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A gas cell for stopping, storing and polarizing radioactive particles

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ABSTRACT

A radioactive beam of ^{20}Na is stopped in a gas cell filled with Ne gas. The stopped particles are polarized by optical pumping. The degree of polarization that can be achieved is studied. A maximum polarization of 50% was found. The dynamic processes in the cell are described with a phenomenological model.

1. Introduction

Particles of a radioactive secondary beam can be stopped in high-pressure buffer gas, where they can be trapped sufficiently long to study their decay, if their lifetime is shorter or of order of the typical diffusion time. If the beam particles neutralize to atoms, the nuclei of certain elements can be spin-polarized by optical pumping. This method for studying polarized particles was developed by Otten and coworkers [1] and more recently employed by Backe et al. [2], Young et al. [3], and Voytas et al. [4]. We have exploited it to study Lorentz violation in weak interactions, i.e. the question whether the integrated β-decay rate depends on the nuclear-spin direction with respect to an absolute reference system [5,6]. The analysis of these experiments required an effective description of the time dependence of the polarization, which will be discussed in this paper.

The measurements were made with a beam of ^{20}Na stopping in Ne buffer gas. By reversing the polarization direction and by switching the particle beam on and off, the characteristic time dependence of the polarization can be measured and the dynamics in the gas cell can be inferred to some extent. The relatively short half-life of ^{20}Na of 0.45 s is essential for these measurements.

The polarization technique used here requires neutralization of the incoming beam. Therefore, the experimental situation is analogous to gas catchers operated to extract secondary ion beams [7,8]. We discuss the operation of our gas cell in this context. A difference is that in this experiment stable Na can be evaporated into the gas cell.

The gas cells discussed here operate with noble gas; the ionization potential of the noble gas element is higher than that of the incoming particle such that it can remain singly charged. However, to which extent the particles in a fast ion beam are neutral, once they thermalize in a gas cell, remains an open question. If they remain ions, they can be extracted by flowing the buffer gas out. Ion catchers operate on this basis, a recent review is in Ref. [7]. If the particles neutralize, they can be re-ionized by two-step laser resonance ionization, which is element selective. A recent review of such Laser Ion Sources (LIS) is in Ref. [8].

A detailed study of neutralization in LIS is in Refs. [9,10]. Also the role of chemical binding of the stopped ion with trace molecules in the buffer gas has been discussed there. Here we show that by adding natural Na we appear to bind those molecules that otherwise would bind ^{20}Na. We find that the polarization maximizes to about 50% and the polarization lifetime of ^{20}Na is a few seconds.

The outline of this paper is as follows. We describe the experimental setup and the basic experimental observations. To facilitate the discussion of our results the time scales of various relevant processes in the gas cell are quantified. Next, our experimental results are presented and a phenomenological description is given. We conclude with a summary of our findings.

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2. Experimental setup

We used the secondary ^{20}Na beam from the TRIμP facility in Groningen [11]. The relevant nuclear properties of ^{20}Na are displayed in Fig. 1. The energetic beam of approximately 20 MeV/nucleon entered through a metallic foil (Havar) into a gas cell filled with neon at 7 atm absolute pressure. The schematic setup is shown in Fig. 2. The fiducial part of the setup is made from a stainless steel (316LNS) cube with 70 mm sides and 38 mm bore diameter in the three principal directions. The cell was filled with neon (purity 5.0) through a liquid-nitrogen cooled trap and a gas purifier (SAES FT400-902). The gas was first circulated through the purifier. The cell was evacuated and refilled through the same system prior to the experiment. The gas is not circulated during the experiment, because the stopped particles need to stay inside the fiducial volume. Metal seals and valves were used. Natural sodium atoms can be evaporated into the cell by heating a commercially available sodium dispenser (SAES AMD). Aluminum foils were placed in front of the cell such that the beam stops in the middle of the fiducial volume. The position fine-tuning was made by appropriately rotating one of the foils for maximizing the count rate in the detectors.

The laser beam was tuned to the ^{20}Na D_1 transition adjusted for the buffer gas pressure ($\lambda = 589.782$ nm). Pressure broadening of about 50 GHz mixes the hyperfine states. The laser beam is split into two beams with opposite light helicity and recombined again onto the same optical path. Actuators are used to block either beam or both beams. A beam expander magnifies the profile of the laser beam to an approximately Gaussian shape with 1.2 cm full-width-half-maximum. This laser beam is guided by silver mirrors and passes through fused silica windows (diameter 29 mm) of the gas cell. The average laser-light intensity delivered to the gas-cell fiducial area is $s_A = 2 \times 10^{-2}$ W cm^{-2}. The windows are surrounded by coils in Helmholtz configuration for a magnetic field of about 15 G aligned with the laser beam.

The β particles from ^{20}Na decay have an endpoint energy of 11.7 MeV. β particles with energy exceeding about 2 MeV can pass through the window and the mirror. The average velocity of the detected β particles is 99% of the light speed. They are measured with two thin scintillation detectors, that are insensitive to γ rays. Each β detector has an opening angle of $\Delta\theta = 22^\circ$ centered relative to the polarization axis, i.e. $\langle \cos\theta \rangle = 0.99$.

Fig. 3 displays the β-particle rates measured in periods with the primary ^{20}Ne beam on (0–2 s) and off (2–4.1 s). In three consecutive periods, the samples were first polarized in one direction (0–4 s), then in the opposite direction (4.1–8.1 s), and in the third period (8.2–12.2 s) the laser light was off. The additional 0.1 s was required for operation of the actuators, here the polarization is undefined. The data of many sequences have been averaged here to obtain good statistical accuracy for each 4 s period.

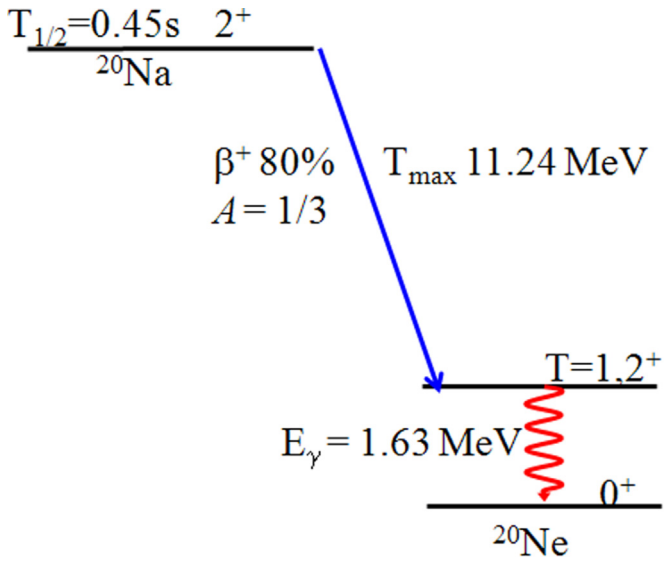

Fig. 1. Relevant decay properties of ^{20}Na.

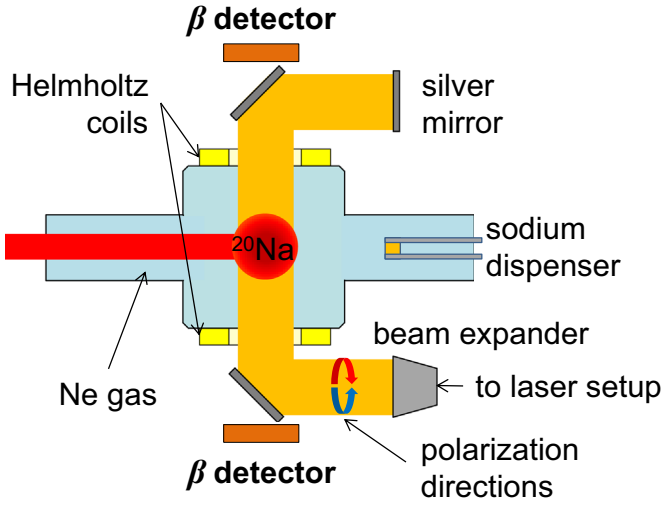

Fig. 2. Schematic drawing of the buffer-gas cell, the ^{20}Na beam, the light beams, and detectors.

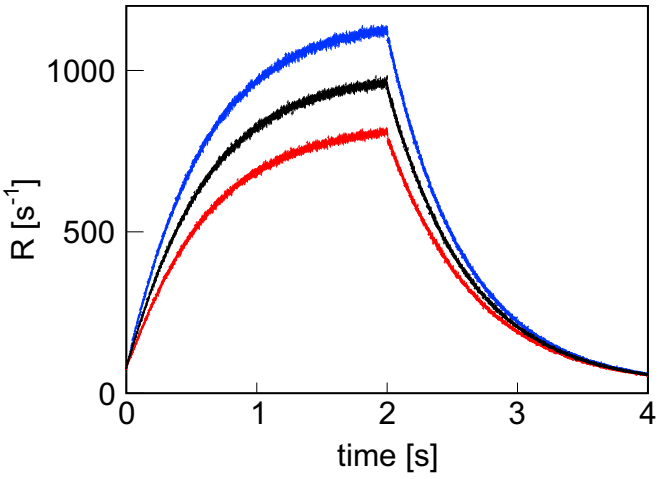

Fig. 3. The measured β rates in one of the detectors. The top (blue) and bottom (red) curves are data points obtained with opposite helicity of the laser light. The middle curve displays the decay rate when the laser light was absent. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

The β-asymmetry parameter $A_{Wu} = 1/3$ for a $2^+ \rightarrow 2^+$ Gamow–Teller transition. Therefore, to good approximation, the count rate in the β-particle detectors is $R^{\pm}_{L(R)} \propto 1 \mp (\pm) A_{Wu} P$, where the signs depend on the direction of the polarization ($\pm$) and the place (L/R) of the detector. The polarization is $P = A_\beta / A_{Wu}$. The count rate asymmetry A_β is given by

$$A_\beta = \frac{\sqrt{R_L^+ R_R^-} - \sqrt{R_L^- R_R^+}}{\sqrt{R_L^+ R_R^-} + \sqrt{R_L^- R_R^+}}. \quad (1)$$

The observed value corresponding to the data in Fig. 3 is shown in Fig. 4. The maximum polarization of about 50% is achieved when the beam is on, while it drops when the beam is off. This observation is central to the discussion in Section 4.