Intense Low Energy Positron Beams

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abstract

Intense positron beams are under development or being considered at several laboratories. Already today a few accelerator based high intensity, low brightness e^+ beams exist producing of the order of $10^8 - 10^9 e^+/\text{sec}$. Several laboratories are aiming at high intensity, high brightness e^+ beams with intensities greater than $10^9 e^+/\text{sec}$ and current densities of the order of $10^{13} - 10^{14} e^+ \text{ sec}^{-1} \text{ cm}^{-2}$. Intense e^+ beams can be realized in two ways (or in a combination thereof) either through a development of more efficient β^+ moderators or by increasing the available activity of β^+ particles. In this review we shall mainly concentrate on the latter approach. In atomic physics the main thrust for these developments is to be able to measure differential and high energy cross-sections in e^+ collisions with atoms and molecules. Within solid state physics high intensity, high brightness e^+ beams are in demand in areas such as the re-emission e^+ microscope, two dimensional angular correlation of annihilation radiation, low energy e^+ diffraction and other fields. Intense e^+ beams are also important

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for the development of positronium beams, as well as exotic experiments such as Bose condensation and Ps liquid studies.

1. INTRODUCTION

In atomic physics the e^+ constitutes a unique probe into various kinds of collision phenomena. Together with its e^- partner, it is possible experimentally to learn about the relative importance of the several interaction terms between the probe (e^+ , e^-) and the atom or molecule. This is attributable to the fact that some properties of e^+ and e^- are identical while others differ in a known way. As examples, the static interaction between e^+ and an atom is repulsive while in the case of e^- - atom interaction, it is attractive, in e^- collisions the exchange force may be important, whereas in e^+ collisions positronium formation plays a significant role at low impact energies. These differences are clearly visible when comparing e^+ and e^- total cross-sections in collisions with atoms and molecules [1] of which an example is shown in Fig. 1 for the case of He. When comparing total ionization cross-sections [2-5] for e^+ and e^- impact, differences in the result should shed further light onto this important scattering channel. By adding the proton, p , and the antiproton, $\bar{p}$, to the e^+ and e^- probes it does become possible to separate between mass and charge effects. This quartet of particles were used to establish that the main reason for the difference in the double ionization cross-section for e^- and p impact is associated with a charge rather than a mass effect [6].

Most of the experiments referred to above were carried out using low intensity e^+ beams ($<10^5$ e^+ /sec). Positron beam intensities of this magnitude are sufficient for most integrated cross-section measurements (not close to threshold, and not at high impact energies) however, it is clear that higher intensity and better quality e^+ beams are in demand for precise measurements of single (double...) differentially collision cross-sections. Other areas of atomic physics that will greatly benefit from high intensity, high brightness e^+ beams are threshold effects, Ps formation at high impact energies, Ps beams for collision studies, formation of Ps compounds and others.

The situation in solid state physics with e^+ , much parallel that in atomic physics. Here many techniques such as the Positron Re-emission Microscope [7], Low Energy Positron Diffraction (LEPD) [8], Positron induced Auger Electron Spectroscopy (PAES) [9], Positron Energy Loss Spectroscopy (PELS) [10] and Low Energy Ps Diffraction (LEPSD) [11] have all been proven to work on a demonstration level. In order for these techniques to become developed and established in surface science, intensities greater than 10^8 e^+ /sec are needed. 2D Angular Correlation of Annihilation Radiation (2D ACAR), when combined with low energy e^+ needs of the order of 10^9 e^+ in order to become practical and useful as those carried out in bulk studies. In addition, the well established e^+ technique of defect profiling may benefit from an intense e^+ beam

as these type of measurements then can be carried out using a micro beam allowing for direct measurements on active devices, and will allow three-dimensional defect mapping.

Today, most e^+ beams use ^{22}Na as the source of β^+ particles with a typical strength of 0.1 Ci (about the maximum commercially available). When combined with a standard tungsten β^+ moderator [12] which has a total combined efficiency of $2 \cdot 10^{-4}$ (defined as the ratio of low energy e^+ /sec to the β^+ activity of the source) a low energy e^+ beam intensity of $5 \cdot 10^5$ e^+ /sec with a diameter of 6-10 mm may result. If a solidified noble gas is used to moderate [13] the β^+ 's the e^+ intensity may be increased to about $5 \cdot 10^6$ e^+ /sec. Existence alternatives to the ^{22}Na are to generate the fast β^+ 's by pair production using 100 MeV e^- or to use ^{58}Co or ^{64}Cu to deliver the β^+ 's.

Below we review the various approaches which have been undertaken in order to produce intense high brightness low energy e^+ beams. The main emphasis will be on how to produce a high intensity of β^+ particles though some remarks are concerned with the moderation of the β^+ 's. Before continuing it may be appropriate to state that the availability of intense e^+ beams do not in general provide the solution to many of the interesting measurements lying ahead and that it is still a careful design that makes an experiment successful. In this respect, it may be useful to recall

that the first measurements of $e^+ - \text{He}$ total collision cross-section were carried out using a beam intensity of $10 \text{ e}^+/\text{sec}$ [14].

2. INTENSE e^+ BEAMS.

Several routes to intense e^+ beams have been taken. These range from production β^+ 's through pair production, ^{64}Cu produced in high neutron flux reactors to the production of massive amount of ^{58}Co . Accelerator production of short lived β^+ sources has also been investigated. In addition a successful attempt has been made in slowing down β^+ 's from 350 keV to about 10 keV which are subsequently moderated to produce a few eV e^+ .

β^+ sources. Several isotopes can be used to supply the fast β^+ particles. These can be produced in nuclear reactions using neutrons or other particles and a suitable target. Let J represents the flux of the activating particles and σ the cross-section for the nuclear transformation then the maximum specific activity of the target is given by

$$\frac{n_{\beta^+} \cdot \lambda}{n} = \frac{\sigma \cdot J}{\frac{\sigma \cdot J}{\lambda} + 1} = \sigma \cdot J \quad (1)$$

where n and n_{β^+} are the densities of the target and the activated nuclei, respectively, and λ the decay rate of the β^+ emitter. Eq.

1 assumes that J remains approximately constant throughout the target thickness and ignores loss of the activated nuclei by other channels but β^+ decay. The important factors in selecting a target are σ and J while λ is not important except, perhaps, for practicalities. With a flux of the activating particles of $10^{14}\text{cm}^{-2}\text{sec}^{-1}$ and a cross-section of 10^{-24}cm^2 Eq. 1 yields $n_{\beta} + \lambda/n = 10^{-10}$ which with a target density of 10^{22} atoms/g translates into 27 Ci/g. If it is possible to separate the activated nuclei from the target the specific activity is simply given as $\lambda \cdot 2.6 \cdot 10^{11}$ Ci/g. Presently, only ^{64}Cu has been used to generate intense e^+ beams. At Brookhaven ^{64}Cu can be produced in the High Flux Beam Reactor to a specific activity of 600 Ci/g which corresponds about 120 Ci/g of β^+ activity. Other β^+ emitting isotopes are under considerations at various facilities. ^{58}Co is planned to be used at INEL which when separated from the Ni target may yield a specific β^+ activity as high as 440 Ci/g.

Pair production. An alternative method to produce β^+ particles is by pair production by directing high energy e^- onto a high Z target acting as an electron - positron converter. The high energy positrons emitted from the converter then strike a moderator to produce the low energy e^+ . To optimize the geometry of the convertor - moderator configuration, the thickness of both the convertor and moderator are a complex affair. However, experiments have shown that a convertor thickness corresponding to approximately three radiation lengths is optimum when combined with a moderator which

consists of tungsten foils arranged as a series of vanes [16]. In Fig. 2 the yield of low energy e^+/e^- is shown as a function of the electron beam energy as measured by Howell et.al. [16]. As observed, the low energy e^+ yield increases linearly with the e^- energy above a threshold at around 15 MeV. This particular threshold is a property of the overall configuration/dimension of the $e^- - e^+$ convertor and the moderator and is not directly related to pair production.

In comparison to low energy e^+ produced by radioactive sources which yield basically DC beams, LINAC produced e^+ beams result in a pulsed source of low energy e^+ in a time window of 20 nsec or less which can be very useful for a variety of time of flight measurements [17].

In Table I some important properties of the e^+ beams under development are summarized. The given diameters refer to the beam size at the primary moderator. For those e^+ beams, with a diameter greater than about 1 cm, remoderation of the primary beam is a necessity in order to reduce to phase space. Of the e^+ beams listed only the LLL LINAC beam is fully operational while the parameters of the new configuration of the BNL beam are currently under optimization with the present intensity being 10^8 e^+ /sec. In addition to those listed in Table I, a few LINAC based e^+ beams exist producing of the order of 10^{7-8} e^+ /sec [18-21].

e^+ beams using radioactive isotopes. A schematic layout of the BNL low energy e^+ facility is shown in Fig. 3. The beam uses ^{64}Cu produced in the HFBR and after activation the ^{64}Cu source is transported about 1 km and dropped into the vacuum system through air lock valves. The ^{64}Cu is then evaporated onto a cone 2 cm deep and with bottom and top diameters being, respectively, 1.0 and 1.6 cm. The cone is affixed onto a 4.2 K cooled head. Ne or Kr condensed onto the ^{64}Cu is used to moderate the β^+ 's. The current maximum intensity is $10^8 e^+/\text{sec}$ with the use of a source delivering 8 Ci of β^+ 's. By increasing the source strength to 40 Ci of β^+ 's and by improving the evaporation procedure of the Cu an intensity of $\sim 10^9 e^+/\text{sec}$ is expected. The BNL beam is presently a low brightness intense beam. A brightness enhancement stage is under construction in collaboration with Brandeis University.

The BNL beam can be transported either magnetically or electrostatically. Several beam ports already exist or are currently been installed including ports for atomic collision experiments, the positron re-emission microscope, 2D ACAR, Ps diffraction measurements and PAES.

A clever variation that combines the production of radioactive nuclei with pair production is planned at Institut Laue-Langevin to produce low energy e^+ [2]. In this method, a stable nucleus is produced by thermal neutron capture through the reaction $A(n, \gamma)A+1$. Since $A+1$ is stable, the total energy of the emitted γ 's simply

equals the binding energy of the neutron and is about 6-10 MeV. As the nucleus $A+1$ is stable the γ activity turns off with the neutron beam. This method was first used to produce MeV's e^+ in the reaction $^{48}\text{Ti}(n,\gamma)^{49}\text{Ti}$ with a platinum target serving as the $e^- - e^+$ convertor through pair production. A beta spectrometer was used as a monochromator and about $2 \cdot 10^6$ e^+ /sec were produced with a momentum spread of $\Delta p/p = 1.32 \cdot 10^{-2}$ in the energy range between 1.5 and 4 MeV.

For the production of an intense low energy e^+ beam ^{113}Cd offers a better target for the gamma source [22]. The effective thermal neutron capture cross-section of ^{113}Cd is about 26000 barns which for natural Cd (the abundance of ^{113}Cd is 12.22%) yields an average cross-section of 3000 barns. It takes a layer of about 50 mg/cm^2 of natural Cd to absorb the neutron flux, however, due to burn up of ^{113}Cd and to the specifics of the ILL reactor a thickness of a few 100 mg/cm^2 is considered optimum. Tungsten is planned to be used as a target for pair production as well as a high energy positron moderator. In Fig. 4 is shown layout of the ILL intense e^+ beam. The predicted intensity is about 10^{10-11} e^+ /sec.

Other intense e^+ beams using radioactive sources and conventional moderation technique are in the planning stage at INEL [15] and ANS [23]. At INEL ^{58}Co in pure form is going to be used to provide the β^+ 's and a source strength as high as $2 \cdot 10^4$ Ci which may yield a low energy e^+ beam intensity as high as 10^{12} e^+ /sec when

combined with a solid Ne moderator. The ANS facility is going to use the ^{64}Cu source with a strength of $2 \cdot 10^4$ Ci combined with Ne or Kr to moderate the β^+ and a beam intensity of 10^{12} e^+ /sec is envisioned. The time schedule for an ANS based intense e^+ beam is around the turn of the century.

LINAC e^+ beams. Several LINAC based e^+ beams exist [16,18-21] with most of them yielding e^+ intensities below 10^9 e^+ /sec. The most intense LINAC e^+ beam currently operating is that of LLL [16] which produces $2 \cdot 10^9$ e^+ /sec with a diameter of 1 cm. At the positron factory, JAERI, in Japan [25] a LINAC e^+ beam with an intensity of 10^{10} e^+ /sec is considered. In Table II we list some characteristics of the LLL e^+ beam for the current version together with that of a planned upgrade.

Slowing down of the β^+ spectrum. Presently, the most efficient β^+ moderators are the solidified noble gases with Ne being the best with an efficiency of about 1 % when combined with ^{22}Na [13]. This low efficiency is a result of the large difference of the thickness of the moderator it takes to stop the β^+ spectrum to the distance the e^+ 's can diffuse before annihilation take place (for metal films) or their kinetic energy fall below the e^+ affinity of the moderator (noble gases). One could envision several moderator foils stacked on top of one another with a small vacuum gap between them. Such an approach will certainly result in a large moderation efficiency of the β^+ 's, however, to extract the low energy e^+ 's from

the vacuum gap's between the foils is a difficult and unsolved task.

An approach that has the same effect as the use of several moderator foils has been studied by the PSI group [26]. However, instead of using a large number of moderators to stop the β^+ spectrum only one thin moderator film is used and the β^+ particles not stopped in the moderator are made to return until the complete β^+ spectrum has been slowed down. Such an approach requires confinement of the high energy β^+ 's simultaneously with no confinement of the low energy e^+ . Several configurations of magnetic and electric fields have been studied of which an example is shown in Fig. 4. The β^+ source in the form of ^{79}Kr is condensed onto a thin carbon foil located in a 1.5 kG magnetic field. The solidified Kr also serves as a moderator. The high energy β^+ 's traverse nonadiabatically through a lens arrangement producing a strong radial electric field whereby they receive a large perpendicular (to the 1.5 kG field) velocity. The β^+ 's are made to return to the source/moderator foil by a magnetic bottle field produced by a 9 T superconducting magnet. As observed this arrangement displays left and right hand symmetry and the β^+ 's pass forth and back between the two 9 T bottle fields and thus make many passes through the source/moderator foil. This process continues until the β^+ 's are stopped in the source/moderator foil, that is when they impact on the foil with energies below 5-10 keV. A large fraction of the stopped e^+ 's escape the Kr moderator with a few eV of kinetic energy

and is further accelerated to a few 100's eV. These latter e^+ 's move sufficiently slow that they can pass the electrostatic lens adiabatically and furthermore have a ratio of perpendicular to parallel velocity small enough that they can pass the 9 T magnetic bottle fields. The arrangement of Fig. 4 produces two low energy e^+ beams with a diameter of about 10 cm and the expected intensity is of the order of $10^{10-11} e^+/\text{sec}$.

As an alternative route to increase the moderation efficiency of the β^+ 's, it has been suggested that an electric field assisted moderator (e.g. based on Si or other semiconductors) may provide the solution [27]. An electric field adds a net drift velocity to the random motion of the e^+ . In principle such a moderator may yield an efficiency of about 10 % [28]. Except for one experiment in which solid Ar was charged with e^- 's to provide the electric field [29] the realization of this type of moderator remain to be seen. There is no fundamental reason why it should not be possible to construct a field assisted moderator and once done the implementation of this type of moderator probably represent the cheapest way by which the intensity of a standard e^+ beam can be increased by one or two orders of magnitude. Another advantage of a field assisted moderator is that it may be possible shape the electric field distribution inside the moderator such that a focusing action of the e^+ 's take place during the drift toward the emission side of the moderator. Although not quite adaptable for a field assisted moderator, ideas on how electric field can be shaped

can be found in the literature concerning semiconductor drift detectors [30].

Moderately intense e^+ beams for university laboratories. All of the schemes for the production of intense e^+ discussed above can only be realized at large scale universities or facilities. For a standard university laboratory, however, it is possible to move above the ^{22}Na level by using to the short-lived (10 min) ^{13}N isotope. The use of the ^{13}N e^+ emitter was first suggested by Stein [31] and has recently been tested at BNL [32]. The ^{13}N is produced at fairly low energies through the reaction $^{12}\text{C}(d,n)^{13}\text{N}$. At BNL 1.8 MeV deuterons at a few μA were directed onto targets of graphite and diamond. After the irradiation the targets were flipped to face a standard tungsten moderator and the yield of low energy e^+ was measured and compared to that obtained by an encapsulated ^{22}Na source. The results show that the peak intensity of e^+ for 1 μA of deuteron current corresponds to that delivered by a 1 mCi ^{22}Na . With the advent of compact low cost accelerators capable of producing 1-5 mA of deuterons at 2-4 MeV peak intensities in excess of 10^7 e^+ /sec should result using a tungsten moderator. In order to keep the ^{13}N confined to the target the maximum deuteron beam power which can be dumped on to the graphite target is about 2 kW while for the diamond target (10 times higher thermal conductivity) one will be able to exceed this limit.

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Apart from the higher intensity of low energy e^+ which can be obtained using the ^{13}N source as compared to ^{22}Na or ^{58}Co , the ^{13}N has another advantage in that the deuterons can be focussed down to a diameter of about 1 mm on the target. This by itself increases the brightness of the e^+ beam by at least an order of magnitude over what can be achieved with ^{22}Na which has a source diameter of 4 - 6 mm.

A practical advantage of the ^{13}N includes that it takes only a few hours after activation for the β^+ source to cool down to a negligible radiation level. A disadvantage, but manageable, of this source is that it requires an additional shielding for the neutrons and some neutron activation will be present.

3. CONCLUSION

We have reviewed several approaches to produce intense low energy positron beams. The methods range from pair production to the production of large quantities β^+ emitters. Beside the experimental needs, the best technique to produce intense positron beams depend much on the facilities locally available. The development of intense e^+ beams are important for the positron field as well as for the physics community in general. Within the fields of atomic and solid state physics a lot can be learned by comparing the interactions of electrons and positrons with identical targets. This is especially true for atomic collision physics and for areas

within solid state physics such as diffraction (LEED, LEPD, LEPSD) and Electron/Positron Energy Loss Spectroscopies. Furthermore, intense positron beams are in demand in field like the positron re-emission microscope and 2D-ACAR .

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Figure Captions

Fig. 1 Total electron and positron helium scattering cross-sections [1].

Fig. 2 Low energy positron yield per electron as a function electron energy for a LINAC based positron beam [16].

Fig. 3 A schematic layout of the BNL intense positron beam facility. The beam uses up to 200 Ci ^{64}Cu as the β^+ source and solid Kr as moderator.

Fig. 4 The schematics of the source section of the proposed intense e^+ beam at ILL [22]. The β^+ 's are produced by pair production by gamma's from neutron activated ^{113}Cd . The tungsten vanes act as the $e^- - e^+$ convertor as well as the moderator.

Fig. 5 The PSI twin beam scheme [24]. In this concept, the complete β^+ spectrum from ^{79}Kr is slowed down in the source moderator foil located in the center. Two so-called "spurt devices" together with two 9 T super conducting magnets confine the high energy β^+ particles while allowing moderated e^+ to escape. The β^+ particles are slowed down by making multiple passes through the source moderator foil.

Table I: Some Properties of Proposed e^+ Beams

Proposed	e^+ /sec	dia (cm)	Moderator	Source
BNL	$>10^9$	1	Ne	^{64}Cu
CEBAF[24]	$4 \cdot 10^{10}$		W	Pair Production
ANS[23]	10^{12}	30	Ne/Kr	^{64}Cu
ILL[22]	10^{10}	10	W	Pair Production
INEL[15] Phase I	$10^9 - 10^{10}$	6	W/Ne	^{58}Co
INEL[15] Phase II	10^{12}	30	Ne	^{58}Co
LLL[16]	$2 \cdot 10^9$	1	W	Pair Production
PSI[26]	10^{11}	10	Ne	Cyclotron ^{79}Kr or ^{18}F
Positron Factory JAERI[25]	10^{10}	1	W	Pair Production

Table II, Operating parameters of the LLNL LINAC

Item	present	upgrade
Operating cost	900k\$/year	900k\$/year
Development cost	0	-10M\$
Beam energy	100 MeV	240 MeV
Beam current	100/400 μ A	100/400 μ A
Positron current	100/400pA*	>240/920pA
Muon intensity	0	-10 ⁶ μ /s

* 100pA = $6 \cdot 10^6$ e⁺/s

Fig 1

Fig 2

High Intensity Positron Beam at BNL

Fig 2

Fig 4

fig 5

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