Difference in the yields of even and odd Yb isotopes in multistep photoionization by polarized laser beams

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The polarization of the laser beams has been found to affect the yields of even and odd Yb isotopes from a natural isotopic mixture in selective three-step photoionization through a Rydberg state. The experimental results are interpreted.

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Isotopically selective photoionization of atoms is achieved through an isotopic shift or a difference in the hyperfine structures of different isotopes.[1] Zel'dovich and Sobel'man[2] have called attention to the possibility of an isotopically selective excitation which would result in different yields of even and odd isotopes. This method would use $J=0 \to J'=0$ transitions, because these transitions are no longer forbidden for odd isotopes with a nonzero nuclear spin. In this letter we are reporting the first observation of selective photoionization of even and odd isotopes through the excitation of atoms by polarized light, even with a linewidth greater than the isotopic shift. An effect of polarization on the isotope yields has been observed in the selective, three-step photoionization of a natural mixture of Yb iostopes.

In the experiments we used a beam of Yb atoms which were excited in three steps by laser beams to the $18p\,^3P_2^0$ Rydberg state and then ionized by an electric-

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field pulse (Fig. 1a). The yield of photoions of the various isotopes in the first step was determined with the help of a narrow-band dye laser which could be tuned by varying the pressure.

The dye lasers used in these experiments were pumped with a copper-vapor laser. The output linewidth of the laser used in the first step was $\Delta\nu_L^{(1)} = 0.04\ \text{cm}^{-1}$ The laser output frequency was tuned over an interval of 0.5 cm^{-1} by varying the pressure. In the two other steps of the excitation we used wide-band lasers with $\Delta\nu_L^{(2,3)} = 0.8\ \text{cm}^{-1}$. The average bean power levels of the lasers used in the first, second, and third steps were 30, 6, and 20 mW, respectively. The pulse repetition frequency was 10 kHz. The beams from all the lasers were linearly polarized in the horizontal plane. The polarization was changed by inserting $\lambda/4$ plates in the laser beams.

The laser beams intersected the atomic beam between two electrodes, to which an ionizing voltage pulse was applied after a 50-ns delay with respect to the laser pulses. The electric field in the gap between the electrodes was 10 kV/cm. The apparatus of Ref. 3 was used to produce the atomic beam and to detect the ion current.

Figure 2 is a plot of the ion current against the output wavelength of the laser used in the first step, for the cases of linear (Fig. 2a) and circular (Fig. 2b) polarization of the beam in the first step. The beams in the second and third steps were lin-

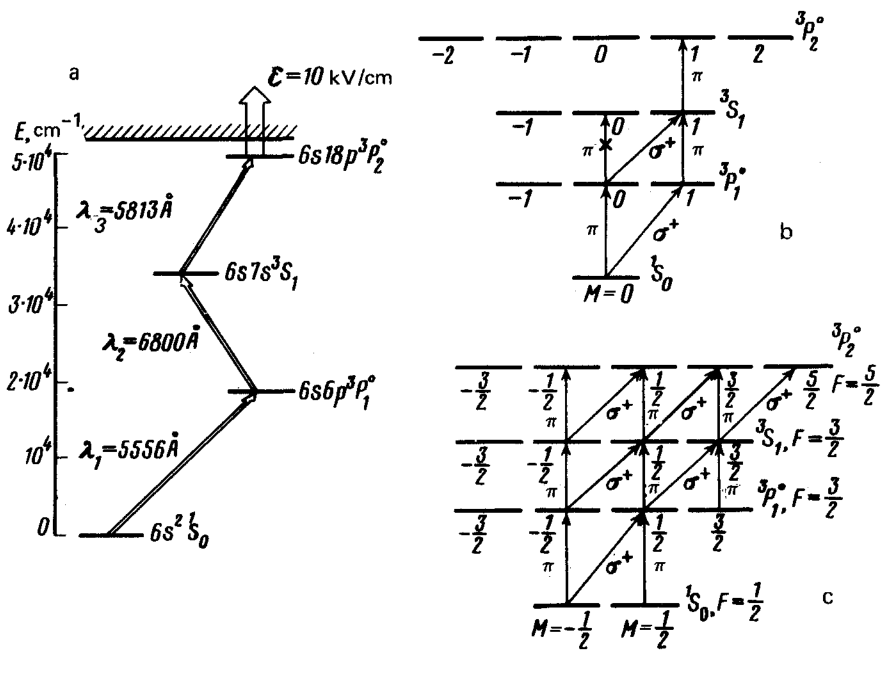

FIG. 1. (a) Scheme for the excitation and ionization of the ytterbium atom by laser beams and and electric field; (b) scheme for the excitation of even isotopes; (c) one possible pathway for the excitation of the isotope ^{171}Yb.

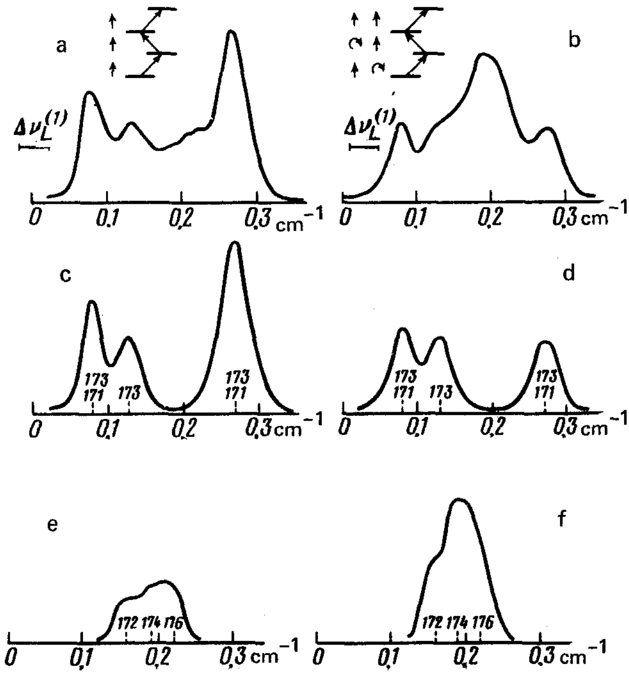

FIG. 2. Ion current vs. the wavelength used in the first excitation step. (a) Linear polarization; (b) circular polarization; (c) and (d) odd isotopes of ytterbium; (e) and (f) even isotopes of ytterbium (spectra c, d, e, and f were calculated from experimental spectra a and b).

early polarized in these particular experiments. The spectrum retained the same shape as in Fig. 2b when a linearly polarized beam was used in the first step and a circularly polarized beam in the second. The linewidth of the laser beam used in the first step was not small enough to allow us to evaluate the effect of each individual isotope, but we were able to distinguish the effects of even and odd isotopes in the experimental spectra (Figs. 2c–2f).

Comparison of the spectra shows that the yield of the even isotopes increases when we switch from a linearly polarized beam to a circularly polarized beam. Under these experimental conditions the degree of polarization of the laser beam was $10-10^2$. The spectrum in Fig. 2a was obtained at a degree of polarization of 10 and with saturation of the second-step transition. The effect of the even isotopes can thus be seen. A better selectivity, i.e., a better separation of even isotopes from odd isotopes, can be achieved by reducing the second-step beam power to achieve linear operation and by increasing the degree of polarization of the laser beam.

The results can be interpreted as follows. The cross section for a transition between two magnetic sublevels of hyperfine-structure components of two terms is[4]

$$\sigma(\gamma JIFM; \gamma' J' IF' M' \propto |(\gamma J || D || \gamma' J')|^2 (2F+1) \tag{1}$$

$$\times(2F'+1)\begin{Bmatrix} J & F & I \\ F' & J' & 1 \end{Bmatrix}^2 \begin{pmatrix} F & 1 & F' \\ -M & q & M' \end{pmatrix}^2, \qquad q = 0, \pm 1,$$

where $(\gamma J \| D \| \gamma' J')$ is the reduced matrix element of the transition dipole moment, which is the same for all isotopes of a given element. The polarization dependence of the cross section is determined by the 3*j* coefficient. In multistep excitation of a mixture of isotopes there are certain combinations of transitions and laser-beam polarizations for which only odd isotopes are excited. Let us examine such a case: the three-step photoionization of Yb isotopes through Rydberg states (Fig. 1).

For the even isotopes (Fig. 1b) the nuclear spin is $I=0$. For the $^3P_1^0 - {}^3S_1$ transition in the case $M=M'=0$, the 3*j* coefficient, $\left(\begin{smallmatrix} 1 & 1 & 1 \\ 0 & 0 & 0 \end{smallmatrix}\right)$, is zero, so that the cross section for this transition is zero. The yield of even isotopes is zero if linearly polarized beams are used in the first and second excitation steps. If the beam in one of these steps is linearly polarized, while that in the other is circularly polarized, the corresponding transitions marked in Fig. 1b are allowed, and the yield of even isotopes will be nonzero.

In the case of odd isotopes (Fig. 1c) transitions can occur in all three excitation steps, since F and M take on half-integral values, and for an arbitrary polarization of the light there are always transitions for which the 3*j* coefficient in (1) is not zero. Nevertheless, the yield of odd isotopes may depend on the polarization, since a change in the polarization will change the numbers of magnetic sublevels that are excited in intermediate states.

In summary, these experiments show that even and odd isotopes can be separated with the help of laser beams whose linewidth is greater than the isotopic shift. This method can be used to separate and detect isotopes of alkaline earths and other elements, for example, Zn, Cd, Hg, and Pd.

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