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SEARCH FOR RESONANT STATES IN POSITRON-ELECTRON SCATTERING USING A POSITRON GAS TARGET *

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Abstract

Narrow correlated positron-electron peaks discovered in superheavy nuclear collisions may be signatures for previously undetected neutral particle-like objects having masses of 1-2 MeV/c^2. We have designed an experiment to definitively test this hypothesis by searching for resonant states formed directly in the scattering of monoenergetic electrons incident on a gas of cold positrons confined magnetically in a Malmberg trap. This technique will provide a hundred-fold improvement in sensitivity to e^+e^- resonances compared to previous positron-beam, thin-foil scattering experiments. Together with a recoil-shadow technique, this experiment will explore a five decade range in neutral-particle lifetimes (10^{-13}s to 10^{-8}s) which cannot be probed directly by other methods.

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1. Introduction

Since their discovery at GSI Darmstadt in 1985 by the EPOS Collaboration [1], the origin of the narrow correlated e^+e^- peaks emitted from heavy-ion collisions has remained a mystery. At least three sets of correlated e^+/e^- lines in each of two collision systems (U+Th and U+Ta) have been firmly established [2], which cannot be attributed to conventional nuclear or atomic processes. The peaks appear to arise from the two-body decays of previously undetected neutral objects of mass 1.63, 1.77, and 1.83 MeV/c^2, having lifetimes between $\sim 10^{-19}$ s to $\sim 10^{-9}$ s. Moreover, the existence of narrow peaks has been confirmed by an independent group at GSI [3], and most recently by ourselves and co-workers with a new spectrometer at the LBL SuperHILAC [4]. The simplest interpretation of these data in terms of a family of new <u>point-like</u> elementary particles (e.g., axion-like bosons) is unlikely in light of negative results from a variety of particle search experiments [2,5]. It has been pointed out, however, that a spatially extended object (e.g. with a radius $\geq$ 100 fm) would have evaded detection so far, and might in a natural way account for both the existence of the several e^+/e^- lines (in terms of a spectrum of internal excitations) and the low velocity ($\leq$0.2c) with which the objects are emitted in the HI collisions [6]. Many theoretical models proposed to date, ranging from non-perturbative effects in QED to new types of fermions and/or fundamental interactions, but none has yet been proven to quantitatively reproduce the heavy-ion observations [5].

2. Previous Experiments

Several experiments have investigated the neutral particle hypothesis by attempting to create these states directly in the time-reversed process, namely by searching for their resonant contribution to elastic positron-electron (Bhabha) scattering at center-of-mass energies equal to the invariant mass of the anomalous e^+e^- pairs [7,8]. This channel is insensitive to the size or internal structure of such a state, and the resonance cross-section is simply described by Breit-Wigner theory. Over the relevant lifetime range, the decay widths Γ_{e+e-} are narrow compared the experimental resolution, so the expected signal equals the energy-integrated BW cross-section divided by the CMS energy spread

$$\sigma_{exp} = (\pi/2)\ \sigma_{BW}\ \Gamma_X\ /\ \delta E_{cms},$$

where

$$\sigma_{BW} = (2J+1)\ 4\pi\ h^2\ (M_X{}^2c^4 - 4m^2c^4)^{-1}\ (\Gamma_{e+e-}/\Gamma_X)^2$$

is the Breit-Wigner cross-section at $E_{cms} = M_Xc^2$. It is known that two photon decay is small compared the e^+e^- channel ($\Gamma_{2\eta}/\Gamma_{e+e-} \leq 2 \bullet 10^{-3}$ [9]), and assuming that the e^+e^- branch is the dominant decay mode ($\Gamma_{e+e-} \approx \Gamma_X$), $\sigma_{BW} \approx$ 2100 barns for a spin J=0 object of mass $M_X = 1.83$ MeV/c^2.

Previous searches for resonant e^+e^- scattering have all involved positrons incident on thin foils (usually Be). The momentum of the bound target electrons, when transformed to the CM system, leads to a spread in the CMS collision energy ($\delta E_{cms} = 7.8$ keV for Be [8]), which limits the size of the expected signal, and hence the sensitivity to resonances above the underlying elastic scattering continuum ($d\sigma_{e+e-}/d\Omega \approx 20$ mb/sr at $\theta_{cms} \approx 90^o$). The present limit [7] is $\sigma \bullet \Gamma \leq 6.3$ b•eV, or $\tau_{e+e-} > 3.5 \bullet 10^{-13}$ s, beyond which little progress can be expected using atomic targets.

Several groups have attempted to extend the excluded parameter range to longer lifetimes by exploiting the large velocity of the CMS ($v_{cm} \approx 0.8c$) with the use of recoil shadow or beam-dump techniques. (A Grenoble experiment claims to exclude $4.5 \bullet 10^{-12}$ s $< \tau_{e+e-} < 7.5 \bullet 10^{-12}$ s [10].) These results however are highly sensitive to the detailed interaction of the extended objects in that they require that the object penetrate the rather thick target (Grenoble: 4.6 mg/cm^2 Be) or beam-dump material. A re-examination of the heavy-ion data [11] indicates that the peak positrons and electrons are likely emitted in the vicinity ($\sim 10^3$ fm) of the colliding heavy ions, implying that the neutral state may be created and quickly destroyed in the nuclear Coulomb field. Assuming a polarization mechanism for its dissociation, proportional to the square of the electric field, the calculated absorption length in Be is only ~ 1 mg/cm^2. Substantially thinner targets are therefore required for a meaningful, essentially model-independent, search for long-lived states. Dissociation of the object in the nuclear field also invalidates the 10^{-9} s upper lifetime limit derived from the fiducial volume of the EPOS spectrometer, raising the possibility of a much narrower production width Γ_{e+e-} (longer decay time τ_{e+e-}) in vacuum.

3. Experimental Design

We have designed a new experiment [12] which both achieves a greater sensitivity to the direct production of resonance states, and uses a thinner target to provide model-independent sensitivity to long-lived states. This is accomplished by using a "gas" target of magnetically confined leptons to circumvent the resolution limitations imposed by the Fermi momentum of bound electrons in solid targets. To obtain useful e^+e^- scattering rates (~ 1 Hz for $\theta_{cms} \geq 90°$) in light of the availability of only weak ($\sim$pA) e^+ beams, we use the combination of an intense e^- beam (~ 10 μA) incident on a cold gas of magnetically confined positrons ($\sim 10^{10}$ e^+/cm^3), as illustrated in Fig. 1. An equilibrium e^+ temperature of ≤ 100 K, and unambiguous lepton identification made possible by a novel detection geometry, will provide a factor of 100 greater sensitivity to resonant e^+e^- scattering (i.e., for τ_{e+e-} <3.5•10^{-11} s) than previous positron-beam, thin-foil experiments.

3.1 Positron Trap

The positrons will be stored in a magnetic trap, which consists of a coaxial array of cylindrical gold-plated copper electrodes mounted along the axis of a 1 meter long 6 Tesla solenoid magnet. Radial confinement is provided by the strong magnetic field, and the positrons are confined axially within a given section by biasing the adjacent electrodes on either side of the plasma column to a positive voltage. This so-called Malmberg trap was developed and has been used extensively by J.H. Malmberg and co-workers at U.C. San Diego to investigate non-neutral single-component pure-electron plasmas [13]. Their cryogenic high-field version has demonstrated the feasibility of a high electron density and low temperature required for this experiment. An e^-plasma forms as a column of nearly uniform density which spins as a rigid rod about its symmetry axis (due to ExB forces from the radial space charge electric field) with a constant total angular momentum (in an ideal trap). Azimuthal asymmetries in, or misalignments of the trap electrodes and/or magnetic field appear as RF sources by the rotating plasma column, and exert torques which tend to radially deconfine the plasma. We have fabricated an confinement structure in which the electrodes are mounted in a precision ceramic V-block to provide a mechanical tolerance of 2.5 μm over a 60 cm length. Absolute alignment with the field axis is achieved by superconducting magnetic shim coils, and we expect an azimuthal uniformity of $\delta B_\perp/B \ll 10^{-4}$. Confinement times of up to 300 s may be achievable.

One important feature of a high-field trap is that the thermal energy of the leptons, exhibited as cyclotron motion superimposed on the ExB rotation, is dissipated by synchrotron radiation in the strong magnetic field. This provides a natural cooling mechanism for the positrons which will be exploited to offset the Coulombic heating of the plasma by the injected electron beam. The choice of the positron plasma and electron beam parameters presented above and in the following discussion represents a reasonable optimization of various competing effects, such as the plasma filling vs. containment times, electron beam heating vs. radiative cooling rates, possible beam-plasma instabilities, and the need for a reasonable e^+e^- scattering rate. The magnitudes of the relevant physical processes are summarized in Table 1 for our nominal conditions, together with their functional dependence on various parameters such as positron density, plasma radius and length, and beam current (n_{e+}, r_{e+}, L_{e+}, and I_{e-}, respectively).

The positrons will be injected along the solenoid axis into the trap from the LLNL intense low-energy pulsed positron source (driven by a 100 MeV e^- Linac) [14]. Each e^+ beam pulse will be electrostatically accelerated to ~5 keV in order to penetrate the strong magnetic field, during which it will be compressed to $\sim 10^{-2}$ cm and have attained significant transverse energy. The positrons must be re-moderated in the high field region to typically a ~2 eV energy spread, and will be trapped by time-of-flight utilizing the pulsed time structure of the beam ($\delta t \sim 1$ ns, 1440 Hz repetition rate). Once confined, the positrons will radiatively cool on a 0.1 s time scale to the ambient 4.2 K temperature of the LHe cooled electrodes. After a ~25 s long injection phase, the trap will contain a 30 cm long by 1 mm diameter thread-like plasma of $2.5 \bullet 10^9$ positrons, having an average density of 10^{10} cm^{-3}.

3.2 Electron Beam

Once the trap is filled with positrons, the electron beam from a

National Electrostatics Corporation model 9SDH-2e 3 MV Pelletron accelerator will be injected along the axis of the solenoid. The ~10 μA beam current, chosen to achieve an equilibrium positron temperature of ≤100 K (~8 meV), will produce a beam-target luminosity of ~$2 \cdot 10^{25}$ $e^+e^-/cm^2/s$, providing a ~0.5 Hz event rate for e^+e^- scattering with $\theta_{cms} \approx 90°$, comparable to previous beam-foil experiments. Including the e^- beam energy resolution (≤500 eV peak-to-peak), we will achieve a collision energy spread in the CM system of $\delta E_{cms} \leq$ 200 eV (compared to 7.8 keV for Be target experiments). The electron beam energy will be fine-tuned at any given Pelletron setting by floating the entire electrode structure to high voltage. In this way, we plan to reduce systematic errors in normalizing adjacent points of the excitation function by continuously sweeping the beam energy by ±10 keV, and recording the instantaneous voltage offset with each scattering event trigger. The Pelletron beam energy operating range of 0.6 to 2.7 MeV will allow investigations over an e^+e^- pair invariant mass range of 1.29 to 1.95 MeV/c^2.

3.3 Lepton Detection

The scattered positrons and electrons will be detected with ≥90% collection efficiency and ≤10 keV energy resolution in an array of Si detectors at the downstream end of the trap. A novel collection geometry has been developed which exploits the adiabatic elongation of the lepton orbits as they are transported out of the solenoid along the axis to a low field region (~1 kG). Here the positrons and electrons are deflected by a localized transverse dipole field (formed by SmCo permanent magnets) and spiral (with opposite helicity) in the fringe field of the solenoid into the separate detector arrays. Positrons are further unambiguously identified by the coincident detection of their 511 keV annihilation radiation in an array of

NaI crystals surrounding the detector.

A prototype of this spectrometer, using a 2.7 T solenoid, has been successfully tested at the LBL SuperHILAC in which we measured coincident positrons and electrons emitted from a U beam injected along the axis to a Ta target located in the center of the solenoid [4]. In our first shakedown run, we achieved a 15-fold improvement over the EPOS Spectrometer e^+e^- detection efficiency, and have at least qualitatively confirmed the existence of narrow e^+e^- peaks in U+Ta collisions. Minor improvements presently underway will yield a 25-fold increase over the EPOS efficiency for additional runs planned for the near future.

The measured laboratory energies of the leptons and the e^+/e^- discrimination will allow complete reconstruction of the CM collision kinematics. This is a substantial improvement over present beam-foil experiments which fail to distinguish positron from electron. We will concentrate our search for resonance states at backward CMS scattering angles (e.g., 90^o - 180^o), whereas other experiments measure only the total symmetrized cross-section around $\theta_{cms} \approx 90°$ [7] where the elastic scattering continuum is three times more intense. Combined with the above improvement in CMS energy resolution, we expect a factor of 100 increase in sensitivity.

Systematic uncertainties will be minimized by sweeping the beam energy as well as by redundant normalizations to the forward-angle elastic scattering continuum, the integrated beam current, and the total e^+ charge and beam-plasma overlap which are measured destructively at the termination of each fill-scatter-dump cycle. A limit on the existence of peaks at a level of 0.3% above the elastic scattering continuum, comparable to the Grenoble result, translates into a $\sigma \bullet \Gamma \leq 0.2$ b•eV limit on the integrated cross-section, extending the explored region of parameter space to lifetimes of $<3.5 \bullet 10^{-11}$ s.

3.4 Recoil Shadow

The existence of neutral objects with long lifetimes will be investigated with a recoil-shadow geometry as indicated schematically in Fig. 2. An annular filter, thick enough to stop or substantially degrade the energy of prompt elastically scattered positrons and electrons, will be placed downstream of a short segment (~5 cm) of e^+ plasma. The e^- beam, and any long-lived neutral objects, will pass through the hole into a relatively background-free region where infrequent e^+e^- decay events will be detectable. An optional conversion foil (which plays the role of the thick Be target or U target in heavy-ion collisions) may be used to stimulate the decay of the very long lived objects which would otherwise exit the magnetic trap. This technique will cover the lifetime range of $\sim 5 \cdot 10^{-12}$ s $< \tau_{e+e-} < 10^{-8}$ s, and has the significant advantage over previous experiments [10] in that the target has $\geq 10^6$ times fewer charge centers per cm^{-2} than ~1 mg/cm^2 thick Be targets (i.e., an effective thickness of $\sim 10^{-9}$ g/cm^2). The polarization-dissociation cross-section is approximately 10^{12} times smaller in the e^+ plasma target. Whereas solid-target experiments may be sensitive only to objects $\ll 100$ fm, we will be sensitive to objects of up to $>10^7$ fm radius.

4. Summary and Status

Combining the increased sensitivity to neutral resonance states due to the low temperature of the target positrons, with the model-independent sensitivity for long-lived objects of the recoil-shadow technique, this experiment will constitute a definitive search for new neutral particle-like objects throughout the five decade range in lifetimes (10^{-13}s $< \tau_{e+e-} < 10^{-8}$s) which cannot be reliably and unambiguously probed by other methods.

Fabrication of the positron trap electrode structure is essentially complete, as is the PC-based computer control system and μVAX-based plasma diagnostics system. We presently await the delivery of the high azimuthal uniformity 6 T solenoid from Nalorac Cryogenics Corporation, and the 3 MV electron Pelletron from National Electrostatics Corporation. Scattering experiments may begin in late 1991.

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FIGURE CAPTIONS

Figure 1. Schematic diagram of e^+e^- scattering experiment. A positron plasma is formed by capturing positrons from the LLNL pulsed e^+ source. The electron beam is then injected along the axis, and scattered positrons and electrons are transported out of the trap region to a Si detector array. Positrons are identified by coincident detection of 511 keV photon in NaI crystal.

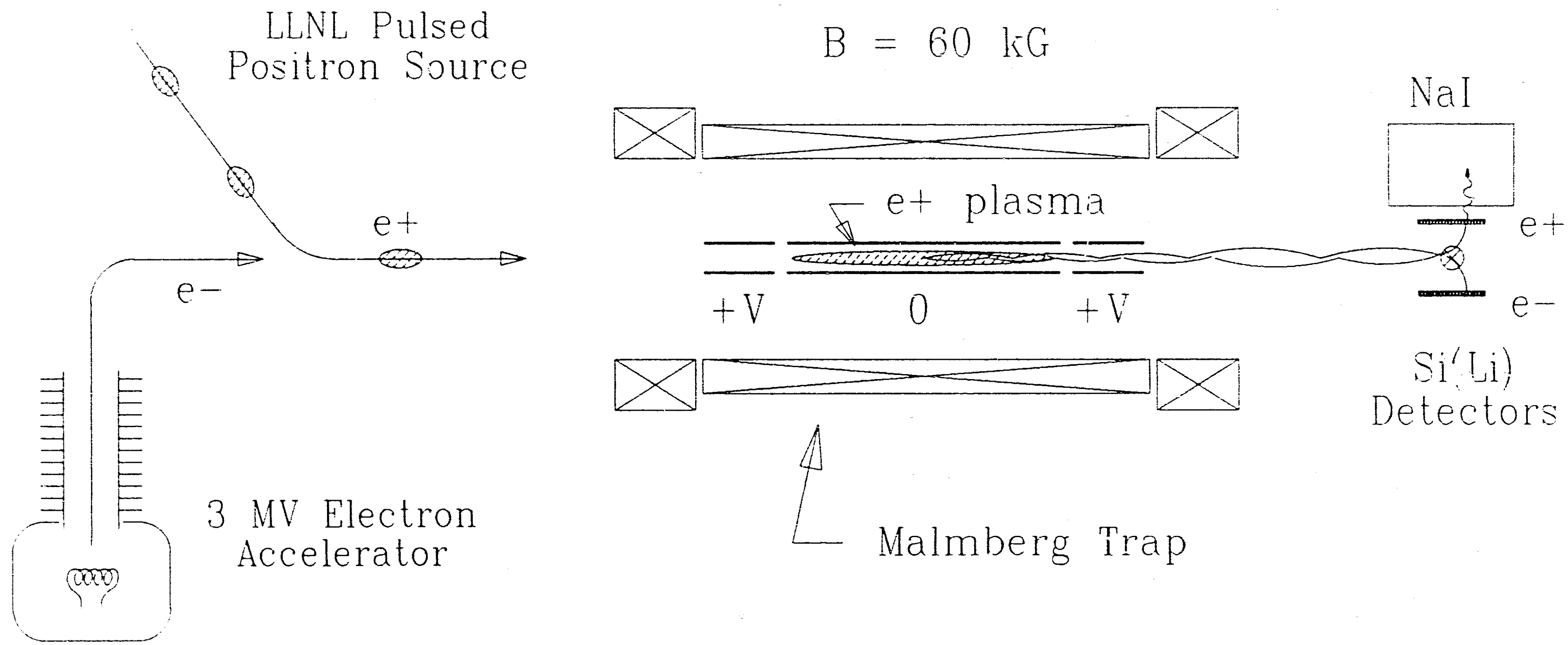
Figure 2. Recoil-Shadow arrangement for investigating long-lived neutral objects. The annular filter stops elastically scattered positrons and electrons. Long-lived states decay downstream in a reduced-background region. An optional converter foil stimulates the decay of very long-lived objects.

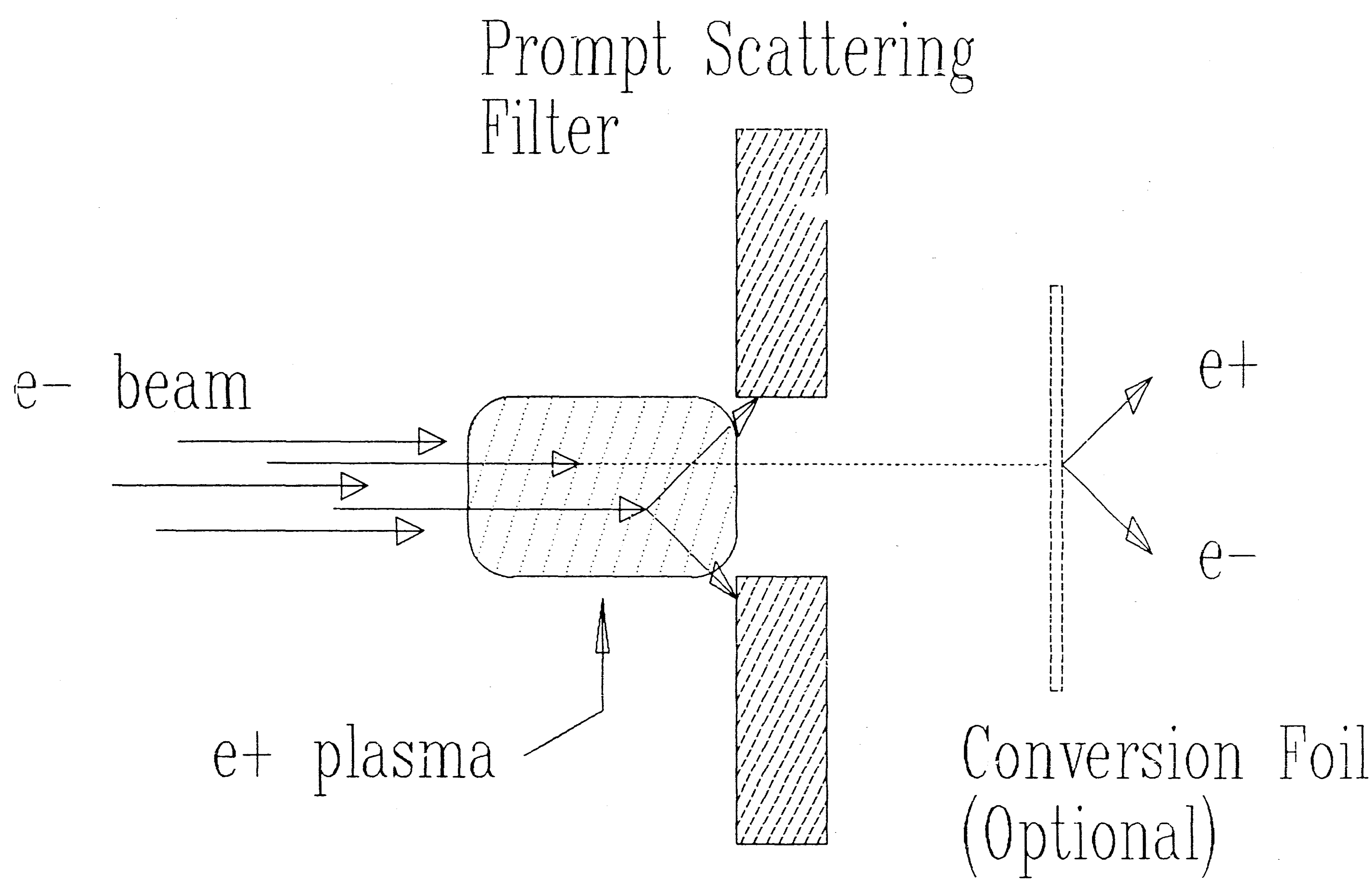
TABLE CAPTION

Table 1. Design values of important experimental parameters and their dependence on the magnetic field (B), electron beam current (I_{e-}), and positron plasma density (n_{e+}), radius (r_{e+}) and length (L_{e+}). Nominal values for these parameters are B = 6 T, I_{e-} = 10 μA, $n_{e+} = 10^{10}$ cm^{-3}, and r_{e+} = 0.5 mm. A 30 cm long e^+ plasma column is assumed to be divided into 15 segments each L_{e+} = 2 cm long.

TABLE 1

Experimental Parameter	Functional Dependence		Design Value
Confinement Time	$t_{1/2}$	$\propto B^2 L_{e+}^{-2} n_{e+}^{-2}$	$\approx$ 300 s
Fill Time	t_{fill}	$\propto n_{e+} r_{e+}^2 L_{e+}$	$\approx$ 25 s
Cyclotron Cooling Time	t_{rad}	$\propto B^{-2}$	$\approx$ 0.11 s
Beam Heating Rate	dE_{e+}/dt	$\propto I_{e-} r_{e+}^{-2}$	$\approx$ 0.08 eV s^{-1}
Equilibrium e^+ Temperature	kT_{e+}	$\propto I_{e-} r_{e+}^{-2} B^{-2}$	$\approx$ 0.008 eV
$e^+ e^-$ Scattering Rate	$\langle R \rangle$	$\propto I_{e-} n_{e+} L_{e+}$	$\approx$ 0.5 s^{-1}


LLNL Pulsed
Positron Source
e+
e−
3 MV Electron
Accelerator
B = 60 kG
e+ plasma
+V
0
+V
Malmberg Trap
NaI
e+
e−
Si(Li)
Detectors


Prompt Scattering
Filter
e- beam
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Conversion Foil
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