6

Why coincidence experiments?

There are many reasons why the ability to perform coincident electron scattering measurements, provided by a "continuous wave" (c.w.) accelerator greatly increases the power of electron scattering. Let us first review some of the essentials.

The kinematics for the coincident electron scattering process (e, e′ X) are defined in Fig. 6.1. Here the incident and scattered electron determine a scattering plane and an orthonormal system of unit vectors $\mathbf{e}_i$ with $\mathbf{e}_3$ along $\boldsymbol{\kappa} \equiv \mathbf{k}_1 - \mathbf{k}_2$ and $\mathbf{e}_2$ in-plane. Note that this frame is invariant under a Lorentz transformation along $\boldsymbol{\kappa}$ to the C-M system of the target and virtual photon. We use $\mathbf{q}$ to denote the momentum of the produced particle X. The reaction plane is then defined by the two vectors $(\boldsymbol{\kappa}, \mathbf{q})$. The orientation of $\mathbf{q}$ and the reaction plane are specified by polar and azimuthal angles (θ_q, ϕ_q) in the orthonormal system (Fig. 6.1). The angles $\phi_q = \pi/2, 3\pi/2$ produce an *in-plane* configuration.

The S-matrix for the process (e, e′ X) is given by

$$S_{fi} \quad = \quad -\frac{ee_p}{\hbar c\,\Omega}\bar{u}\gamma_\mu u\,\frac{1}{k^2}\int e^{ik\cdot x}\langle\Psi_{p'};q^{(-)}|\hat{J}_\mu(x)|\Psi_p\rangle\, d^4x \qquad (6.1)$$

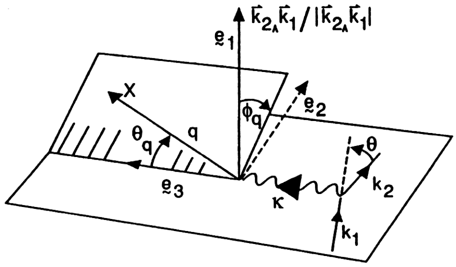

Fig. 6.1. Kinematics for basic coincident electron scattering process (e, e′ X).

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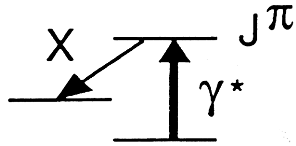

Fig. 6.2. Intermediate state J^{π} characterizes angular distribution of emitted particle X.

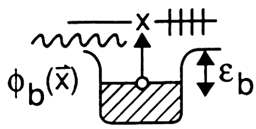

Fig. 6.3. Basic nuclear coincidence process (e, e′ N).

What one measures is again the Fourier transform of the transition matrix element of the electromagnetic current density between exact Heisenberg states of the target. The final state now consists asymptotically of a target state $|\Psi_{p'}\rangle$ and an emitted particle X with four-momentum q; it is constructed with incoming wave boundary conditions.

What can one learn about the structure of nuclei and nucleons from such experiments? First, if the reaction (e, e′ X) proceeds through an intermediate state of the target with given J^{π} (Fig. 6.2), then that J^{π} characterizes the angular distribution of X. The virtual photon orients the target along $\boldsymbol{\kappa}$. Angular correlation measurements of the emitted particle with respect to the virtual photon determine the contributing multipolarities. Furthermore, all values of J^{π} at any ω can again be accessed by increasing (κR).

Moreover, in contrast to inclusive scattering (e, e′) where the cross section is given by the sums of squares of the transition multipoles (see part 2), (e, e′ X) involves interference between amplitudes. One then has the ability to determine small, but important, amplitudes through interference effects.

Consider the basic nuclear coincidence process (e, e′ N) where N is a single nucleon, as illustrated in Fig. 6.3. This process creates a *hole* in the final nucleus [Ja66, Ja73]. Let the initial nucleon binding energy be ε_b and wave function be $\phi_b(\mathbf{x})$. Consider for illustration only the Coulomb interaction and assume the final nucleon can be described by a plane wave: $\exp\{i\mathbf{q}\cdot\mathbf{x}\}$. A measurement of all energies in (e, e′ N) determines the binding energy of the final hole state ε_b. A measurement of all momenta measures the Fourier transform of the hole-state wave function $\tilde{\phi}_b(\boldsymbol{\kappa}-\mathbf{q})$; by basic quantum mechanics, this is the amplitude of the momentum distribution in the state ϕ_b.

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In addition, coincidence capability implies that multiple scattering experiments can be performed. The polarization $\mathbf{P}_X$ of the produced particle X, for example, can be measured through a second scattering. Polarization transfer experiments $(\vec{e}, e' \vec{X})$ that provide precision measurements of the charge form factor of the nucleon [Ar81] now form an important part of electromagnetic nuclear physics.

Furthermore, strangeness is conserved in the strong and electromagnetic interactions; one then only has *associated production* of strange particles, for example through the reaction $^1H(e, e' K^+)\Lambda$.[1] With high enough incident electron energy, the reaction $(e, e' K^+)$ can be accessed. This reaction produces a tagged hypernucleus. By varying the momentum transferred to the nucleus, the Fourier transform of the wave function of the deposited hyperon can be determined.

Moreover, with *multiple* coincidence experiments such as $(e, e' 2N)$ and extreme kinematics, one can investigate the short-range behavior of two nucleons in the nuclear medium.

At the quark level, when quarks are struck in an electroweak interaction, it is not the quarks that emerge from the nucleus, rather it is a hadron. The *hadronization* of quarks is studied in the coincidence reaction $(e, e' X)$.

[1] The reaction notation $A(b, c\,d \ldots)E$ used in this book is a very convenient one. The first and last symbols denote the initial and final target states and the symbols in parenthesis indicate the incident and final detected particles; in the generic case, the last and first symbols may be suppressed. We denote elastic electron scattering by (e, e), inelastic scattering by (e, e'), and coincidence reactions by $(e, e' X)$.