EXTINCTION MONITOR BY USING A DISSOCIATION OF HYDROGEN MOLECULE TO ATOMS WITH HIGH ENERGY PROTON BEAM

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Abstract

Unwanted particles produced in various acceleration stages are detrimental for delayed coincidence experiments involving rare decays such muon to electron conversion. A new monitoring scheme is proposed to realize the beam extinction lower than 10^{-6} for a bunched proton beam. Dissociation of hydrogen molecules into hydrogen atoms is detected by colliding a high-energy proton beam with a low-energy hydrogen-ion beam. The beam extinction is estimated from the collision luminosity with the aid of theoretical dissociation cross section. It is expected that the available beam extinction as low as 10^{-9} could be obtained by using a hydrogen-ion storage ring with a pulsed ion source.

INTRODUCTION

Achieving beam extinction between beam bunches is critically important for delayed coincidence measurement in high sensitivity experiments such as μ to e conversion as well as μ to e + gamma conversion in high-intensity frontier particle physics[1]. A new method for detecting extinction is proposed that uses the collision dissociation between a high-energy proton with an energy of greater than 1 GeV energy and low-energy molecular ions. Dissociation of molecular ions due to a single path collision or a collision between high energy particles and stored molecular ions would separate these molecules into atoms that could be detected as a nuisance particles separate from the main beam bunch. Such a process could be exploited for extinction monitoring. Unwanted particles are produced in various acceleration stages, such as an ion source, during low energy beam transport, medium energy beam transport, high energy beam transport) and injection into and/or capture by the booster ring, or main accelerator and during extraction. Recent experimental and theoretical studies have elucidated why unwanted particles are produced inside an accelerator. In particular, high energy, high current accelerator losses current due to a hallow formation and/or deterioration caused by the space charge force and the non-linear terms of guiding elements, such as resonances crossing and space charge induced emittance growth [2]. Laterally produced unwanted particles at thick slits of collimators, thin foil stripper at injection and septum material at extraction are routinely rejected at collectors located inside an accelerator itself and in transported lines. To conduct an accurate experiment, in addition to the lateral distribution the longitudinal distribution of a pulsed beam should be precisely investigated and tailored to match the requirements at various sections of accelerator facility.

In PRISM (Phase rotation for intense slow muon) and its staging experiment COMET (coherent muon to electron), a slow-extracted bunched proton beam is helpful for reducing the background. This is because the beam related background can be removed by suitable selection of proton pulse timing and the electron signal is detected at times longer than the muon lifetime (about 1 μsec) after a proton bunch. If residual protons are present between the proton pulses, they will produce the beam-related background in the signal timing. To prevent this, the residual protons, the beam extinction should be reduced to 10^{-9} or less.

Thus, monitoring the extinction is crucial for performing extremely high sensitive experiments for rare events such as KOPIO, MECO and COMET [3]

REQUIREMENTS

The proposed experiments KOPIO, and MECO, COMET have very severe extinction conditions[4]. As a brief survey of such conditions we describe the experimental requirements for COMET and PRISM-PRIME. The high sensitivity required for searching for rare elementary processes necessitates a high-flux beam. To realize the target sensitivity of 10^{-16} in the branching ratio of μ^- - e^- conversion, a total flux about 10^{18} muons is required. To achieve this using current muon-beam lines, about 8 x 10^{20} protons with energy of 8 GeV are needed. Assuming a running time 2 x 10^7 s (i.e. about 8 months) a beam intensity of 4 x 10^{13} protons/s is needed. The proton beam needs to be pulsed, and the pulse separation should be about 1 μsec. The signal electrons will be emitted at the target with a lifetime of negative muons (about 1 μsec), thus it will enter the detector in between the proton pulses. On the other hand, the beam-related background will follow the proton pulse timing uced by fast processes. Thus, if there are residual protons between the proton pulses, they will produce beam-related background with the signal timing. In order to prevent the residual protons in between the pulses the proton extinction should be reduced to 10^{-9} or less.

Therefore, beam extinction between beam bunches is critically importance. In the MECO experiment some tests to measure the proton extinction were performed at BNL-AGS. An extinction ratio of about 10^{-7} was achieved. In order to realize lower extinction ratios (such as 10^{-7}~10^{-9}), we have to develop cope new technologies for monitoring beams with extremely low particle densities in a longitudinal direction. In particular, for delayed coincidence experiments of MECO and COMET the time structure of bunched and extracted beam spills should be optimized to reduce the background.

PRINCIPLE FOR EXTINCTION MONITORING

There are several diagnostic methods are available for monitoring the extinction level in an accelerator as well as during beam transport to the target or beam dump. These are Cherenkov radiation detection with a gated photomultiplier, beam loss detection with a high-sensitivity ionization chamber and interaction monitoring with an elementary-particle detector. An extinction ratio of around 10^{-7} have so far been achieved.

We here consider the new technique for measuring extremely low extinction levels using a Coulomb dissociation of energetic molecular ions in a beam-to-beam collision. The method takes into account the dissociation cross section, the collision luminosity and the atomic hydrogen detection efficiency. A beam-to-beam collision bunched beam with an almost the same micro bunch structure would be suitable for the measurement of an extinction between intra micro beam bunch. The principle of the monitor is schematically shown in Fig. 1. The single-path collision and collision between stored hydrogen ions are two collisions used by this method.

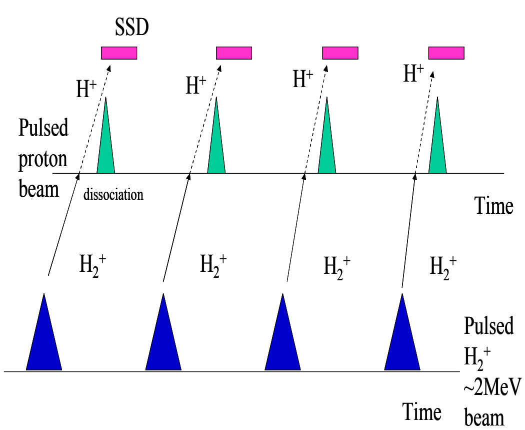

Figure 1: Principle of extinction monitor and micro structure of beam.

a) Collision of molecular ion beam with one path

The system consists of a gated or pulsed ion source, static or pulsed acceleration system and beam transport to the collision section via a focusing system. A pulsed cusp source, a 2.45 GHz ECR ion source or a PIG source with a gated electrode (additional anode) would be the most suitable sources for generating a hydrogen 1^+ ion beam since a high plasma temperature is not necessary[5,67,8]. These ion sources are capable of producing more than 1mA (around 10^{+13} H_2^+/sec) when operated in either pulsed or DC mode. It is important to accelerate ions up to ~100 keV to be able to discriminate the atom signal from noise after a collision. The system is shown in Fig. 2

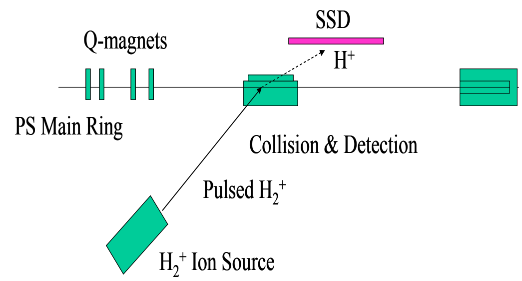

Figure 2: Single path collision scheme.

b) Collision of molecular ion beam with a storage ring

A pulsed ion source would be suitable for producing a molecular-ion beam and injection it into a storage ring. Thus, we propose a cusp source and 2.45-GHz ECR ion source. The storage and acceleration ring can accelerate H_2^+ ions beam up to 1mA around 1 MeV. The time structure of micro bunch will be almost the same or wider that of the proton beam from main ring. The proton beam and the stored hydrogen beam will be collided in the straight section. A small dipole magnet will be located in the collision section to detect and analyze dissociated hydrogen atoms of about 0.5 MeV. This will not affect the optics of the original proton beam. A schematic view of the system is shown in Fig. 3.

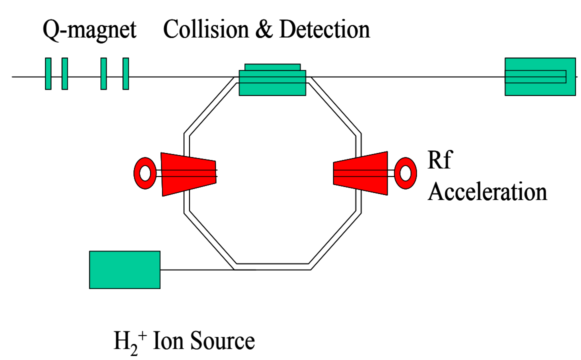

Figure 3: Storage and acceleration ring of H_2^+ ion and detection section of dissociated atoms.

LUMINOSITY CONSIDERATION

A one-path scheme ***a***) or a storage scheme ***b***) will be investigated in terms of a quantity called the collision luminosity (L) for beams is often, which is defined as:

$$L = N_{proton} \cdot N_{mol.}$$

where $N_{proton} \cdot N_{mol.}$ is the product of high energy proton number per second and the number of stored hydrogen molecule ions per second. We assume the collision angle is almost zero degree (for a case of scheme ***a*** a zero-degree collision would be impossible). We also assume that the two collision beams have the same geometrical factor and that the event rate for dissociation with a solid state detector array is given by as $N = L\,\varepsilon\,\sigma$, at a detection efficiency (ε) of 100 %.

There are no experimental data for a dissociation cross section for a high Lorentz factor, although a large number of data has so far been obtained for low-energy electron transfer experiments such as excitation and ionization. The existing data is for cross sections for electron stripping from $^3He^+$ ions at a medium energy, $\sigma_{STRIP} = 1.05 \times 10^{-17}$ cm^2, and for electron capture by $^3He^{++}$ ions, $\sigma_{CAP} = 1.12 \times 10^{-25}$ cm^2 at a projectile energy E^3_{He} = 450 MeV [9]. At higher energy by using Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory [10] the first measurement of cross sections for orbital electron capture has been achieved. If we assume that molecular dissociation is caused by a stripping process in a high-energy collision we can estimate the cross section estimated for the stripping process. We need to extend an asymptotic expansion form of the Born approximation. According to Gillespic [11] $\sigma_{strip} = 8\pi a_0^2 I (v_0/v)^2$, ~ 8 x 3.14 x $(5.29 \times 10^{-9})^2$ x 2.98 x $(2.19 \times 10^8 / 0.994 \times 3 \times 10^{10})^2$

where the Bohr radius a_0 = 5.29 x 10^{-9} cm, the Bohr velocity v_0 = 2.19 x 10^8 cm/s, v is the ion velocity, Z_t is the atomic number of target and Z_p is the atomic number of the projectile. The parameter I is called the ionization collision strength and it is given by integrating the momentum transfer

$I \sim 1.24/Z_p^2\{ Z_t (1 + 0.105Z_t - 5.4 \times 10^{-4}Z_t^2)\} = (1.24/1) \times 2 \times (1.205) = 2.988$

Thus, the stripping cross section for β=0.994 proton might be 10^{-19} cm^2 (based on the stripping cross section based on the former equation). It is reasonable to assume that the dissociation cross section of at least $\sigma=10^{-18}$ cm^2 will need to be account for [12]. The available luminosity $L= N_{proton} \times N_{mol.}$ at the (desired) extinction ratio of 10^{-9} can be calculated using N_{proton}/sec=10^{13} x 10^{-9} and $N_{mol.}$/sec= 10^{15} . An event rate for dissociation would be about 10 events/sec from $N_{event} = L\, \varepsilon\, \sigma$ *and* $L = 10^4 \times 10^{15} = 10^{19}$. Thus, we could obtain sufficient counts in a few minutes to ensure a statistical error of less than a few percent.

CONCLUSION

The proposed scheme for monitoring extremely low extinction ratios has the potential to be a versatile tool for high-intensity frontier particle physics. By using solid-state detectors of reaction particles, the proposed system will be is more resistant to radiation than other systems such as optical detector systems. Collision and dissociation luminosity should be estimated using more precise experimental data, which could be obtained at several high-energy laboratories. These investigations of the micro-bunch structure of accelerated particles will result in further advances in beam dynamics investigations using electron accelerator as well as hadron accelerators.

ACKNOWLEDGEMENTS

We gratefully acknowledge a valuable discussion for dissociation cross section of relativistic molecule with the late Professor Mineo Kimura who suddenly passed away.
This work was supported by the Grant-in-Aid of Scientific Research, Ministry of Education, Culture and Sports, No. 19540292 and was supported by the Japan Society for the Promotion of Science under Grant-in Aid for Creative Scientific Research (Project No. 15GS0211).

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