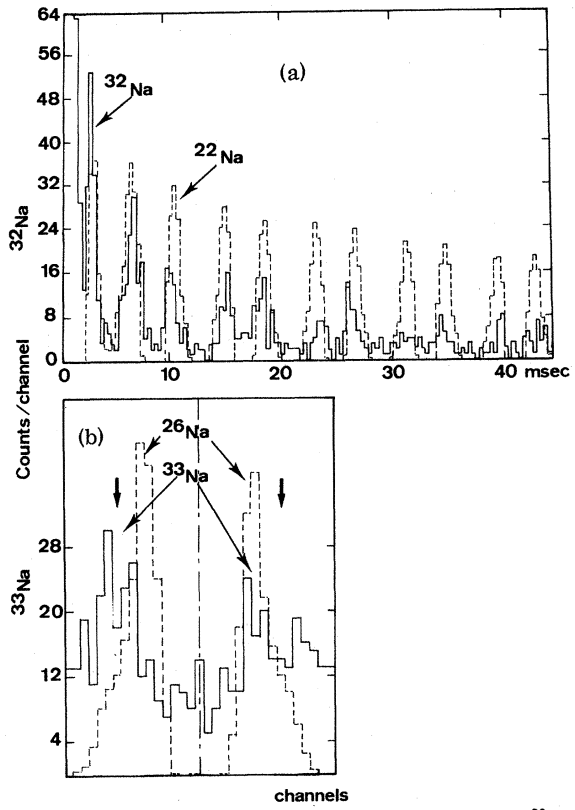

FIG. 1. (a) Diffusion and radioactive decay of ^{32}Na. Following a proton pulse, a triangular modulation of the accelerating potential results in a series of peaks at times when the ion beam is in phase with the slit. The ^{22}Na (dashed) serves as a peak-position calibration and as a diffusion-time reference. The ^{32}Na peaks can be seen to decrease faster with time because of radioactive decay. (b) Existence of ^{33}Na: The three consecutive pairs of peaks where the signal-to-background ratios are the most favorable have been added channel by channel; the ^{26}Na (dashed) serves as calibration. Arrows indicate the center of gravity of the ^{33}Na peaks. The positions do not coincide with ^{26}Na because of an inaccurate setting of the magnetic field. The displacements are symmetrical, however, as expected from the time symetry of the modulation. The peak shape, apparent from ^{26}Na, indicates that the correct value of the background should be taken in the middle interval.

the positions expected from the calibration with the known isotope ^{22}Na. The intensities are significantly over the background which appears between the peaks.

(iii) The decrease in intensity with time for long-lived ^{22}Na is purely due to diffusion, while radioactive decay results in a faster decrease for ^{32}Na. The ratio of intensities of corresponding peaks as a function of time then gives directly the radioactive decay as

$$I(32)/I(22) = \exp(-\lambda_{32} t). \quad (1)$$

The results are given in Table I for ^{32}Na and other short-lived Na isotopes.

A search was made for ^{33}Na using the same procedure during a 3-h experiment with a total of 7×10^{15} protons, and Table II gives the number of counts at the locations where ^{33}Na peaks are expected. It is seen that a significant number of counts over the background arises for the

TABLE I. Half-life measurements (msec).

	Previous Measurements		This work[c]
^{26}Na	978 ± 22[a]	1040 ± 30[b] 1030 ± 60[b]	1070 ± 30
^{27}Na	288 ± 2[a]		295 ± 10
^{28}Na	34 ± 1[a]		35.7 ± 1
^{29}Na	47 ± 3[a]		48.6 ± 2
^{30}Na	55 ± 3[a]		55 ± 3
^{31}Na	16.5 ± 4[a]		17.7 ± 1
^{32}Na	...		14.5 ± 3
^{33}Na	...		20 ± 15

[a]See Ref. 1.
[b]See Ref. 9.
[c]For ^{26}Na and ^{27}Na, the new values are the results of a re-analysis of the data of Ref. 1: As the contribution of the preceding burst to the diffusion of the long-lived reference isotope could not be neglected, in their case, Eq. (1) was not strictly valid as was assumed in Ref. 1, and a correction has been made in the present work. For ^{28}Na, ^{29}Na, ^{31}Na the new values are the weighted means of the measurements of Ref. 1 and of new measurements made with the same method (^{31}Na) or with a β telescope (^{28}Na, ^{29}Na).

TABLE II. Number of counts at the locations where the successive ^{33}Na peaks are expected.

Time (msec)	Counts of ^{33}Na over background	Subtracted background
8	24 ± 10	35 ± 6
11	13 ± 9	
13	35 ± 9	25 ± 5
16	21 ± 8.5	
18	27 ± 8	16 ± 4
21	27 ± 8	
23	8 ± 8	27 ± 5
26	6 ± 8	
28	15 ± 9	34 ± 6
31	6 ± 8.5	

first three pairs of peaks. Adding them channel by channel [Fig. 1(b)], two peaks of ^{33}Na are found with 86 ± 15 and 61 ± 15 counts, respectively, after a background of 76 ± 9 has been substracted. This grouping thus establishes the particle stability of ^{33}Na even though the statistics on the six individual peaks is not adequate to deduce precise information on the half-life. The stability of ^{33}Na was indeed expected because of the existence of ^{32}Na and the extra stability due to the neutron pairing energy.

Following the same procedure as for ^{32}Na, the isotopes ^{48}K, ^{49}K, and ^{50}K were found. However, their half-lives were not short compared with the diffusion time, and hence could not be determined. We also observed the new neutron-rich isotopes ^{227}Fr and ^{228}Fr produced in the spallation of the uranium target.

The cross sections for formation of all the sodium and potassium isotopes in this high-energy reaction are shown in Fig. 2. The error bars on ^{33}Na represent the two extreme values for the half-life of ^{33}Na (5 and 35 msec) that could be compatible with the least-squares fit to our data.

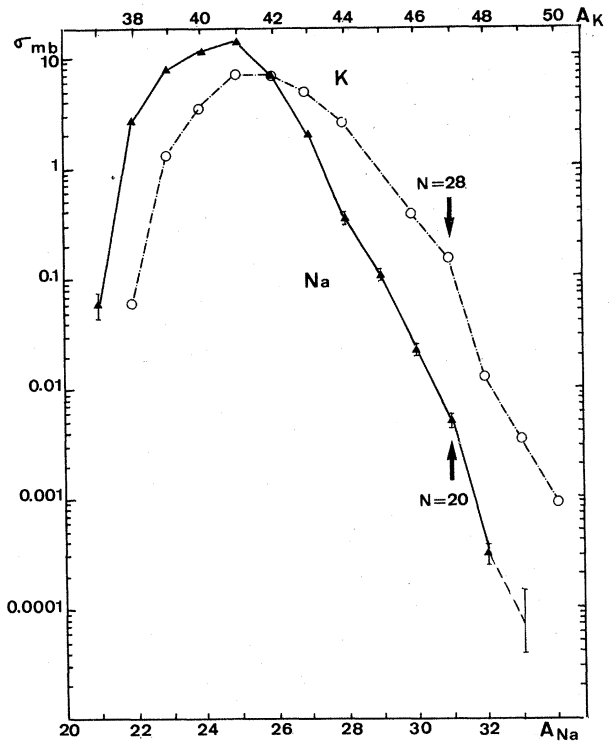

FIG. 2. Cross section for production of isotopes of sodium and potassium in the reaction of 24-GeV protons on uranium. Notice the abrupt decreases between ^{31}Na and ^{32}Na, and ^{47}K and ^{48}K, after the closure of the $N = 20$ and 28 shells, respectively.

It can be seen that the cross sections show a more or less regular decrease of a constant factor until ^{31}Na, closing the $N = 20$ neutron shell, and ^{47}K, closing the $N = 28$ neutron shell.

The decreases at ^{31}Na-^{32}Na and ^{47}K-^{48}K are, respectively, factors of 3.5 and 5 greater than the average decreases. These dramatic breaks seem to be associated with shell effects, and one can expect that the continued decrease in cross sections for other isotopes in the same shells will be moderate. This conclusion is not substantially affected by the uncertainties in the half-life of ^{33}Na and gives strong support to the experimental possibility of detecting by the same technique nuclei that are still richer in neutrons.

According to Garvey *et al.*,[2,3] extremely neutron-rich isotopes are predicted to be bound with regard to one- and two-neutron decay. In particular, the Na isotopes with $20 \leq N \leq 28$ are predicted to be bound if N is even, and marginally unbound (by about 200 keV) if N is odd. Our results indicate the probable existence of many such isotopes which are yet to be found in the same neutron shell. There is even more evidence that nuclei may be slightly more bound than Garvey *et al.* predict, because ^{32}Na (as indeed ^{11}Li, ^{14}B, and ^{19}C) has been found experimentally bound when predicted marginally unbound. It would be interesting to check on the stability of ^{34}Na and ^{36}Na to confirm this point.

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Giant Resonances in the High-Energy Inelastic Scattering Continuum*

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The details of the structure previously observed in the high-energy proton-scattering continuum are inspected for collective multipole contributions. Evidence is shown that in the $E^* \approx 10$–25-MeV excitation region of the ^{40}Ca continuum, at least dipole, quadrupole, and octupole excitations contribute to the structure of the cross section $[\sigma(\theta, E^*)]$. While the dipole and quadrupole strengths exhaust most of their corresponding sum rules, the octupole component does not. The possible nature of the less structured component at this continuum region is discussed.

In a series of inelastic proton-scattering experiments performed several years ago by Tyren and Maris,[1] the excitation region encompassing the giant dipole state was studied for several light- and medium-weight nuclei. With a bombarding energy of $E_p = 185$ MeV, the authors observed structure in this continuum region which they interpreted as excitation of the giant dipole state. Recently, however, Lewis and Bertrand[2] have shown that structure in the giant resonance region can also be seen in the continuum of proton scattering at $E_p = 62$ and 66 MeV. But the excitation energy (in both the 185- and 60-MeV measurements) and strength (for $E_p = 62$ MeV) are incompatible with a dipole state and a quadrupole interpretation is suggested. Furthermore Satchler[3] has shown that the angular distribution for the whole enhanced region of the continuum is most compatible with an isovector dipole + isoscalar quadrupole interpretation, in which the sum rules for both are essentially exhausted.

It is the purpose of this communication to show that the detailed shape of the continuum structure or scattering cross section $[\sigma(\theta, E^*)]$ reveals the presence of at least three multipoles or resonance states which contribute to the collective strength in the continuum.

Data points from Ref. 1 were extracted[4] and reduced by subtraction of the underlying (slowly energy varying) background. Examples corresponding to the giant dipole region of ^{40}Ca and ^{51}V are shown in Fig. 1. Observation of a few angles shows that marked variations in the energy center occur as a function of angle. In particular the energy centroid of the composite resonance lies at a lower excitation energy for the larger scattering angles. It should be noted that this trend is opposite to that expected from the possible influence of quasifree scattering.

In order to unfold the composite resonance into specific resonance states, it was assumed that the giant dipole state is indeed excited and contributes to the spectral shape. The position of the dipole state is taken from the (γ, n) systematics[5] and the shape is a Lorentz curve with a total width $\Gamma = 4$ MeV. In all cases the dipole is seen to contribute to only the highest excitation region of the composite resonance as illustrated in Fig. 1. Assuming that the remaining strength could be composed of additional resonances with $\Gamma \leq 4$ MeV, at least two more resonances (if $\Gamma = 4$ MeV) were found to be necessary to explain the angle dependence of the spectral shapes. The strongest component resonance occurs about 2–3 MeV below the dipole resonance. This explains why the resonance energies reported by Tyren