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Isotope Shift of Eleven Cesium Isotopes Determined by Atomic-Beam Laser Spectroscopy

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Isotopes of $^{123-137}$Cs produced by spallation of lanthanum and separated in mass by the ISOLDE on-line facility have been transformed into an atomic beam which is illuminated with a tunable cw dye laser. From the sensitive detection of the optical resonance lines at 459 nm, the hyperfine structure of $^{123-132}$Cs, ^{137}Cs, and ^{130m}Cs has been determined. The interpretation of isotope shifts, in terms of variation of charge radii, is discussed.

A previous experiment[1] had shown that the hyperfine structure (hfs) and isotope shift (IS) of short-lived sodium isotopes produced by spallation could be studied on line by a new mehtod of Doppler-free optical spectroscopy associated with a mass spectrometer. Recent developments[2] have increased the precision to about 1 MHz and also the sensitivity, so as to reach the very neutron-rich $^{26-31}$Na produced by the CERN proton synchrotron.

The purpose of the present Letter is to describe an extension of the method to the determination of hfs and IS of mass-separated radioactive cesium isotopes that are available at the ISOLDE isotope separator on line with the CERN synchrocyclotron.[3] The same setup—with further modifications that are described elsewhere[4]—has been used to discover the D_2 atomic resonance line of the element francium.

In essence, the experiment[1] rests upon the detection of optical transitions that occur when a tunable-laser beam interacts with a perpendicular collimated beam of the atoms to be studied. If the laser is tuned to the frequency of one of the D lines, optical pumping will change the population distribution between the magnetic substates $m_J = \pm\frac{1}{2}$ of the ground state of the atoms. This 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 $m_J = -\frac{1}{2}$.

The experimental setup is summarized in Fig. 1. The 60-keV Cs$^+$ ions from ISOLDE first have to be converted into the thermal atoms of an atomic beam. For that purpose they are implanted at a grazing incidence (2°) in the inner surface of a tantalum tubular target coated with yttrium. Since this is known to be a low-work-function material, upon heating at about 900°C, the implanted cesium should reevaporate largely in the form of neutral atoms. In order to enhance the directivity of the atomic beam, the tubular target is an assembly of three tubes 40 mm long and 1 mm in diameter. Tests with stable ^{133}Cs$^+$ indicated that the desorption time was 150 msec (half-maximum).

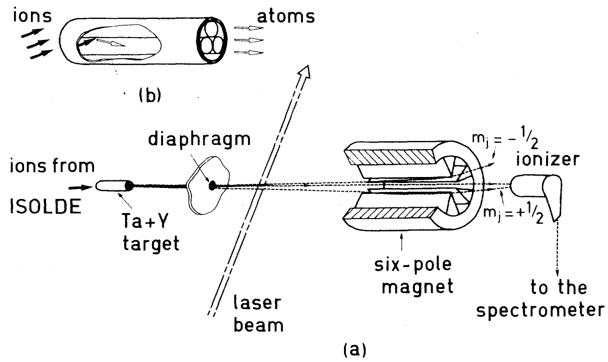

FIG. 1. (a) Schematic view of the experiment; (b) details of the tubular target.

TABLE I. Experimental results for the dipole constant of the $7\,^2P_{1/2}$ state and for the relative isotope shifts in the line $\lambda = 459.4$ nm.

^{x}Cs	$A\,(7\,^2P_{1/2})$ (MHz)	$\delta\nu^{133,x}$ (MHz)
^{123}Cs	341(12)	259(12)
^{124}Cs	90(7)	261(6)
^{125}Cs	348(11)	152(11)
^{126}Cs	103(7)	208(7)
^{127}Cs	369(11)	94(13)
^{128}Cs	131(7)	155(6)
^{129}Cs	392(11)	53(9)
^{130}Cs	192(9)	56(8)
^{130m}Cs [a]	17(2)	83(12)
^{131}Cs	183(4)	−9(6)
^{132}Cs	144(4)	60(15)
^{137}Cs	103(3)	−104(6)

[a] From relative intensities of the two negative resonances there is a preference for the positive sign of the magnetic moment of the $I = 5$ isomeric state in ^{130}Cs.

The laser is a commercial cw, tunable dye laser working in single mode. Its frequency is controlled and can be varied by steps through a device based on a Michelson interferometer (the "sigma-meter") that is described elsewhere.[5] Because of the present availability of blue light from stilben and coumarin dyes this first experiment was one on the 6^2S-$7^2P_{1/2}$ transition at 459.4 nm. Since dyes are now becoming available in the proper spectral region, we are considering to base future work on the $6S$-$6P$ transition in the 850-nm region.

An efficient and sensitive detection of the atoms focused by the six-pole magnet is achieved by counting them with an electron multiplier after they are ionized and passed through a mass spectrometer. The surface ionizer is a hot tantalum cone, twisted as seen in Fig. 1. Even though mass separation of radioactive nuclei is already achieved by ISOLDE, the mass spectrometer is still necessary in order to eliminate the high background of stable impurity ions from the hot ionizer. The overall efficiency of the apparatus (counted ions versus ISOLDE ions) stands between 10^{-6} and 10^{-5}. From independent knowledge of the geometric efficiencies of the atomic beam and mass spectrometer, it is deduced that the efficiency of neutralization should be around 20% at present.

Based on the spallation of lanthanum or the fission of uranium, ISOLDE produces cesium isotopes from ^{115}Cs to ^{149}Cs.[3] With a transmission of $\gtrsim 10^{-6}$, we estimate from the intensities given in Ref. 3 that IS can be determined in a string of isotopes extending from ^{119}Cs to ^{146}Cs, crossing the $N = 82$ shell closure and two regions of nuclear deformation.[6]

We report here, as the results of a first run, the isotope shift in the line $\lambda = 459.4$ nm ($6s\,^2S_{1/2} - 7p\,^2P_{1/2}$) of 11 Cs isotopes and the isomer shift of ^{130m}Cs. This was done by scanning the two hyperfine components ($F = I + \frac{1}{2} \rightarrow F' = I \pm \frac{1}{2}$) of the line by a step-by-step advance of the laser frequency by increments of 3.75 MHz. Simultaneously a fluorescence signal from a ^{133}Cs reference beam was recorded. Using the known spins and hyperfine splittings of the atomic ground state of the investigated isotopes[7-9] and the hyperfine splitting of the excited state of ^{133}Cs,[10] the magnetic dipole hyperfine constants $A(7^2P_{1/2})$ and the isotope shifts were obtained. Including these results, which are given in Table I, the isotope shifts of the isotopes $^{123-137}$Cs and the isomer shifts of ^{130m,134m}Cs are now known.[11-13]

Our values of the isotope shift are in good agreement with previous work on ^{127,129,131,132,137}Cs with an uncertainty which is already smaller than in previous work and that we think we can still substantially decrease.

Changes in nuclear charge radii are proportional to the field shift which is obtained by subtracting the mass-dependent effects from the optical isotope shift. While the normal mass effect (nms) is readily calculated from the reduced mass, the specific mass effect (sms) depends on details of correlations between electronic moments which are difficult to evaluate. A discussion of theoretical calculation and experimental data on neighboring elements lead Ullrich and Otten[11] to

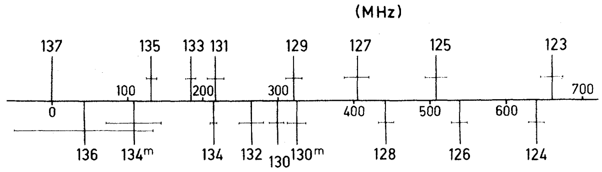

FIG. 2. Relative isotope shifts $\delta\nu_{exp}-\delta\nu_{nms}$ with respects to ^{137}Cs. The values for $^{134,135,136}Cs$ are taken from Ref. 11, the value for ^{134m}Cs from Ref. 12.

choose

$$\delta\nu_{sms} = (0 \pm 1.2)\delta\nu_{nms} .$$

Figure 2 gives the field shift with respect to ^{137}Cs the assumption of these authors and adopts $\delta\nu_{sms}=0$. We point out, however, that in the case of sodium the sms was found to be larger than theory had predicted by a large factor, so that caution should be exercised in adopting an assumption based on present theories. The question can only be solved eventually when high-precision measurements of isotopes shifts of electronic or muonic x rays become available.

Using the range of plausible assumed values for the sms, and the field constant F given in Ref. 11, and assuming further that the screening factor is the same for the $6S$-$6P$ and $6S$-$7P$ transitions, we obtain the changes in nuclear radii $\delta\langle r^2\rangle$ plotted in Fig. 3. The experimental errors lead to an uncertainty in the $\delta\langle r^2\rangle$ values of only $\sim 5\times10^{-3}$ fm^2 (except for ^{136}Cs), while neglecting the specific mass effect may result in much larger uncertainties.

As can be seen from Fig. 3 the values for $\delta\langle r^2\rangle$ differ by about a factor of 5 from those expected for a uniformly charged sphere. This behavior has been explained[11] by assuming that away from closed-shell $^{137}_{55}Cs_{82}$ there is a steadily increasing contribution to the isotope shift from a deformation term. Adopting the numerical values of Ref. 11 in this two-parameter analysis, i.e.,

$$\delta\langle r^2\rangle_{A,137} = 0.5\delta\langle r^2\rangle_{unif}^{A,137} + 0.4\langle r^2\rangle_{unif}\,\delta\langle\beta^2\rangle_{A,137},$$

one finds that the deformation $\langle\beta^2\rangle^{1/2}$ is still increasing between ^{127}Cs and ^{123}Cs. In our two limiting assumptions for the sms we find for ^{123}Cs

$$0.20 \leq \langle\beta^2\rangle^{1/2} \leq 0.27.$$

For a systematic discussion in terms of nuclear deformation and nuclear shell effects, an extension of the isotope-shifts measurements to other Cs isotopes and also measurements of nuclear electric quadrupole moments are necessary.

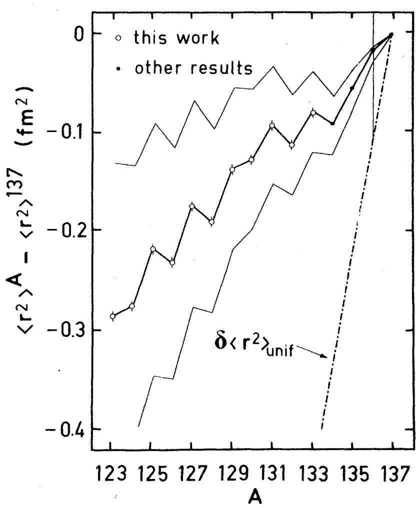

FIG. 3. Differences of charge radii for Cs isotopes derived from optical isotope shifts for different values of the specific mass effect. Middle curve, sms = 0; upper curve, sms = − 1.2 times the nms; lower curve, sms = + 1.2 times the nms. The dashed line gives the change of the nuclear radius for a uniformly charged sphere of radius $R = 1.2A^{1/3}$ fm.

These experiments are in preparation. The possibility of determination of quadrupole moments from the hyperfine structure of the $^2P_{3/2}$ state has already been tested during the present experiments. The quadrupole interaction constants $B(7p\,^2P_{3/2})$ found for $^{131,132}Cs$ are in very good agreement with the values known from optical double-resonance measurements.[14] By improving the experimental conditions the accuracy on the determination of the transition frequencies should become high enough to determine the B factors also in those Cs isotopes in which the quadrupole interactions is smaller than in $^{131,132}Cs$.

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Production of Positive Pions from the Bombardment of ^{9}Be and ^{12}C with 200-MeV Polarized Protons

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Differential cross sections and analyzing power for reactions ^{12}C(p,π^+) and ^{9}Be(p,π^+) leading to discrete final states in the residual nuclei have been measured in the angular range from 35° to 135° using 200-MeV polarized protons. The shape of the angular distribution of analyzing powers is essentially independent of the residual nuclear state, indicating a strong dependence upon reaction mechanism rather than nuclear structure.

The (p,π) reaction has attracted considerable interest since the pioneering studies of Dahlgren, Höistad, and Grafström,[1] in which individual nuclear states were resolved. The possibility of extracting interesting nuclear structure information has been the primary motivation for studying such reactions involving large momentum transfers. To make possible the extraction of such nuclear structure information, several models[2-8] for the reaction mechanism have recently been discussed.

With a single exception[9] all previous work in this area has been done with unpolarized proton beams. The (p,π) program at TRIUMF has employed a polarized beam[10] to permit measurements of the analyzing power of the pion production reaction as a function of production angle, as well as the differential cross sections which are normally used to test the reaction-mechanism models. Measurements of pion production associated with the bombardment of ^{12}C and ^{9}Be by 200-MeV protons are presented in this Letter.

Pions having energies up to 100 MeV were detected with a broad-range, 0.5-m-radius Browne-Buechner magnetic spectrograph. The detection system consisted of a 24-element scintillation counter hodoscope on the focal plane. An aperture counter and three additional scintillation counters above the focal plane provided timing and dE/dX information essential for reduction of background.[11]

Both the beam polarization and intensity were monitored during the runs using the (p,p) elastic scattering reaction occurring at a thin CH_2 target located downstream of the pion production target. A monitor count corresponded to the coincident detection of a proton scattered at 26° to the left (right) with respect to the beam direc-