Effect of magnetic field on isotope-selective photoionization of atomic samarium using polarized lasers

A C Sahoo, P K Mandal, M L Shah, R C Das and Vas Dev

1 Laser and Plasma Technology Division, Bhabha Atomic Research Centre, Trombay, Mumbai, 400085, India
2 Homi Bhabha National Institute, Training School Complex, Anushakti Nagar, Mumbai, 400094, India
E-mail: vasdev@barc.gov.in

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Abstract

The effect of an external magnetic field on the isotopic selectivity in a two-color three-step polarization-based isotope-selective photoionization of atomic samarium has been studied. Isotope-selective photoionization of samarium is realized through a level scheme having total angular momentum (J) sequence 0–1–1–continuum by using two lasers linearly polarized in the same direction and the isotopic selectivity is measured by varying the magnetic field strength perpendicular to the laser polarization axis while keeping the delay between the laser pulses fixed and vice versa. The experimental data have been analyzed and compared with the results of the numerical calculations. The magnetic field perpendicular to the laser polarization axis present in the laser-atom interaction region has been found to degrade the isotopic selectivity. Further, the Lande factor (g_0) of the excited energy level 16 690.76 cm⁻¹ (J = 1) of samarium has been determined from the observed oscillation in the isotopic selectivity. The value of g_0, thus obtained, is in good agreement with that reported in the literature.

1. Introduction

Resonant isotope-selective photoionization spectroscopy has played a key role in understanding the complex atomic structures in atomic physics and in applied research such as isotope-selective photoionization processes, ultra trace analysis, etc [1–8]. Practical realization of isotope-selective photoionization process requires both high efficiency and isotopic selectivity. In the isotope-selective photoionization process, isotopic selectivity in laser induced photoionization is achieved by choosing excitation schemes in two ways. One is based on isotope shifts, where the target isotope is selectively excited by narrow bandwidth lasers and subsequently ionized by another laser [1, 4, 9, 10]. The other one is based on the atomic alignment induced by polarized lasers [11–15], where odd mass-number isotopes with non-zero nuclear spin are allowed for selective excitation and subsequent ionization due to hyperfine interactions and even mass-number isotopes with zero nuclear spin are prohibited from excitation by choosing proper angular momentum of the levels and the laser polarizations. The former one is suitable for isotopes having large isotope shifts and lasers with narrow bandwidth. In this method, for achieving high selectivity, it is necessary to avoid a situation where the targeted isotope has an overlapping absorption spectrum with undesired isotope. If this is inevitable [16–18], and the isotope shifts are small [19], then the latter one is highly suitable for selective photoionization. Isotope-selective photoionization based on atomic alignment using polarized lasers has been applied to Pt group metals [20], ytterbium [12, 21], tin [22], zirconium [14, 23], gadolinium [13, 15, 24]. Due to high thermal neutron absorption cross section (40 140 barns) of 149Sm [25], among the seven stable isotopes of samarium, Renier et al [26] investigated the potential use of enriched Samaria (Sm_2O_3) as burnable poison in the fuel pellets of pressurized water reactors. Recently Seema et al [27] applied the isotope-selective photoionization approach based on polarization selection rules to samarium using broadband lasers. More recently, Locke et al applied this method to selectively photoionize odd mass-number isotopes of palladium [28]. However, isotopic selectivity in this method may get affected by an external magnetic field or imperfect polarizations of the lasers used. In a situation especially, in atomic vapor...
laser isotope separation processes where vapors are generated by electron beam, the presence of the magnetic field in the laser-atom-interaction region due to electron beam bending magnet may affect the selectivity of the process severely. Therefore, it is important to study the atomic excitation dynamics and loss of selectivity under the influence of an external magnetic field to quantify the process accurately.

Guyadec et al [13] studied the effect of an external magnetic field on the resonant three-color three-step selective photoionization of gadolinium atoms. They demonstrated the loss of selectivity in the presence of external magnetic field under which the atomic alignment was destroyed by the precession of angular momentum and causing ionization of even isotopes. Niki et al [24] analyzed the influence of an external magnetic field on the excitation dynamics numerically using rate equations with linearly polarized lasers having rectangular pulse shape. They showed that ionization rate of undesired (even) isotopes is quantitatively related with the laser excitation rate, the magnetic field strength and the angle between the magnetic field and the laser polarization axis. Lim et al [29] studied the effect of magnetic field on selectivity by linearly polarized lasers numerically using density matrix formalism. They also predicted permissible strength of magnetic field to obtain enough selectivity for the targeted isotope of zirconium and gadolinium. Tokita et al [30] presented experimental results on the effect of magnetic field on gadolinium laser isotope separation and compared with the calculated results. Most of these studies were carried out on isotope-selective photoionization of gadolinium using the excitation scheme having total angular momentum sequence as $2\cdot2-1-0$.

In this paper, we report experimental results of the magnetic field effect on isotopic selectivity in a two-color three-step polarization-based isotope-selective photoionization of $^{149}\text{Sm}$ where selective photoionization is done through a level excitation scheme $0\text{ cm}^{-1}(J=0)\rightarrow 16690.76\text{ cm}^{-1}(J=1)\rightarrow 33645.4\text{ cm}^{-1}(J=1)\rightarrow$ continuum, where $J$ is the total angular momentum of the atomic level, by using two pulsed dye lasers linearly polarized in the same direction. Photoionization experiments using this level scheme $(0\rightarrow1\rightarrow1\rightarrow\text{continuum})$ are conducted under an external magnetic field and the isotopic selectivity (ratio of $^{152}\text{Sm}$ to $^{146}\text{Sm}$) is measured by varying the magnetic field strength perpendicular to the laser polarization axis while keeping the delay between the laser pulses fixed and vice versa. The effect of the magnetic field on isotopic selectivity is also investigated numerically using rate equations with linearly polarized, Gaussian shape laser pulses and compared with the experimental results. To our knowledge, this is the first report of magnetic field effect on samarium isotope separation using polarized lasers. Further, we also report the Lande factor $(g_J)$ of the excited level $16690.76\text{ cm}^{-1}$, determined from the observed oscillation in the isotopic selectivity.

2. Photoionization scheme for selective ionization of samarium

The photoionization scheme used for selective ionization of odd mass-number isotopes of samarium ($^{149}\text{Sm}$) is shown in figure 1. In this scheme, the samarium atom was excited and ionized by two lasers in a two-color three-step photoionization process i.e. $\lambda_1+2\lambda_2$, where $\lambda_1$ and $\lambda_2$ are the first- and second-step laser wavelengths, respectively. The selective photoionization of $^{149}\text{Sm}$ is realized by exploiting combination of total angular momentum sequence $0\rightarrow1\rightarrow1\rightarrow\text{continuum}$ of the level scheme and the polarization of the lasers used in these experiments. In case of even mass-number isotopes, the transition between magnetic sublevels $m_j=0$ to $m_j=0$ in the second step, with $\Delta J=0$, is forbidden according to the electric dipole selection rules [27] when the lasers

![Figure 1. Schematic of excitation pathway used for two-color three-step photoionization of samarium. $E_1 \parallel E_2$, where $E_1$ and $E_2$ are electric field vectors of laser polarization.](image-url)

are linearly polarized in the same direction. Hence, no ionization of even mass-number isotopes is expected. But, in case of odd mass-number isotopes due to their non-zero nuclear spin (7/2), further excitation and subsequent ionization through hyperfine manifolds are allowed, thus, resulting selective ionization of odd isotopes of samarium.

3. Numerical calculations

Samarium atom was assumed to be excited step-wise and subsequently ionized through the broadband lasers through the level excitation scheme shown in figure 1. As described before the two-color three-step ionization scheme employs two laser pulses but three photons to ionize samarium atom. In the case of broadband lasers, the interaction time i.e. laser pulse width is much larger as compared to its coherence time which is equal to the inverse of the laser line width and hence, transition between different optical energy levels is incoherent. In such cases multi-step photoexcitation dynamics can be described by rate equations [31].

In the frame with quantization axis parallel to the laser polarization axis which we call frame ‘A’, the atomic photoexcitation dynamics in the absence of an external magnetic field is governed by the following rate equations [24]

\[
\frac{d\rho^A_{m,m}}{dt} = - (\rho^A_{m,m} - \rho^A_{m,0}) W^A_{1m} + A_{10} \rho^A_{0,m},
\]

\[
\frac{d\rho^A_{m,m}}{dt} = (\rho^A_{m,0} - \rho^A_{m,m}) W^A_{1m} - \frac{\rho^A_{m,m}}{\tau_1} \rho^A_{m,m} - (\rho^A_{m,m} - \rho^A_{m,2}) W^A_{2m} + A_{21} \rho^A_{m,2},
\]

\[
\frac{d\rho^A_{m,m}}{dt} = (\rho^A_{m,2} - \rho^A_{m,m}) W^A_{2m} = \frac{\rho^A_{m,m}}{\tau_2} - \rho^A_{m,m} W^A_{21}.
\]

\[
\frac{d\rho^{ion}}{dt} = \rho^{A_2}_{m,m} W^{ion}_{21},
\]

where \(\rho^A_{m,m}(m = 0), \rho^A_{m,0}(m = -1, 0, 1), \rho^A_{m,2}(m = -1, 0, 1)\), are the populations of the magnetic sublevels in the ground, first excited, and second excited levels respectively and \(\rho^{ion}\) is the ion population. \(\tau_1\) is the radiative lifetime of the \(i\)th excited energy level. \(A_{i+1}\) is the transition probability between \(i\)th and \((i-1)\)th energy level. The relaxation term containing \(A_{i1}\) in equation (2) and the term containing \(\tau_2\) in equation (3) are neglected in the numerical calculations because the second- and third-step transitions are induced by the photons from the same laser pulse and there is no radiative loss from the second excited level in the process. \(W^A_{km}(t)\) is the photoexcitation rate between \(m\)th magnetic sublevel of upper and lower levels involved in the \(k\)th step transition and expressed as \(W^A_{km}(t) = \frac{\sigma^A_{l,m,l,m} \phi_k(t)}{\Delta \tau}, k = 1, 2, \) where \(\sigma^A_{l,m,l,m}\) is the polarization dependent photoexcitation cross section of the \(k\)th step transition and is related with the isotropic cross section \(\sigma^A_{l,m,l,m}\) as \(\sigma^A_{l,m,l,m} = 3 (2l + 1) \left( \frac{J_u}{m_u} \frac{J_l}{m_l} \right)^2 \sigma^A_{l,m,l,m}\), where \(q = 0\) for linear polarization and ±1 for circular polarizations. Here \(J_u\) and \(m_u\) denote, respectively, the angular momentum quantum number and magnetic quantum number in the lower level and \(J_l\) and \(m_l\) denote those in the upper level. \(\phi_k\) is the photon fluence i.e. number of photons per cm² per pulse, \(\Delta \tau\) is the pulse duration (FWHM) of the laser and \(f_k(t)\) is the Gaussian temporal profile of the \(k\)th step laser as

\[
f_1(t) = 2 \sqrt{\frac{\ln 2}{\pi}} \exp \left\{ -4 \ln 2 (t - t_0)^2 / \Delta \tau^2 \right\},
\]

\[
f_2(t) = 2 \sqrt{\frac{\ln 2}{\pi}} \exp \left\{ -4 \ln 2 (t - (t_0 + D_1 + D_2))^2 / \Delta \tau^2 \right\},
\]

where \(t_0\) corresponds to the peak position of the Gaussian shape laser pulse and \(D_1, D_2\) is the temporal delay between the first and the second step lasers. \(W^{ion}_{21}(t)\) is the ionization rate from the second excited energy level to the continuum and represented as \(W^{ion}_{21}(t) = \frac{\sigma^{21} \phi_k(t)}{\Delta \tau}\), where \(\sigma^{21}\) represents the photoionization cross section from the 2nd excited level to the continuum. The transition probability \(A_{i+1}\), in the case of photoexcitation having atomic absorption line width much less than the laser line width (\(\Delta \omega_l\)), is related to \(\sigma^A\) by the expression [3]
\[ \sigma^k = \frac{\lambda^2 A_{\alpha-1}}{4 \Delta \omega_k}, \]  

(7)

where, \( \lambda \) is the photoexcitation wavelength.

When an external magnetic field is taken into account, the time evolution of \( \rho_{m,m'}^B \) in a frame ‘B’ with quantization axis parallel to magnetic field \( B \) is governed by \([13] \)

\[ \frac{d\rho_{m,m'}^B}{dt} = -i\omega_L (m - m') \rho_{m,m'}^B, \]

(8)

with \( \omega_L = \frac{g_B \mu_B B}{\hbar} \), the Larmor angular frequency, where \( g_B, \mu_B \) and \( \hbar \) are the Lande factor, Bohr magneton and reduced Planck constant, respectively. \( \rho_{m,m'}^B \) in frame A and B can be transferred onto each other using the Wigner rotation matrix \( R(\theta) \) \([33] \)

\[ \begin{align*}
\rho_{m,m'}^A &= R(\theta) \rho_{m,m'}^B R^\dagger(\theta), \\
R(\theta) &= \begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & e^{i\theta} & 0 & 0 \\
0 & 0 & e^{-i\theta} & 0 \\
0 & 0 & 0 & 1
\end{pmatrix},
\end{align*} \]

(9)

where \( \theta \) is the angle between the quantization axis in frame A and that in frame B; that is the angle between laser polarization and the magnetic field direction.

In the presence of an external magnetic field and when \( \theta \) is non-zero, the total angular momentum quantum number \( J \) precesses around the external magnetic field with Larmor precession frequency \( (\omega_L) \). Consequently, the population of the magnetic sublevels is time dependent and is governed by equation \( (8) \). By solving equation \( (8) \) along with the equation \( (9) \) numerically, the temporal evolution of the atomic population of magnetic sublevels of a level having \( J = 1 \) is shown in figure 2(a). In these calculations, we have assumed, \( \rho_{m,m}^A = 1 \) for \( m = 0 \) and \( \rho_{m,m}^A = 0 \) for \( m = \pm 1 \) as initial values (at time \( t = 0 \) and \( g_B = 2.83, \theta = 90^\circ \), \( B = 0.5 \) mT. Figure 2(b) shows the calculated population of sublevels \( m = \pm 1 \) for different values of \( \theta \). It is observed that magnetic sublevels having initially zero population evolves with time in the presence of magnetic field for non-zero values of \( \theta \). For \( \theta = 90^\circ \), the population of \( m = \pm 1 \) sublevels does not only attain the maximum value but at a faster rate also. The temporal evolution of the population in the \( m = \pm 1 \) sublevels leads to the excitation and ionization of even isotopes and results in a loss of selectivity. For a given magnetic field strength the expected loss of selectivity is maximum when \( \theta = 90^\circ \).

The equations \( (1)-(4) \) describe the atomic population dynamics by the laser excitations in the absence of an external magnetic field. In the presence of magnetic field, photoionization yield has been calculated by numerically solving the rate equations \( (1)-(4) \) coupled with the equation \( (8) \) \([24] \).

4. Experimental details

A schematic diagram of the experimental setup used in these studies is shown in figure 3. It consists of two dye lasers (Quantel, model TDL 90), individually pumped by frequency-doubled Nd:YAG lasers (Quantel model YG 981), a high temperature oven assembly coupled to a linear time-of-flight mass spectrometer (TOF-MS) of length one meter having a mass resolution more than 500, an electronic delay generator, a wavelength meter (High Finesse WS 06), a PIN photodiode, a digital storage oscilloscope (DSO) and a PC based data acquisition system. The atomic beam of Sm was produced by resistively heating a tantalum oven containing a few hundred mg of Sm metal to ~750 K in the vacuum chamber maintained at ~5 \times 10^{-7} mbar pressure. The Sm vapors effusing out of an orifice of 1.2 mm diameter were further apertured at a distance of 15 mm by a fixed aperture of diameter 2 mm to produce a well-defined atomic beam in the interaction region. The atomic beam was irradiated at right angles at the interaction zone with two spatially overlapped dye lasers after passing through. The dye lasers are multimode and their spectral width is 0.08 cm^{-1} (~2.4 GHz), which was determined using Fabry–Perot etalon of free spectral range 0.5 cm^{-1}. The typical pulse repetition rate and temporal pulse width (FWHM) are 20 Hz and 5 ns, respectively. Rhodamine 640 and 6G dyes dissolved in ethanol were used for the first-step and second-step dye lasers respectively. The measured laser pulse energy densities of the first and second-step dye lasers (DL1 & DL2) were ~360 \mu J cm^{-2} and ~1.4 mJ cm^{-2} respectively. These energy densities were sufficient to saturate the first and second step transitions. The lasers polarization was controlled by placing a Glan–Taylor polarizer (Altechna, extinction ratio: > 10^4:1) in the path of combined laser beam. The spot size of the combined laser beam in the interaction zone was ~2 mm.

The excitation and ionization pathway used in this experiment is shown in figure 1. The samarium atom was excited from the ground level (0 cm^{-1}) to the first excited level at 16 690.76 cm^{-1} using DL1 tuned to the wavelength 598.97 nm. The DL1 wavelength was acquired using the wavelength meter. Subsequent excitation and ionization were done by the DL2 tuned to the wavelength at 589.64 nm through \( \lambda_1 + 2\lambda_2 \) process. The photo-ions generated in the interaction zone were extracted and accelerated into the flight tube of the TOF-MS.
and detected by a microchannel plate (MCP) detector. The DSO was triggered by the photodiode signal. All signals were monitored on the DSO and transferred to PC. The temporal delay between the lasers was introduced by the electronic delay generator and was monitored on the DSO using the photodiode. Each data point was obtained by taking average of 64 laser pulses. To study the effect of the magnetic field on the photoionization signal, an external magnetic field was produced by a permanent magnet (Eclipse major magnet, CAT No. 862). The directions of the magnetic field, lasers polarization axis and atomic beam are as depicted in the inset of figure 3. The strength of the magnetic field was measured with a gauss meter (HIRST, GM08). The strength of the external magnetic field in the laser-atom-interaction zone was varied by changing the position of the permanent magnet, which was mounted on a linear translational stage for changing the position of the magnet without affecting its orientation.

It should be noted that even in the absence of an external magnetic field there was always some residual magnetic field in the laser-atom-interaction region due to the high current (≈24 A) passing through the resistively heated oven and the terrestrial magnetism which has not been nullified in these experiments. The strength of the residual magnetic field in a direction perpendicular to both the laser polarization axis and laser beam propagation direction has been measured. The measured value of the residual magnetic field is $0.120 \pm 0.003 \text{ mT}$. The details of these measurements will be discussed later. Henceforth, the strength of magnetic field mentioned in all the measurements is the total magnetic field in the direction perpendicular to the laser polarization axis including the residual magnetic field.

Figure 2. (a) The temporal evolution of the population of magnetic sublevels ($m$) of $J = 1$ level for $B = 0.5 \text{ mT}, \theta = 90^\circ$. (b) The temporal evolution of $m = \pm 1$ sublevel population of $J = 1$ level for $B = 0.5 \text{ mT}$ and different values of $\theta$. 
5. Results and discussion

Figure 4 shows the TOF mass spectra of Sm$^+$ produced by performing two-color three-step photoionization with two lasers using the photoionization level scheme as described in figure 1. In the absence of an external magnetic field only odd mass-number isotopes of Sm were observed in TOF mass spectrum (figure 4 trace (a)). Hence, perfect isotopic selectivity (odd to even) was achieved in this case even though the residual magnetic field perpendicular to the laser polarization axis was present in the interaction zone. No loss of the selectivity was observed either, even in the presence of an external magnetic field of high strength, if the direction of magnetic field was parallel to the laser polarization axis i.e. $\theta = 0^\circ$. Even for $\theta = 90^\circ$, no ionization of even isotopes could be observed up to a magnetic field of strength 0.5 mT when both the lasers were synchronous. The reason is that the evolution of the atomic sublevel population induced by the given magnetic field is not sufficient to produce
an observable effect in a small laser-atom-interaction time i.e. laser pulse duration of 5 ns. Therefore, a sufficient delay between two lasers is necessary to observe the effect of the magnetic field in this case. Consequently, a fixed temporal delay of 8 ns was introduced between the lasers before recording all the traces of TOF mass spectra presented in figure 4. As the magnetic field is increased to 0.3 mT, the even isotopes appear in the mass spectra along with the odd isotopes (trace (b)). The photoionization signal of the even isotopes increases further with the increase in the strength of magnetic field (trace (c) and (d)). As shown in figure 4 (trace (e)), the maximum photoionization of the even isotopes was observed at a magnetic field strength of 1.1 mT. Thus, under these conditions the isotope selectivity is lost completely.

Conversely, the effect of magnetic field on the photoionization signal of even isotopes of Sm was studied as a function of temporal delay between the lasers when $\theta = 90^\circ$ and the strength of the magnetic field was kept constant at 0.5 mT. Figure 5 shows the traces of TOF mass spectra of Sm$^+$ for different temporal delays between the two lasers. Again, no measurable loss of isotopic selectivity was observed when both linearly polarized lasers were temporally synchronous (trace (a)). But, once the temporal delay between the lasers was increased, even isotopes also appear along with the odd isotopes in the TOF mass spectra (trace (b)–(d)), thus degrading the isotopic selectivity. The selectivity is lost completely when the delay is increased to 13 ns (trace (e)).

In the numerical calculations presented in figures 2(a) and (b), it is shown that in the presence of magnetic field for non-zero values of $\theta$, the population of magnetic sublevels having initially zero population evolves with time and oscillates with the Larmor frequency. The temporal evolution of the population in the $m = \pm 1$ sublevels leads to the excitation and ionization of even isotopes and the ionization of even isotopes is maximum when $\theta = 90^\circ$. Therefore, even isotopes along with odd isotopes were observed in the mass spectra in presence of the external magnetic field and resulting in a loss of isotopic selectivity.

In figure 6, the signal ratio of $^{154}$Sm$^+$ to $^{149}$Sm$^+$ are plotted as a function of magnetic field strength for three different values of temporal delays between the lasers when $\theta = 90^\circ$. With the exception of few data points at very low magnetic field an excellent match was observed between experimentally measured signal ratio (ratio of peak heights) and the numerically calculated results which are represented by the solid line in the figure. The slight deviation at very low magnetic field could be due to difficulties in realizing the experimental parameters exactly which have been assumed in the calculations. In these calculations, the laser parameters, experimentally measured photon fluence $\phi_1 = 1 \times 10^{15}$ cm$^{-2}$, $\phi_2 = 4 \times 10^{15}$ cm$^{-2}$ are used and values of $\tau_i$ and $A_{10}$ are taken from the literature [34, 35] as $\tau_i = 1.71 \mu$s and $A_{10} = 0.28 \times 10^4$ s$^{-1}$. The value of $\sigma_i^1$ is obtained from the equation (7). We assumed $\sigma_i^2 = 1 \times 10^{-15}$ cm$^2$, $\sigma_{e2}^1 = 1 \times 10^{-17}$ cm$^2$ [36, 37]. Initial population is assumed as $\rho_{00}^\Lambda = 1$, $\rho_{m,m}^\Lambda = 0$ and $\rho_{m,m}^\Lambda = 0$ for $m = -1$, 0, 1, $\rho_{m,m}^\text{ion} = 0$. The Lande factor (g) value of the first excited energy level was taken as 2.83 [38] and that of second excited energy level is assumed to be same as the first excited energy level as it is not reported in the literature. The value of $g_i$ of the second excited energy level is not important here because, firstly, second and third steps are synchronous as they are induced by the same laser and shorter temporal width of the laser pulse and secondly, all the magnetic sublevels of the second excited level are optically connected to the continuum. The calculated results are normalized with the experimental. In the case when both the lasers were synchronous, as shown in figure 6(a), no significant ionization of even isotopes was
observed up to a magnetic field of strength 0.5 mT and beyond this a small ionization of even isotopes was observed which increases slowly with increase in magnetic field strength. Under these conditions, as mentioned before, there is not sufficient time for transfer of atomic population between magnetic sublevels other than during the temporal pulse width of the laser which is 5 ns. Therefore, no significant loss of selectivity was expected in this case. For a temporal delay of 8 ns, the photoionization signal of even isotopes initially increases with the increase in magnetic field and then tends to saturate for a magnetic field of around 1.1 mT (figure 6(b)).

Figure 6. Signal ratio of $^{152}\text{Sm}^+$ to $^{149}\text{Sm}^+$ as a function of magnetic field strength for different temporal delay between the lasers (a) synchronous, (b) 8 ns and (c) 50 ns.
Thus, under a magnetic field of 1.1 mT or more than that the selective ionization cannot be expected when the polarization axis is perpendicular to the magnetic field and the temporal delay between two lasers is 8 ns or the laser pulse width itself is more than 13 ns. Finally when a temporal delay of 50 ns was introduced between the lasers, as shown in figure 6(c), the ratio of $^{152}$Sm$^+$ to $^{149}$Sm$^+$ signals exhibits periodic oscillations with the change in magnetic field strength. As explained by Tokita et al [30] that such a periodic feature is the result of phase shift in the precessional motion during the pulse delay of 50 ns. Thus, result in a periodic loss of isotopic selectivity with the magnetic field.

Finally, the ratio of $^{152}$Sm$^+$ to $^{149}$Sm$^+$ signals as a function of temporal delay between the lasers was studied in the presence of an external magnetic field perpendicular to the laser polarization axis whose strength is fixed at 0.5 mT and the resulting behavior is shown in figure 7. It is observed that the signal ratio of $^{152}$Sm$^+$ to $^{149}$Sm$^+$ exhibits periodic oscillations. The Lande factor of the energy level 16 690.76 cm$^{-1}$ was determined by fitting the experimental data points with the normalized calculated results with value of $g_J$ as a variable parameter. The normalization was done by equating maximum of the ratio of $^{152}$Sm$^+$ to $^{149}$Sm$^+$ signals with the calculated results. The $g_J$ value of the energy level 16 690.76 cm$^{-1}$ is $2.78 \pm 0.06$ which is in good agreement with the value 2.83 reported in the literature [38].

From these measurements, we conclude that in the presence of an external magnetic field which is perpendicular to the polarization axis of the lasers, the temporal evolution of the magnetic sublevels leads to ionization of even isotopes and hence, loss of isotopic selectivity. Further, the degree of loss of selectivity depends on the strength of the magnetic field, laser pulse duration for fixed laser energies and the Lande factor of the energy level involved in the photoionization scheme. Therefore, to minimize the effect of the magnetic field on the polarization-based isotope-selective photoionization process the energy levels having smaller value of the Lande factor in the scheme 0-1-1-continuum should be preferred for achieving high isotopic selectivity. For the given photoionization scheme, if it is required to suppress the amount of ionization of even isotopes of Sm less than 10% of odd isotopes, the strength of magnetic field should be less than 0.7 mT for 5 ns laser pulse width when both the lasers are synchronous as shown in figure 6(a). However, the permissible strength of magnetic field decreases from 0.7 to $\sim 0.2$ mT if the laser pulse is delayed by 8 ns (figure 6(b)).

5.1. Measurement of residual magnetic field

The strength of the residual magnetic field in a direction perpendicular to the polarization axis has been measured by performing photoionization experiments in which the photoionization signal ratio of even to odd mass-number isotopes is measured as a function of delay between the lasers dependence of the signal ratio on the temporal delay between the lasers is shown in figure 8. The strength of the residual magnetic field in the laser-atom-interaction zone perpendicular to the polarization axis was determined by fitting the experimental data points with the normalized calculated results with value of $B$ as a variable parameter. The measured strength of the residual magnetic field for our operating conditions is $0.120 \pm 0.003$ mT.
6. Conclusion

We have studied experimentally the effect of an external magnetic field on isotopic selectivity in a two-color three-step polarization-based isotope-selective photoionization of atomic samarium with a level scheme having total angular momentum sequence 0-1-1-continuum and analyzed the data numerically. The experiments have been carried out in the presence of an external magnetic field using two linearly polarized lasers. The effect of magnetic field on polarization-based isotopic selectivity was studied as a function of magnetic field strength perpendicular to the laser polarization axis while keeping the delay between the laser pulses fixed and vice versa. The experimental results are compared with the numerical calculations. The magnetic field perpendicular to the laser polarization axis present in the laser-atom-interaction region has been found to degrade the isotopic selectivity. The permissible limit of the magnetic field to suppress the amount of ionization of even isotopes of samarium less than 10% of odd isotopes, in this particular case, is found to be less than 0.7 mT for 5 ns laser pulse when both the lasers are synchronous. However, the permissible strength of magnetic field reduces from 0.7 to ∼0.2 mT if the laser pulse is delayed by 8 ns. In addition, we have measured the Lande factor \( g_J \) of the high-lying excited energy levels of samarium at \( 16,690.76 \) cm\(^{-1} \) \((J = 1)\).

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ORCID iDs

A C Sahoo https://orcid.org/0000-0002-7779-1168

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