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High-Resolution Laser Spectroscopy of the *D* Lines of On-Line Produced ^{21,22,24,25}Na Using a New High-Sensitivity Method of Detection of Optical Resonances

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A polyisotopic sodium beam of $^{21-25}$Na, produced by spallation of Al, was illuminated with a tunable cw dye laser. The atomic beam, analyzed by a six-pole magnet is then ionized and detected by use of a mass spectrometer. The results are as follows: isotopic shifts relative to ^{23}Na, ^{21}Na $=-53.5$ mK, ^{22}Na $=-25.3$ mK, ^{24}Na $=+23.1$ mK, ^{25}Na $=+44.6$ mK; $\mu_I(^{25}\mathrm{Na})=+3.685(22)\mu_N$; b factor in the $P_{3/2}$ state of ^{25}Na $=-16(8)$ MHz.

Half-lives,[1] masses, [2] and other properties[3] of short-lived sodium isotopes have recently been determined by use of a mass spectrometer on-line with an accelerator. As an extension of this work, we wished to determine other static properties of these nuclei. We have thus attempted to measure the hyperfine structure and isotope shift (IS) of the atomic *D* lines of sodium isotopes. The purpose of this paper is to present the first results that have been obtained with a newly developed method that could eventually extend our knowledge on the shape and magnetic properties of nuclei far from stability.

The hfs of the ground state of $^{20-24}$Na has already been measured by different methods[4]; recently a determination of the absolute value of the magnetic moment of ^{25}Na has been published.[5] However the hfs of the excited $3P$ states are unknown for the unstable isotopes and there are no data available for isotope shifts.

This type of measurement on a series of isotopes can give interesting indications on nuclear shapes. The observation of irregularities of the hfs and IS of short-lived Hg isotopes[6] has been especially fruitful in that context. In the case of sodium, however, the same method as in Ref. 6 would fail because of the Doppler broadening, and it is necessary to use one of the new methods of Doppler-free high-resolution spectroscopy.[7-9]

The special requirements of our on-line experiment have in fact led to the development of a variant of one[7] of these methods of detection of optical transitions in an atomic beam.[10] In essence this method rests upon the magnetic detection of the optical pumping which occurs when a laser beam is tuned to the frequency of one of the hyperfine components of the *D* lines. This optical pumping changes the population distribution between the states $m_J=\pm\frac{1}{2}$ of the atoms of an atomic beam, and the change is detected by means of a magnetic filter consisting of a six-pole magnet which focuses the atoms with $m_J=+\frac{1}{2}$ and defocuses the atoms with $m_J=-\frac{1}{2}$.

In the actual experiment, the isotopes of sodium are produced in the spallation of aluminum by 150-MeV protons from the Orsay synchrocyclotron. Since this nuclear reaction results in a mixture of the different isotopes and their optical resonances might overlap, it is necessary to separate them on-line using a mass spectrometer.

A highly efficient target has been developed in order to have the best sodium-isotope production. We have used a molten-metal target in a graphite container. It was loaded with 10 g of high-purity aluminum and heated by alternating current up to 900°C. The yield of the spallation reaction $^{27}\mathrm{Al}(p,3pxn)$Na with 150-MeV protons

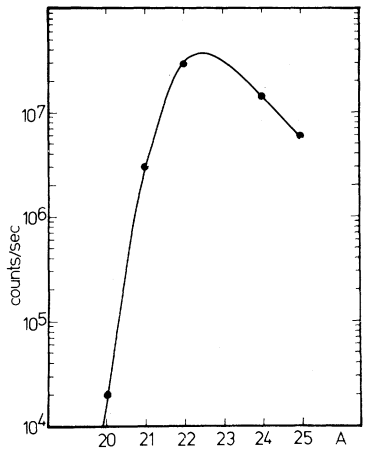

FIG. 1. Isotopic yield of the spallation reaction $^{27}\mathrm{Al}(p, 3pxn)^{25-x}\mathrm{Na}$ with 150-MeV protons.

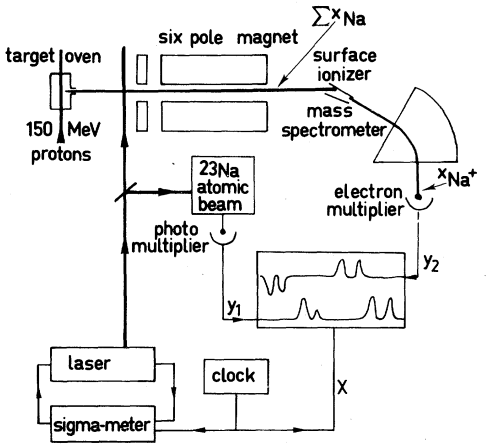

FIG. 2. Schematic view of the experiment.

was studied by directly connecting the target to the thermoionic source of the mass spectrometer. The counting rate after mass separation is shown in Fig. 1. The diffusion delay time in the molten metal is strongly temperature dependent and decreases from 1 min to 10 sec between 850 and 900°C.

This target is used in the present experiment as the oven of the atomic beam. A schematic view is given in Fig. 2. The collimation of the beam is defined by a nitrogen-cooled diaphragm to 30/1. The sodium atoms effusing from the oven interact with the laser beam before passing the six-pole magnet. The outgoing atoms impinge on a hot rhenium surface acting as the ion source of a small magnetic mass spectrometer. Mass-separated ions are counted after the exit slit with an electron multiplier. This device detects equally well atoms of stable or short-lived isotopes.

The laser is a single-mode tunable dye laser of high stability which has been used in other experiments.[11] A new frequency control and scanning system can provide a frequency change by increments of 7.5 MHz (0.25 mK) initiated by pulses from a pilot clock: This system, called "sigma-meter" will be described elsewhere.[12] A small part of the laser light is used to observe the fluorescence signal from an auxiliary ^{23}Na atomic beam which serves as a reference.

For each isotope, the hfs of its D_1 line is recorded in a single scan, together with the corresponding line of ^{23}Na. The duration of the scan is about 10 min. The signals are directly monitored on a two-channel chart recorder and fed simultaneously, by a specially built routing device, into the different subgroups of a multichannel analyzer.

The total beam leaving the oven contains up to 10^8 atoms/sec of ^{25}Na. Because of the different losses, the corresponding counting rate at the detector is then 3000/sec. The background of the electron multiplier due to nuclear reaction is only 30–50 counts/sec. It should be noted however that tailing of ^{23}Na ions at mass 22 results in up to 1000 counts/sec. This could certainly be improved in the future by adding an electrostatic deviation after the magnetic mass spectrometer.

Figure 3 shows the spectra obtained. Our results on the hfs of the $^2S_{1/2}$ ground state are in agreement with the known values obtained by ra-

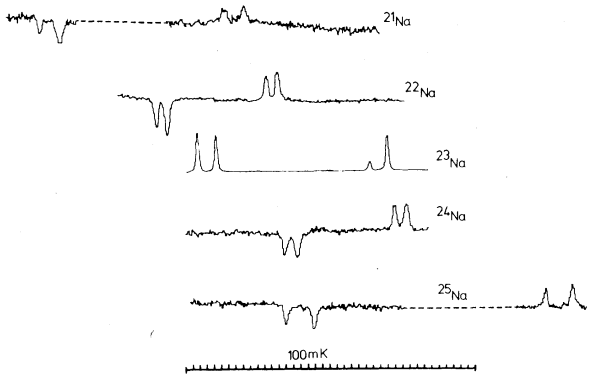

FIG. 3. hfs and IS of the D_1 lines of $^{21-25}$Na isotopes. These lines, measured individually relative to ^{23}Na, are here shown together on a common wave-number scale.

TABLE I. Relative isotopic shifts of $^{21-25}$Na.

Isotopes	Isotopic shift (mK)
^{21}Na-^{23}Na	−53.5(2)
^{22}Na-^{23}Na	−25.3(2)
^{24}Na-^{23}Na	+23.1(4)
^{25}Na-^{23}Na	+44.6(2)

diofrequency techniques for ^{21,22,24}Na within the limits of the statistical uncertainties of the signal and accidental irregularities of the scanning by the sigma-meter. Our value for the magnetic moment of ^{25}Na is $\mu_I = +3.685(22)\mu_N$. The value $|\mu_I| = 3.710(70)\mu_N$ given by Deimling *et al.*[5] is in agreement with our number.

The measured values of the isotope shifts are given in Table I. It appears that the measured values follow the law of the normal plus specific mass effect within the experimental errors. This type of experiment can also lead to a determination of the nuclear electric quadrupole moment if the hyperfine structure of the $^2P_{3/2}$ state can be measured with a good precision. For that purpose, we have also observed the four $(F = 2, 3 \rightarrow F = 2, 3)$ transitions in the D_2 line of ^{25}Na, which were only partially resolved with the present collimation of the atomic beam. From this measurement we have estimated the b factor for the $^2P_{3/2}$ state to be $b = -16(8)$ MHz. An experiment with a better collimation for the measurement of b is in progress.

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