R×B Drift Momentum Spectrometer

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Abstract:

We propose a new type of momentum spectrometer, which uses the **R×B** drift effect to disperse the charged particles in a curved magnetic field.

The **R×B** spectrometer is designed for the momentum analyses of the decay electrons and protons (e^-/p^+) in **PERC** (Proton and Electron Radiation Channel), and can evolve the strong guiding field of **PERC** gradually. In the **R×B** spectrometer, the e^-/p^+ can be adiabatically transported and detected during the analyses.

The **R×B** spectrometer can achieve high resolution and large acceptance of phase space in the measurements, and is especially ideal for particles with low momenta and large incident angles.

Principle of PERC for neutron decay measurements:

The beam station **PERC** aims to perform the experiments of the free neutron β-decay, measure the e^-/p^+ spectra, and the angular correlation coefficients precisely. With these observables, various quantities related to physics in and beyond the **Standard Model** can be derived.

The free neutrons are imported into the **Decay Volume** of PERC, and decay into electrons, protons, and anti-neutrinos, $n \to p^+ + e^- + \bar{\nu}_e$.

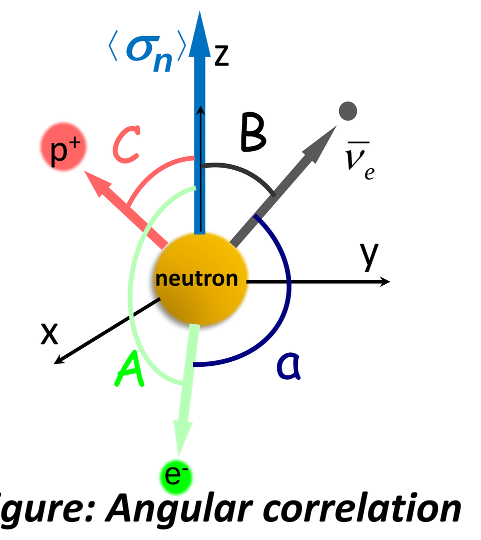


Figure: Angular correlation coefficients in free neutron decay.

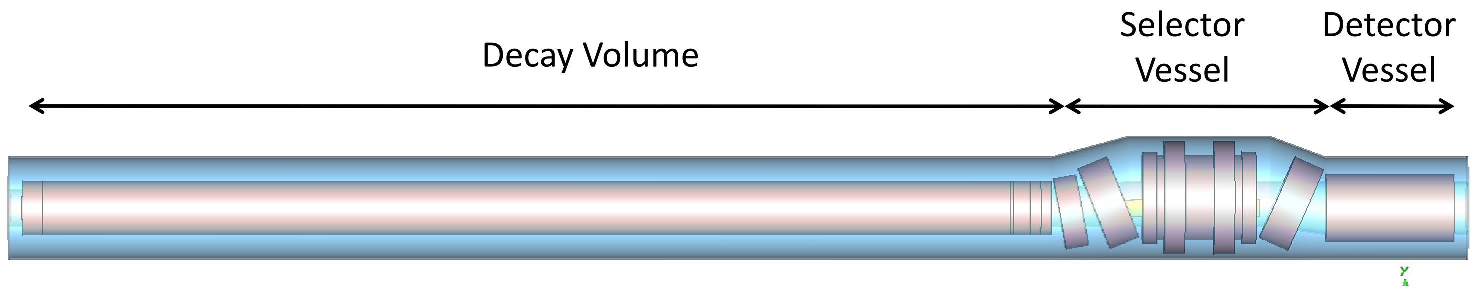


Figure: Sketch of PERC instrument.

A series of coils in PERC generate a curved *B*-field, in which the charged e^-/p^+ keep helically motions. The curved *B*-field can guide the e^-/p^+, from the **Decay Volume** to the **Detection Vessel**, and automatically integrate them over their emission angles.

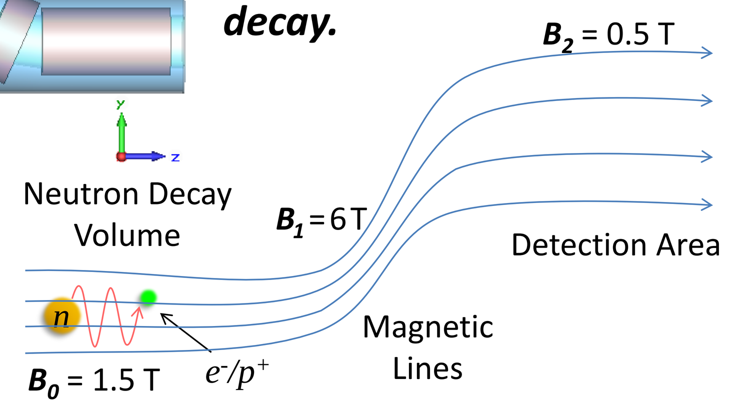


Figure: Sketch of B-field in PERC.

Inefficiency of Dispersive Magnetic Spectrometer:

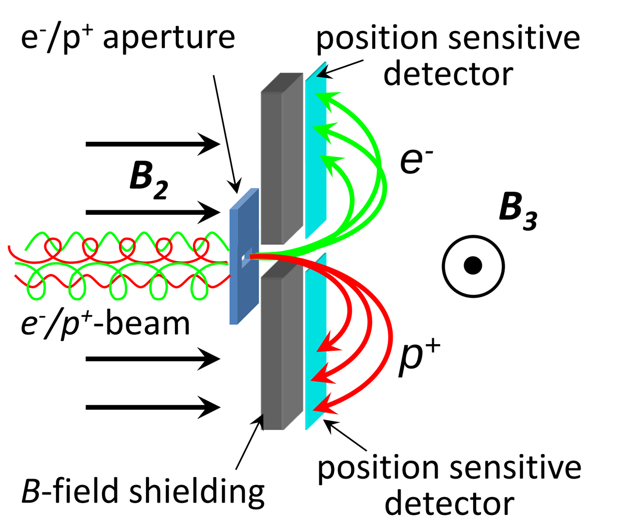


Figure: Sketch of dispersive magnetic spectrometer after PERC.

A dispersive magnetic spectrometer has to eliminate the guiding field B_2 of PERC, then applies an analysing field B_3. The dispersion distances of e^-/p^+ in B_3 represent their momentum.

However, if the *B*-field is drastically decreased, the magnetic field line will spread in vertical directions. The e^-/p^+ will follow the *B*-line, or be bended in the vertical *B*-field, for adiabatic or non-adiabatic transports.

Hence in both cases, the pitch angles of the e^-/p^+ are highly distorted. The distortion highly depends on the field distribution and the e^-/p^+ momenta, thus are not predictable nor controllable. The distribution of the particles can hardly represent their momenta.

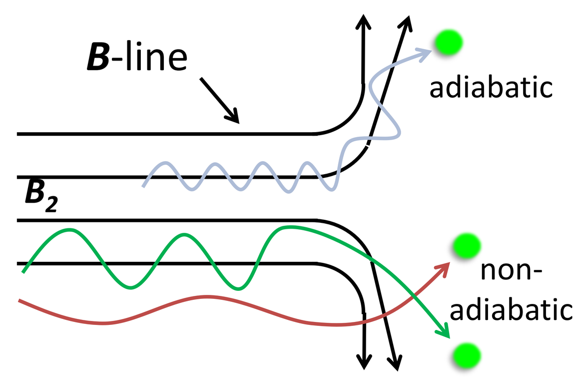
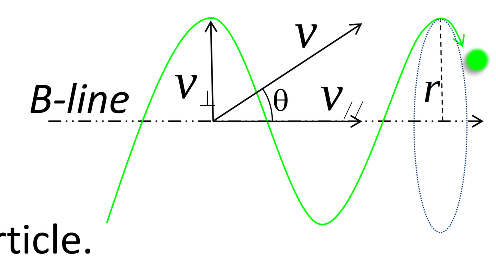


Figure: Sketch of e^-/p^+ motion in drastically decreased B-field.

Principle of R×B Drift Momentum Spectrometer:

When a charged particle propagates in a curved magnetic field, it has the drift effect perpendicular to the magnetic field ***B*** and field curvature ***R***

$$\mathbf{v}_d=\frac{mv^2}{qBR}\left(\cos^2\theta+\frac{1}{2}\sin^2\theta\right)\frac{\mathbf{R}\times\mathbf{B}}{RB}$$



where θ and *v* are the pitch angle and the velocity of a particle.

In a uniformly curved ***B***-field, the ***R*** and ***B*** are constants, hence the curved ***B***-lines are distributed parallel and coaxially. During a time period *T*, the total ***Drift*** distance will be the integration

$$D=\int_T v_d\,\mathrm{d}t=\frac{p}{qB}\cdot\alpha\cdot\frac{1}{2}\left(\cos\theta+\frac{1}{\cos\theta}\right)\ \text{with bending angle}\quad \alpha=\frac{v_{//}\cdot T}{R}$$

which is proportional to the momentum ***p***, and reversely proportional to the ***B*** and the charge ***q***.

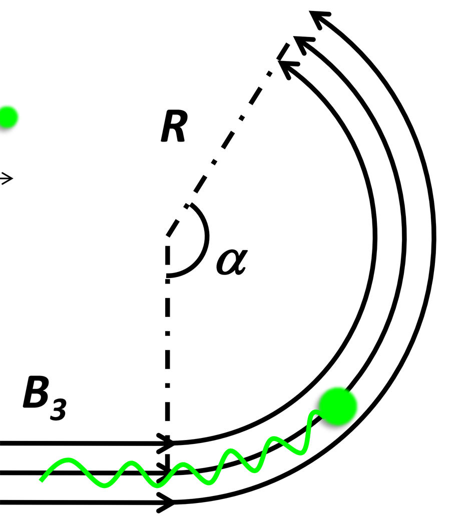


Figure: Principle of R×B Spectrometer .

Design of R×B Drift Momentum Spectrometer:

After PERC, the ***B***-field is gradually decreased from *0.5 T* to *0.15 T* in the spectrometer. Then a series of tilted coils generate a 180° bended ***B***-field, whose strength is kept as B_3 = *0.15 T*. The e^-/p^+ pass the aperture, and follow the B-line then reach the **Detector** on top. During the propagation, the e^-/p^+ drift along the positive and negative *x*-axis, according to their charges and momenta.

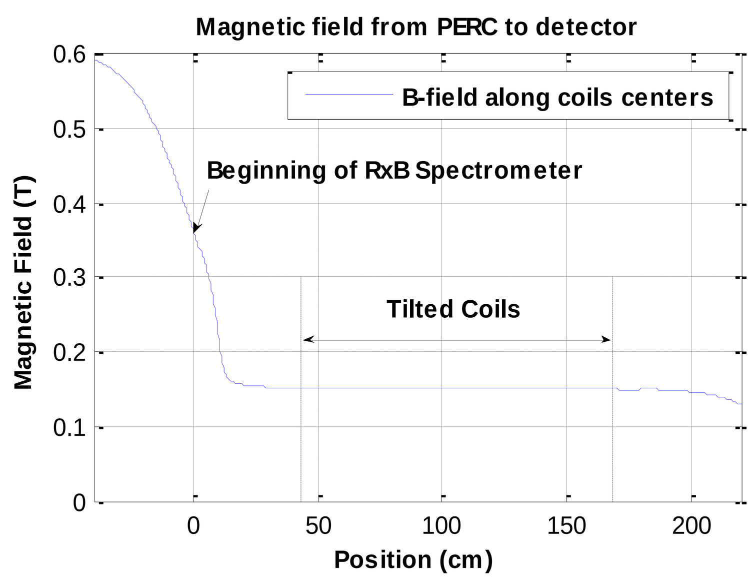


Figure: B-field strength along coil centers from PERC to the R×B Spectrometer.

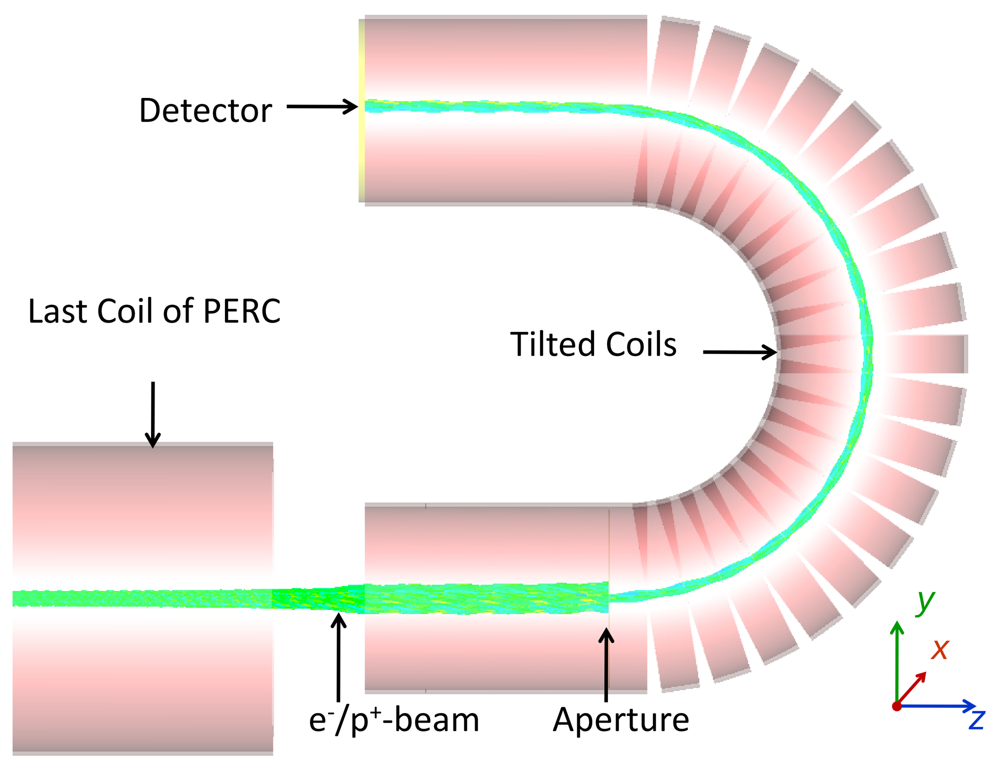


Figure: Design of R×B Spectrometer after PERC.

Hence the **R×B** spectrometer, instead of eliminating the guiding field of PERC, evolves the field smoothly to the analysing magnetic field. The charged particles can be transported adiabatically during the processes, and the angular information of them can be kept and measured.

Simulation of both e^-/p^+ in R×B Spectrometer:

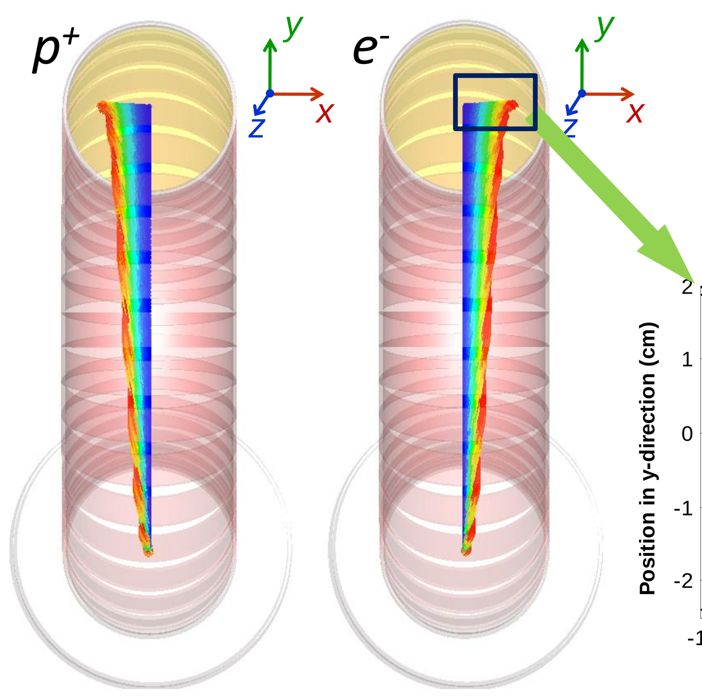


Figure: Simulated p^+ and e^- trajectories with continuous momenta.

From the simulation of the e^-/p^+ trajectories, the dispersion of the particles can be clearly observed.

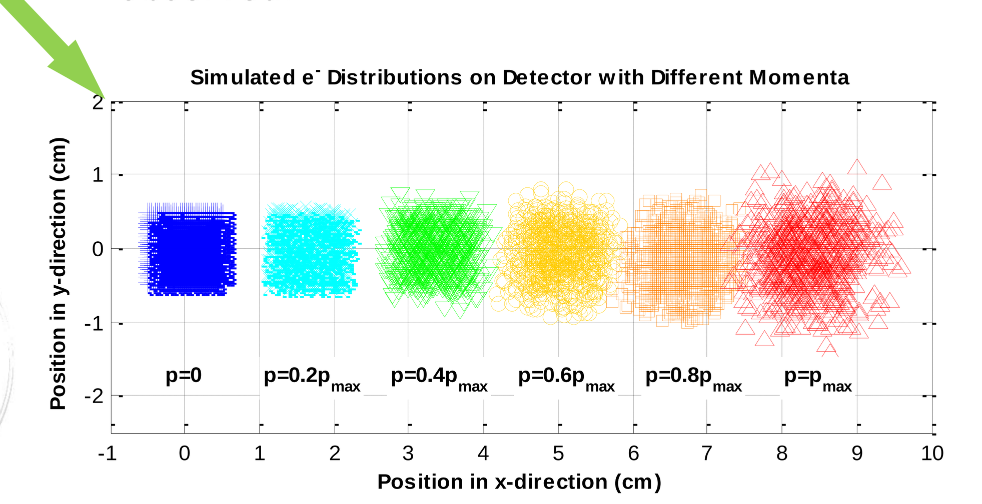


Figure: Simulated e^- distribution on the detector with discrete momenta.

Large Acceptance of Incident Angle:

Because of the presence of the $v_\perp$ component in the **R×B** drift, the correction induced by the incident angle θ in **R×B** spectrometer is much smaller than that in the normal magnetic spectrometer.

Therefore, the **R×B** spectrometer has a large acceptance of the incident angle of the particles. Up to $\theta \leqslant 9.6^o$, corresponding to $\Omega \leqslant 88$ *msr*, the aberration is $\leqslant 10^{-4}$.

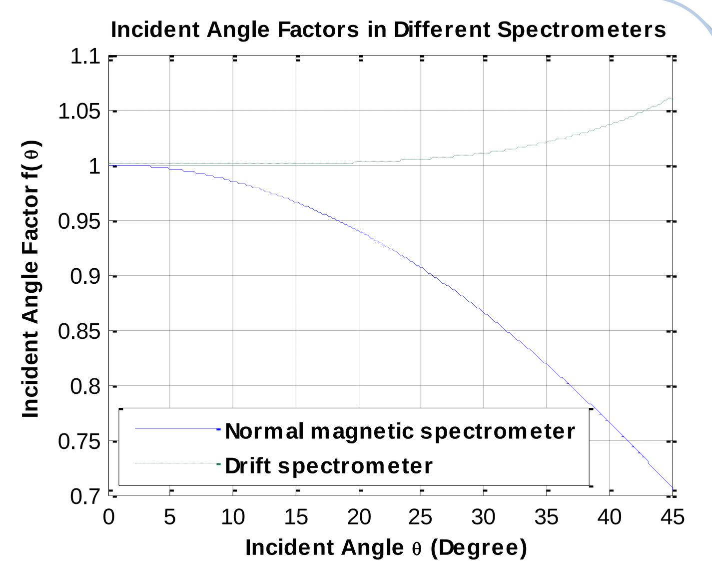


Figure: the θ corrections in magnetic and R×B Spectrometer.

Transfer Function

The motion of the e^-/p^+ particles in the **R×B** spectrometer is defined. The relation between the momentum spectra *F(p)* and the particle distribution *G(x)*, i.e., the trasfer function of the spectrometer can be calculated. Hence by measuring the *G(x)*, the momentum spectrum *F(p)* can be reconstructed in the analyses.

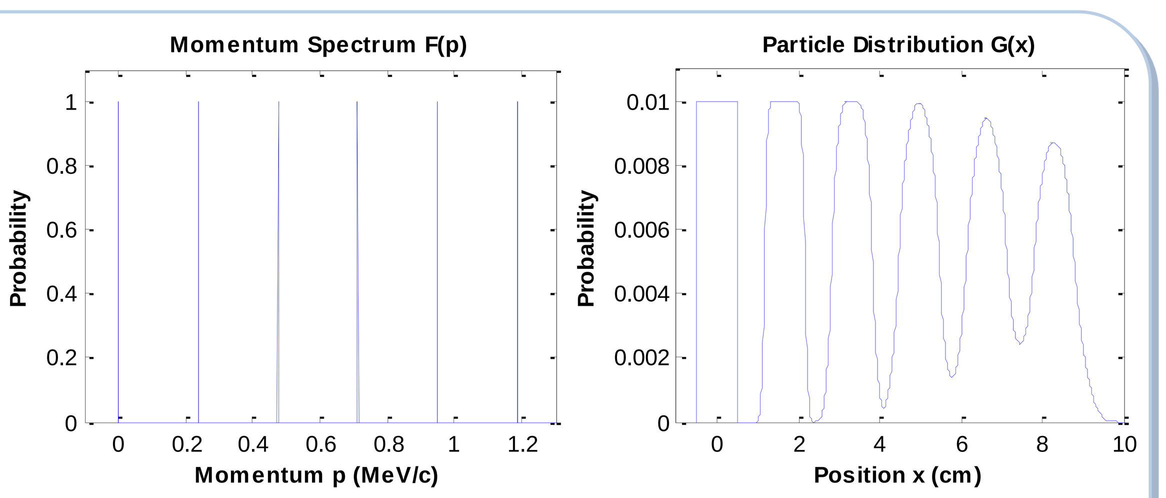
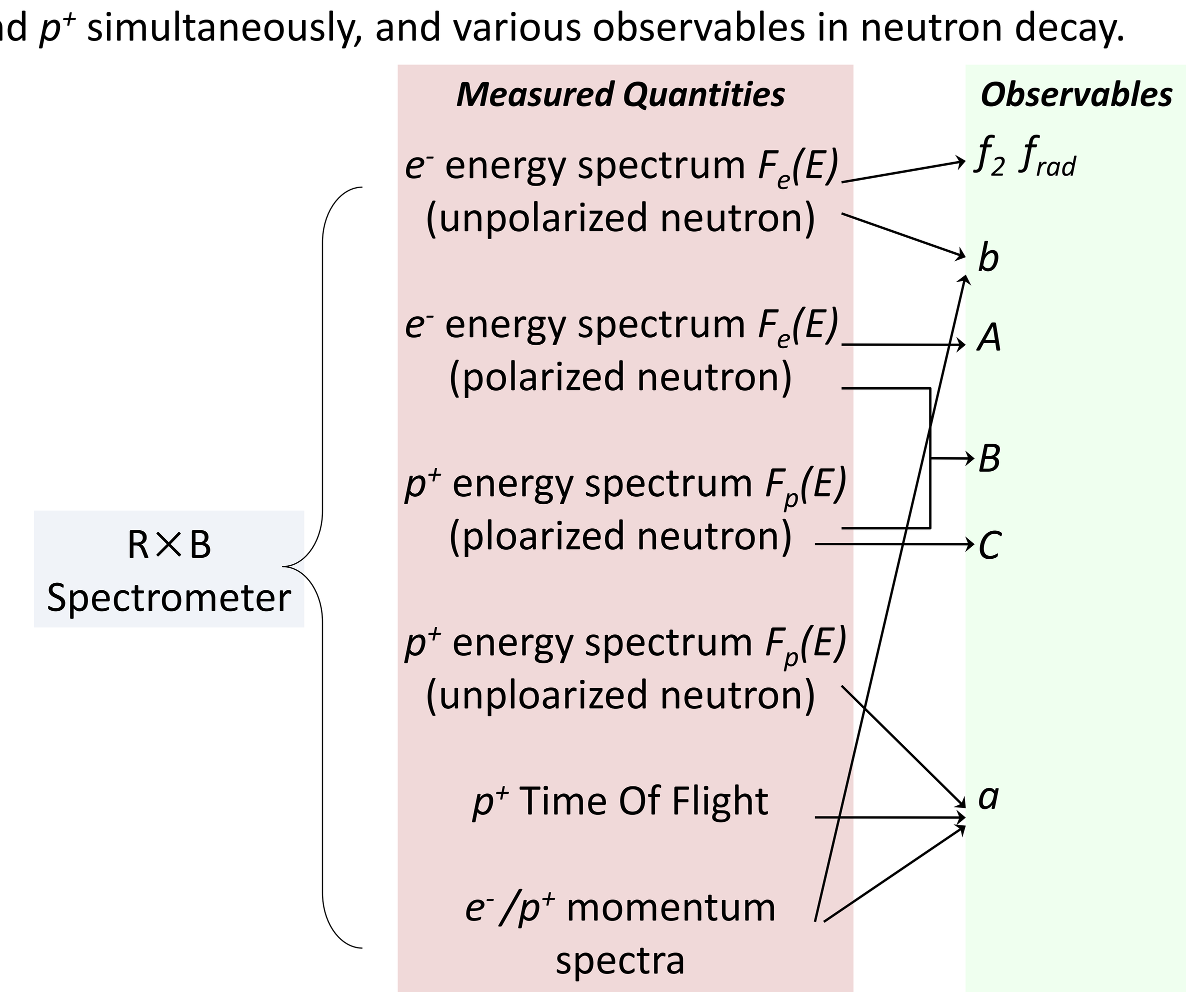


Figure: An example of discrete particle momenta and its distribution on the detector.

Measurable quantities with R×B Spectrometer in neutron decay:

The **R×B** spectrometer is versatile for PERC experiments. It can measure the e^- and p^+ simultaneously, and various observables in neutron decay.



Advantages of the R×B Spectrometer:

- *Adiabatic transports of particles.*
  The e^-/p^+ particles can be adiabatically transported from PERC to the **R×B** spectrometer. The angular distribution of them can be kept and measured.
- *Low momentum measurements.*
  The e^-/p^+ with very small momentum $p \to 0$ can be measured. The low momentum spectra is especially required for the determination of the Fierz term b_F.
- *Large acceptance of incident angle.*
  When $\theta \leqslant 9.6^o$, corresponding to $\Omega \leqslant 88$ *msr*, the direct aberration is very small as $\leqslant 10^{-4}$.

X. Wang et al. *Nucl. Instr. and Meth. A* **701** (2013) 254-261

D. Dubbers et al. *Nucl. Instr. and Meth. A* **596(2)** (2008) 238-247