Production of Atomic Alkali-Metal Beams in Single Hyperfine Sublevels

W. Dreves, H. Jänsch, E. Koch, and D. Fick
Fachbereich Physik, Philipps-Universität, D-3550 Marburg, West Germany
(Received 23 February 1983)

A compact source which produces atomic alkali-metal beams in individual hyperfine sublevels has been developed. The methods are demonstrated with ^{23}Na atoms. Initially nearly all atoms are transferred into one hyperfine sublevel ($|F, m_F\rangle = |2,2\rangle$) by a double-resonance technique using laser optical pumping and rf transitions. Subsequently the other hyperfine sublevels can be populated selectively by an adiabatic high-frequency transition. The hyperfine sublevel populations are determined by laser-induced fluorescence spectroscopy in a magnetic field.

PACS numbers: 29.25.-t, 32.80.Bx, 35.80.+s

Producing a beam of alkali-metal atoms in a single hyperfine sublevel[1] is not only intrinsically interesting, but also a valuable technique applicable in different areas of atomic and nuclear physics. The study of nuclear-spin relaxation of alkali-metal atoms on metal surfaces[2] and the investigation of atomic collision processes[3] will benefit from this tool. Since alkali-metal atoms can be ionized efficiently on hot metal surfaces without destroying the nuclear polarization,[4] one can (in a strong magnetic field) produce ion beams in a single m state of the nuclear spin. Even though they have not been used up to now such beams might be successfully employed in the study of polarization phenomena in beam-foil excitation. Of great current importance is the use of accelerated, highly polarized Li and Na beams in the investigation of heavy-ion interactions.[5]

Experience in the application of polarized Li ions in nuclear reaction studies performed with the polarized alkali-metal ion source in Heidelberg[4] stimulated efforts to increase the polarization of the beam. Such an improvement is particularly important for ^{23}Na, since for these ions partial depolarization during the acceleration process[4] has to be faced. A great advantage of polarization experiments is the possibility of extracting observables from relative measurements which compare cross sections for particle beams in different polarization states. In general beams with maximum polarization of each possible rank $k \leq 2I$ are necessary.[6] This requirement is easily met provided one is able to produce beams in all the different magnetic substates of the nuclear spin, one at a time. From the measurements performed with beams in these states one can then extract all polarization observables.

At first glance, optical pumping would seem to be a straightforward method for producing beams of alkali-metal atoms in a single hyperfine sublevel,[7] since these atoms can be excited easily by a tunable single-mode dye laser. In successive excitation cycles circularly polarized radiation transfers several quanta of angular momentum to the atoms which finally should all end up in the hyperfine sublevel with maximum m value. However, two major tasks must be solved experimentally before beams in a single selected hyperfine sublevel can be produced.

(i) In general the mode structure of a dye laser does not permit the simultaneous excitation of both hyperfine levels ($F = 1$ and 2) of the ground state. For ^{23}Na, which has been chosen for demonstration, the splitting of these levels is 1772 MHz. If an appreciable reduction of the atomic beam flux can be tolerated these difficulties may be solved by deflecting the atoms in the hyperfine level $F = 1$ by a Stern-Gerlach magnet.[8] To avoid this drawback a double-resonance technique using, simultaneously, radiofrequency transitions and laser optical pumping was applied in order to transfer nearly all atoms into the ground-state hyperfine sublevel $|F, m_F\rangle = |2, 2\rangle$.

(ii) The other hyperfine sublevels can be populated selectively by an adiabatic high-frequency transition[9] operated in a magnetic field of intermediate strength. Installed following the double-resonance section this device can transfer atoms in the hyperfine sublevel $|F, m_F\rangle = |2, 2\rangle$ into any other one of the $F = 2$ multiplet.

The experimental setup is sketched in Fig. 1. A ^{23}Na atomic beam effusing from an oven is collimated and excited within an rf resonator by circularly polarized D_1 radiation of a single-mode dye laser. Transitions between adjacent hyperfine sublevels can be induced by a subsequent high-frequency transition. A detailed in-

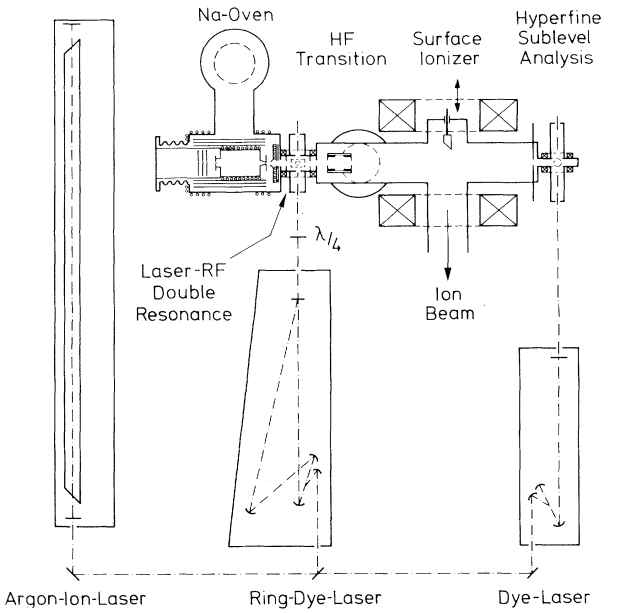

FIG. 1. Apparatus for the production of atomic alkali-metal beams in single hyperfine sublevels. The main components are a laser-rf double-resonance section and a hf transition operated in a magnetic field of medium strength. The hyperfine sublevel populations are detected by laser-induced fluorescence spectroscopy in a magnetic field. The vacuum system has a length of approximately 1 m.

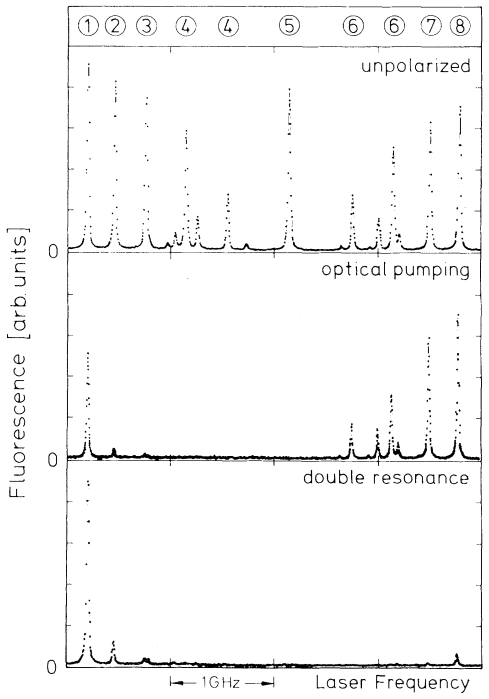

FIG. 2. Fluorescence of a ^{23}Na atomic beam in a magnetic field as a function of the laser frequency. Upper part: unpolarized beam; center part: beam optically pumped with circular D_1 light of a laser (transition $F=2\rightarrow F'=2$, $\Delta m_F=+1$); lower part: beam pumped by a laser-rf double-resonance technique.

vestigation of the various components of the source requires the technique to measure the population of the hyperfine sublevels. For this purpose the method of laser-induced fluorescence spectroscopy in a magnetic field was applied.[10] The atomic beam is excited at normal incidence by linearly polarized D_1 light in a magnetic field of 50 mT parallel to the laser beam (Fig. 1). From the fluorescence signals recorded as a function of the laser frequency one can directly obtain the occupation numbers of the hyperfine sublevels since the ratios of the excitation probabilities can be deduced by means of angular momentum algebra. A spectrum of an unpolarized beam (Fig. 2, upper part) consists of a variety of lines. The most prominent ones are labeled by a number indicating the hyperfine sublevel out of which the atom was excited. The levels are numbered according to their energy in a magnetic field by $|2,2\rangle$ = "1," $|2,1\rangle$ = "2," ..., $|1,1\rangle$ = "8." From these measurements the relative occupation numbers were determined with an uncertainty of less than 0.01.

The effect of optical pumping with right-circularly-polarized light of a single-mode dye laser alone is exhibited in the center part of Fig. 2. The laser power was about 180 mW/cm^2. The D_1 transition $F=2\rightarrow F'=2$ was chosen for the pumping process. As expected from calculations of rate equations (Table I, theory) the beam finally consists of atoms in level 1 and those with $F=1$, levels 6, 7, 8 (Table I). The residual intensity corresponding to level 2 suggests imperfect circular polarization of the incident light.

One new idea of the present experiment was to induce high-frequency transitions with $\Delta m_F=0$ between the hyperfine levels $F=1$ and $F=2$ simultaneously with the optical pumping. As the hyperfine sublevel 1 is not affected by this process all atoms should finally end up in this level. The rf power applied to the $\lambda/2$ cavity was about 35 W at 1772 MHz corresponding to a field strength of the order of milliteslas while the external static magnetic field was kept about 50 μT. It turned out that the resonance frequency of the rf transition becomes less critical because the optical pumping leads to an appreciable broadening of the hyperfine sublevels with $F=2$. On the other

TABLE I. Occupation probabilities of the hyperfine sublevels of a ^{23}Na atomic beam prepared in different ways. The experimental values were extracted from Fig. 2 (center and lower parts).

Hyperfine sublevel $\|F, m_F\rangle$	Level number	Laser optical pumping, theory	Laser optical pumping, expt.	Double resonance technique, expt.
$\|2,2\rangle$	1	0.24	0.21	0.78
$\|2,1\rangle$	2		0.02	0.10
$\|2,0\rangle$	3			0.04
$\|2,-1\rangle$	4			
$\|2,-2\rangle$	5			
$\|1,-1\rangle$	6	0.18	0.20	
$\|1,0\rangle$	7	0.28	0.28	0.02
$\|1,1\rangle$	8	0.31	0.29	0.06

hand the rf power necessary to induce the transitions increases as well. First results of such an experiment are exhibited in the lower part of Fig. 1 from which the occupation numbers of Table I were extracted. The measurements show that 78% of the atoms end up in hyperfine sublevel 1. In the future the optimum interplay of optical and high-frequency transitions has to be investigated in more detail. This will certainly improve the results furthermore.

The double-resonance region is followed by a "medium field transition" ($0.15 \lesssim X = g_J \mu B/h\Delta\nu \lesssim 0.20$), which was developed on the basis of an adiabatic weak-field transition, a device commonly used in polarized ion sources.[4,9] It works in a static magnetic field B_0 with a gradient $B' = dB/dx$ parallel to the direction of the atomic beam. Transitions between m_F and $-m_F$ are then induced by high-frequency radiation (5–10 MHz) in the Zeeman regime where the hyperfine sublevels of a multiplet are equidistant. At higher magnetic field strength the spacings of adjacent levels become unequal. Thus for a fixed frequency the various transitions are induced in different magnetic fields. For ^{23}Na they differ by more than 0.5 mT at 60 MHz, where the measurements presented here were done. In a magnetic field B_0 with a negative gradient B' one first induces the transition between levels 1 and 2, then between 2 and 3, 3 and 4, and at last 4 and 5. As the different transitions are spatially separated one can interrupt the process by a proper choice of the length of the transition and the magnetic field.

In the experiment the negative gradient B' and

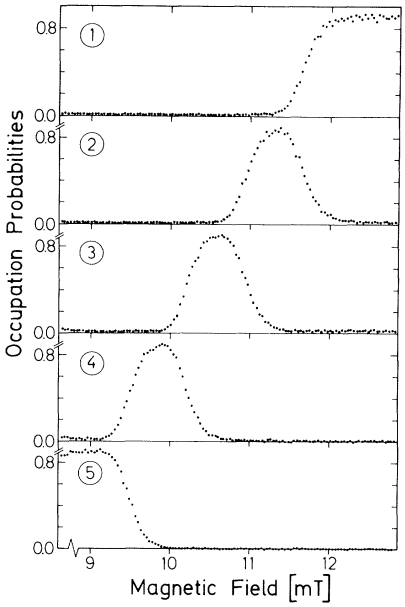

FIG. 3. Occupation probabilities of levels 1 to 5 behind the "medium field transition" section as a function of the magnetic field B_0 in the center of the transition region.

the high frequency were kept fixed at 0.8 mT/cm and 60 MHz, respectively. In order to start with an atomic beam of particles nearly all in sublevel 1 the beam was polarized in this case by optical pumping in front of a sextupole magnet.[8] The results are illustrated in Fig. 3, exhibiting the occupation probabilities of the hyperfine sublevels 1 to 5 behind the transition section as a function of the magnetic field B_0 in the center of the magnet. At high fields ($B_0 > 12$ mT) no transitions occur at all. The particles remain in sublevel 1. With decreasing field strength they first undergo only the transition from level 1 to 2. At still lower fields ($B_0 \approx 10.7$ mT) the transition 2 to 3 is induced additionally, and so on. In the lowest fields displayed in Fig. 3 the atoms have been transferred from level 1 to level 5.

Each of the levels is populated to more than 90% at the corresponding optimum magnetic field. These measurements indicate that an adiabatic high-frequency transition operated in a magnetic field of medium strength works nearly perfectly. It allows the exchange of populations of neighboring hyperfine sublevels almost completely. Thus it is an excellent tool to populate each of the hyperfine sublevels if one starts with an atomic beam in the sublevel 1.

Obviously these methods can be applied to atomic alkali-metal beams other than ^{23}Na as

well. They allow the construction of compact devices which might even be mounted in terminals of high-voltage accelerators since space and power consumption are low and the laser system can be installed on ground potential.

This research was supported by the Bundesministerium für Forschung und Technologie, Bonn.

[1]The term "hyperfine sublevel" is used for one level with specific magnetic quantum number m_F out of the hyperfine multiplet F.

[2]B. Horn, W. Dreves, and D. Fick, Z. Phys. B 48, 335 (1982).

[3]H. Kleinpoppen, Adv. At. Mol. Phys. 15, 423 (1979), and references therein.

[4]E. Steffens, Nucl. Instrum. Methods 184, 173 (1981).

[5]D. Fick, Annu. Rev. Nucl. Part. Sci. 31, 53 (1981).

[6]M. Simonius, in *Polarization Nuclear Physics*, Lecture Notes in Physics Vol. 30, edited by D. Fick (Springer-Verlag, Berlin, 1974).

[7]L. W. Anderson and G. A. Nimmo, Phys. Rev. Lett. 42, 1520 (1979).

[8]W. Dreves, W. Kamke, W. Broermann, and D. Fick, Z. Phys. A 303, 203 (1981).

[9]W. Haeberli, Annu. Rev. Nucl. Sci. 17, 373 (1967).

[10]H. Jänsch, E. Koch, W. Dreves, and D. Fick, to be published.