Particle physics

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(I am the one in the back)

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Plan

- Schedule can change according to needs, with practice classes becoming theory classes (and, less likely, viceversa)
- Homework will be assigned for practice, required for passing the final exam (alternatively: written test)
- Oral exam: one topic for nuclear physics, one for particle physics (syllabus will be updated)

theory	practice
09/08 — 16-18	
09/11 — 12-14	
09/18 — 12-14	
	09/22 — 16-18
10/02 — 12-14	
	10/06 — 16-18
10/09 — 12-14	
10/16 — 12-14	
	10/20 — 16-18
11/06 — 12-14	
	11/10 — 16-18
11/13 — 12-14	
11/20 — 12-14	
	11/24 — 16-18
11/27 — 12-14	
12/04 — 12-14	
	12/08 — 16-18
12/11 — 12-14	

Elementary particles

Elementary particles: fundamental, indivisible constituents of all matter

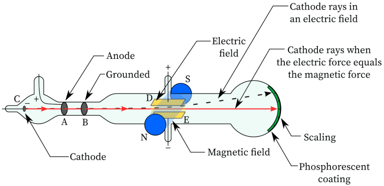
- come in different types, characterised by properties such as mass, spin, electric charge, and others
- all particles of the same type are identical, and so indistinguishable

Aim of elementary particle physics: study properties and interactions of elementary particles, through which macroscopic objects are ultimately built

- earliest idea: Democritus (6th century b.C.)
- earliest *sound* idea: Dalton's atomic theory (beginning of the 19th century), atoms=indivisible constituents. . .
- . . . which were actually divisible, and made up of "more elementary" constituents
- "elementarity" depends in practice on the length scale we can explore: $\Delta x \sim \hbar/\Delta p$, so limited by highest available energy

Brief history: the birth of particle physics

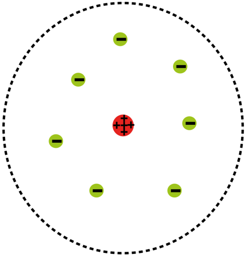
1897 *electron* (e), J. J. Thomson



Stolen from [1]

- cathode rays deflected by magnetic field → streams of light, negatively charged particles
- using perpendicular crossed electric and magnetic fields, tuned so that the stream was undeflected, $v/c = E/B$
- from the deflection in the presence of the electric field only, he determined their charge-to-mass ratio
- energy estimated from the heat generated by the stream when hitting the screen the end of the tube.

Brief history: early years



Stolen from [2]

1908-1917: *proton* (p), E. Rutherford *et al.*

- planetary model of the atom: electrons orbiting around a positively charged *nucleus* containing almost all the mass
- each positive charge = one hydrogen nucleus = proton

1932: *neutron* (n), J. Chadwick

- mismatch between mass and charge of the nucleus
- fixed by neutron: neutral but essentially same mass as proton

Brief history: early years

1905: *photons* (γ), M. Planck, A. Einstein, *et al.*

- in subatomic processes EM radiation $\sim$ el. neutral, massless particles, energy prop. to radiation frequency (photons)
- only way to explain photoelectric effect (Einstein, 1905) and the scattering of light on particles at rest (Compton, 1926)
- *EM interaction* $\sim$ exchange of a stream of photons between electrically charged objects.

1908-1917: *proton* (p), E. Rutherford *et al.*

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Brief history: strong interactions

Q. How do protons (and neutrons) stay together in nuclei?
A. *Strong interaction*: strong (overcome EM repulsion), short-ranged (no macroscopic effects)

1934, H. Yukawa: strong interaction mediated by a new particle – the *meson* – in analogy with EM and the photon

- proton and neutron $\in$ *baryons*; baryons and mesons $\in$ *hadrons*
- estimate of mass from range of force $\sim 1/6$ of proton mass

1936: new particle, right mass found in cosmic rays by Anderson & Neddermeyer. . . but *not* Yukawa's meson!

1946-47 Powell, Lattes, Occhialini: *two* new particles in cosmic rays

- heavier one, shorter lifetime, disintegrated almost entirely in the upper atmosphere – the *pion* (π), the true Yukawa meson
- lighter one, longer lifetime, originally identified with the meson but interacts little with nuclei – the muon (μ), into which the pion decays
- muon was not expected (I. Rabi: "Who ordered that?"): sort of heavier electron, grouped with it in the family of *leptons*

Brief history: antiparticles

Theory:

1928-1931, P. A. M. Dirac: prediction that to each particle corresponds its *antiparticle*: same mass but opposite electrical (and other) charge(s)
1928-1931, W. Pauli: AHAHAHAH LOL

Experiment:

- 1932: *positron*, C. D. Anderson
- 1955: *antiproton*, E. Segrè & O. Chamberlain
- 1955: *antineutron*, B. Cork

Some particles, like the photon, are their own antiparticles;
electric neutrality is however a necessary but not sufficient condition

Brief history: weak interactions

Q. How can the energy spectrum of the electron in nuclear β decays be extended, if only two decay products are observed (p, e^-)?
A. One more particle is produced, which is neutral, (at least almost) massless, and hard to observe

- 1930 W. Pauli: the *neutrino* (ν) hypothesis
- 1933 E. Fermi: first theory of β decay, *weak interaction*
- 1956 Reines & Cowan: first observation
- 1950s-1960s: several experiments show
  - neutrino $(\nu) \neq$ antineutrino $(\bar{\nu})$
  - two types of neutrinos, one corresponding to the electron (ν_e), one corresponding to the muon (ν_μ), and respective antineutrinos $(\bar{\nu}_e, \bar{\nu}_\mu)$
  - included in the lepton family
- Weak interaction responsible for β decays and for processes involving neutrinos still poorly understood at this stage

Brief history: the hadron zoo

Everything in place except for the uselessness of the muon, but ...

1947: kaon (K), G. D. Rochester & C. C. Butler

- hadron of the meson subfamily, mass intermediate between π and p
- "strange" particle: created via strong interactions, decays slowly via weak interactions
- more hadrons (strange and non-strange) found in the following years: the hadron "zoo"

1964, Gell-Mann, Zweig: *quark model*

- mesons and baryons not elementary but bound states of *quarks* and *antiquarks* – "more fundamental" particles
  - meson = quark+antiquark,
  - baryon = three quarks, antibaryon = three antiquarks
- three types: *up* (u), *down* (d), and *strange* (s)
- neatly accomodates the hadron zoo, predicts the Ω baryon (obs. 1964, V. A. Barnes *et al.*)
- fully accepted with the discovery of the fourth quark: 1974, J/ψ meson and *charm* quark (c), B. Richter *et al.*; S. Ting *et al.*

Brief history: completing the Standard Model - matter

From here on:

- 1975: tau lepton (τ), M. Perl *et al.*, corresponding neutrino immediately theorised
- 1977: *bottom* or *beauty* quark (b), L. Lederman *et al.*, sixth quark immediately theorised
- 1995: *top* or *truth* (t) quark, CDF and DØ experiments at Fermilab
- 2000: ν_τ, DONUT experiment at Fermilab

Six quarks, six leptons and corresponding antiparticles = *matter particles*

Brief history: completing the Standard Model - interactions

Weak and strong interactions modelled on the basis of Quantum Electrodynamics (QED): interaction= exchange of particles

- mediator role of pion (not elementary anymore) taken over by *gluons* (g), interactions described by Quantum Chromodynamics (QCD)
- part of the theoretical problems of weak interactions solved by introducing *intermediate vector bosons*: W (charged) and Z (neutral), (1983, UA1 and UA2 experiments at CERN)
- remaining problems fixed by *Higgs boson* (H), (2012, ATLAS and CMS experiments at CERN)
- theory describing weak interactions unified with EM, is the Glashow-Salam-Weinberg model
- GSW+QCD= *Standard Model* of particle physics

Photons, gluons, W and Z: *interaction particles*

Higgs boson: *the God(damned) particle* (L. Lederman)

	matter families/generations			gauge bosons	the God(damn) particle
	I	II	III		
quarks	2.2 MeV $\frac{2}{3}$ $\frac{1}{2}$ u up	1.28 GeV $\frac{2}{3}$ $\frac{1}{2}$ c charm	173.1 GeV $\frac{2}{3}$ $\frac{1}{2}$ t top	0 0 1 g gluon	125 GeV 0 0 H Higgs boson
quarks	4.7 MeV $-\frac{1}{3}$ $\frac{1}{2}$ d down	96 MeV $-\frac{1}{3}$ $\frac{1}{2}$ s strange	4.18 GeV $-\frac{1}{3}$ $\frac{1}{2}$ b bottom	0 0 1 γ photon	
leptons	0.511 MeV -1 $\frac{1}{2}$ e electron	105.7 MeV -1 $\frac{1}{2}$ μ muon	1.777 GeV -1 $\frac{1}{2}$ τ tau	91.2 GeV 0 1 Z^0 Z boson	
leptons	< 2.2 eV 0 $\frac{1}{2}$ ν_e electron neutrino	< 0.17 MeV 0 $\frac{1}{2}$ ν_μ muon neutrino	< 15.5 MeV 0 $\frac{1}{2}$ ν_τ tau neutrino	80.4 GeV -1 1 W^- W boson	

mass charge spin X name of part X

Matter particles

- All spin-$\frac{1}{2}$ fermions
- Two groups: *quarks* (interact strongly) and *leptons* (e, μ, τ and neutrinos, do not interact strongly)
- Three *families* (or *generations*): from lighter to heavier $[(u, d); (e, \nu_e)]$, $[(c, s); (\mu, \nu_\mu)]$, $[(t, b); (\tau, \nu_\tau)]$

  (e, ν_e) etc. are also known as lepton families
- To each particle $\rightarrow$ antiparticle with same mass and spin, and
  - opposite charge for charged particles (quarks, e, μ, τ)
  - opposite helicities (spin component in the direction of motion) for ν
- Masses span five orders of magnitude: $m_e = 0.5\,\mathrm{MeV}$, $m_t = 170\,\mathrm{GeV}$ (and possibly more, since m_ν are small but yet unknown)
- All matter particles interact through the weak interactions, while only quarks are affected by the strong ones; quarks and charged leptons interact also electromagnetically, while neutrinos do not

Interaction particles

- All spin-1 bosons
- photon, γ: $m_\gamma = 0$, electrically neutral (i.e., it does not self-interact); mediates the electromagnetic interactions
- IVB, $W^\pm$ and Z: $m \neq 0$, Ws electrically charged while Z neutral; mediate the weak interactions;
- gluons, g: $m_g = 0$, electrically neutral; mediate the strong interactions
- IVB interact with each other and self-interact; g interact with each other and self-interact; IVB and g do not interact with each other

Bonus particle: Higgs boson H

- spin 0, massive, electrically neutral
- essentially provides mass to all other elementary particles
- interacts with IVB but not with the photon or with the gluons (hence these are massless)

Graviton (G): hypothetical quantum of gravitational interactions, not observed yet

Natural units

Speed of light c (from SR) $\rightarrow$ translate m into E, t into x
Planck's constant $\hbar$ (from QM) $\rightarrow$ translate t into E^{-1}

- Mass unit: from Einstein relation $E = mc^2$

$$[m] = [E]/c^2 = \mathrm{eV}/c^2$$

- Time/length unit: from Planck-Einstein relation $E = \hbar\nu$

$$[t] = \hbar/\mathrm{eV}$$

$$[l] = c[t] = c\hbar/\mathrm{eV} = \hbar c/[E] = \hbar/[c(\mathrm{eV}/c^2)] = \hbar/(c[m])$$

- Charge unit: from Coulomb energy $U = e^2/(4\pi r)$

$$[e]^2 = [E][l] = [\hbar c]$$

In particle physics we use *natural units*, i.e., we choose units such that

$$\boxed{\hbar = c = 1}$$

$$[l]_{\mathrm{NU}} = [m]_{\mathrm{NU}}^{-1},\ [E]_{\mathrm{NU}} = [m]_{\mathrm{NU}},\ [l]_{\mathrm{NU}} = [t]_{\mathrm{NU}},\ [e]_{\mathrm{NU}} = 1$$

Natural units (contd.)

Examples:

- Compton length (length scale associated to a particle)

$$\lambda_C = \frac{\hbar}{mc} \overset{\text{NU}}{=} \frac{1}{m}$$

- *Fine structure constant* (dimensionless)

$$\alpha = \frac{e^2}{4\pi\hbar c} \overset{\text{NU}}{=} \frac{e^2}{4\pi}$$

Typical energy unit: electronvolt (eV; $\mathrm{MeV} = 10^6\,\mathrm{eV}$, $\mathrm{GeV} = 10^9\,\mathrm{eV}$)

$1\ \mathrm{eV} = 1.6 \cdot 10^{-19}\, J$: energy acquired by an electron travelling through an electric potential difference of $1\ V$, practical in accelerator experiments

Typical length unit: fermi (fm), $1\ \mathrm{fm} = 10^{-15}\ m$

Conversion between fm (SI) and MeV^{-1} (NU):

$$\hbar c \simeq 197\ \mathrm{MeV} \cdot \mathrm{fm}$$

In NU the left-hand side is one, so $1\ \mathrm{fm} \approx \frac{1}{5}\,\hbar c/\mathrm{GeV} \overset{\text{NU}}{=} \frac{1}{5}\mathrm{GeV}^{-1}$

Building up matter

From the matter particles via the forces mediated by the interaction particles one can ultimately build up all the matter surrounding us

1. hadrons from quarks: free quarks not observed in Nature, always bounded within mesons and baryons – *confinement*
   - mesons = bound states of a quark and an antiquark
   - baryons = bound states of three quarks
2. nuclei from protons and neutrons (but this is nuclear physics)
3. atoms from nuclei and electrons (but this is atomic physics)
4. molecules from atoms (but this is molecular physics)

   ...

42. Life, the Universe and Everything (but this is science fiction) [3]

Matter can be stable (it remains unchanged if we leave it alone) or unstable (even leaving it alone it decays, i.e., breaks apart): e.g., protons and electrons are stable; neutrons, pions, and muons are not

Building up matter: mesons

$$\boxed{\text{Meson} \approx q\bar{q}}$$

- lightest mesons (also lightest hadrons): pions π^-,π^0,π^+
  - $m_\pi \approx 140\,\mathrm{MeV}$ $(m_{\pi^0} < m_{\pi^\pm})$
  - built from lightest quarks and antiquarks: u, d, $\bar{u}$ and $\bar{d}$
  - bound states with total quark spin $S_q = 0$ and orbital angular momentum $L_q = 0 \to$ pion spin $J = 0$
- meson state depends on S_q and L_q of $q\bar{q}$, so same quark content $\not\Rightarrow$ same meson
  - ρ mesons have the same quark content of the pions, but in a combination with $S_q = 1$ and $L_q = 0 \to \rho$ spin $J = 1$
- meson state depends on quark content
  - kaons K (contain a strange quark)
  - J/ψ ($c\bar{c}$ state)

Building up matter: baryons

Baryon $\approx qqq$

- lightest baryons: proton (uud), neutron (udd)
  - $m_{p,n} \approx 1\,\mathrm{GeV}$, $m_n > m_p$, with $|m_n - m_p|/m_p \ll 1$
  - n decays into p via β decay, p is stable
- p is stable since lightest baryon: *baryon number* (number of baryons minus number of antibaryons) is conserved, p cannot decay into anything $\rightarrow$ stability of ordinary matter
- no conserved meson number; in fact, even the pion is not stable and decays (mostly) into a muon and a muonic antineutrino
- heavier baryons exist with the same quark content but in different spin/orbital angular momentum states, and/or with different quark content
  - Δ^+ and Δ^0 have same quark content as p and n but $J = \frac{3}{2}$
  - $\Lambda = uds$

meson	quark content	spin	charge	mass
π^+	$u\bar{d}$	0	$+1$	$135\mathrm{MeV}$
π^-	$d\bar{u}$	0	-1	$140\mathrm{MeV}$
π^0	$u\bar{u}, d\bar{d}$	0	0	$140\mathrm{MeV}$
ρ^+	$u\bar{d}$	1	$+1$	$775\mathrm{MeV}$
ρ^-	$d\bar{u}$	1	-1	$775\mathrm{MeV}$
ρ^0	$u\bar{u}, d\bar{d}$	1	0	$775\mathrm{MeV}$
K^+	$u\bar{s}$	0	$+1$	$494\mathrm{MeV}$
K^-	$s\bar{u}$	0	-1	$494\mathrm{MeV}$
K^0	$d\bar{s}$	0	0	$498\mathrm{MeV}$
$\bar{K}^0$	$s\bar{d}$	0	0	$498\mathrm{MeV}$
J/ψ	$c\bar{c}$	1	0	$3.1\mathrm{GeV}$

baryon	quark content	spin	charge	mass
p	uud	$\frac{1}{2}$	$+1$	$0.938\mathrm{GeV}$
n	udd	$\frac{1}{2}$	$+1$	$0.940\mathrm{GeV}$
Δ^+	uud	$\frac{3}{2}$	$+1$	$1.232\mathrm{GeV}$
Δ^0	udd	$\frac{3}{2}$	$+1$	$1.232\mathrm{GeV}$
Λ	uds	$\frac{1}{2}$	0	$1.1\mathrm{GeV}$

Building matter: the rest of the story (in brief)

Reductionist approach:

- quarks and gluons via strong interactions $\rightarrow$ hadrons
- protons and neutrons via strong interactions $\rightarrow$ nuclei
  - $Z=$ n. of protons, $A=$ n. of protons and neutrons
  - some are stable, some are not
- nuclei and electrons via EM interactions $\rightarrow$ atoms
  - atoms with nuclei having same Z but different A=isotopes
- more atoms via EM interactions $\rightarrow$ molecules

From here on only EM interactions matter: molecules and their interactions are already chemistry material; organic chemistry is the basis of molecular biology, and so on. . .

Elementary particles and fundamental interactions should govern all the phenomena, but as the complexity of the system grows new (collective) phenomena appear, and things get complicated. . .

Elementary processes of particle physics: decays

Elementary processes are of two types: **decays** and scattering processes

- Stable particles: proton, electron, neutrinos (treated as massless), photon + antiparticles (+ stable nuclei, but we will not discuss them)
- All other hadrons and leptons, IVB, and Higgs, *decay*, i.e., "break up" in various ways yielding ultimately stable particles

$$X \longrightarrow X_1 \, X_2 \, \ldots \, X_n$$

- Classifications in fundamental and composite, stable and unstable, or observable and unobservable are independent:
  - fundamental, stable and observable (e.g., the electron)
  - fundamental, unstable and observable (e.g., the muon)
  - composite, stable and observable (e.g., the proton)
  - fundamental, stable and unobservable (e.g., the up quark in a proton)

  ...
- An unstable particle can decay in different ways (*decay channels*)

Lifetime of an unstable particle

Typical life span of unstable particles:

- Half-life, $t_{\frac{1}{2}}$: time in which half of a large sample of unstable particles of some type decays
- Lifetime, τ: $\tau = t_{\frac{1}{2}} / \ln 2$

Empirically, decay rate (prob. of decay/unit time/particle) is t-independent

$$dP = \Gamma dt$$

dP: probability for a particle to decay over infinitesimal time interval dt

$\Gamma = \sum_i \Gamma_i$: *total decay width*, time-independent total decay rate
Γ_i: *partial decay width*, decay rate in channel i

Particles decay independently from each other, sample size $N(t)$ obeys

$$dN(t) = -\Gamma N(t) dt \Rightarrow N(t) = N(0) e^{-\Gamma t} = N(0) e^{-\frac{t}{\tau}}, \quad \tau \equiv \Gamma^{-1}$$

Γ_i / Γ: *branching ratio* (or *fraction*) of channel i (relative probability that the decay will take place through channel i)

particle	main decay mode	lifetime
μ^-	$\mu^- \to e^- \nu_\mu \bar{\nu}_e$	$2.2 \cdot 10^{-6} s$
n	$n \to p e^- \bar{\nu}_e$	$8.8 \cdot 10^{2} s$
π^+	$\pi^+ \to \mu^+ \nu_\mu$	$2.6 \cdot 10^{-8} s$
π^0	$\pi^0 \to \gamma\gamma$	$8.4 \cdot 10^{-17} s$
Δ^0	$\Delta^0 \to p\pi^-, n\pi^0$	$5.6 \cdot 10^{-24} s$

Decays and conservation laws

Not all ways of decaying are allowed: both kinematical and dynamical constraints restrict available channels

Kinematical constraint from energy-momentum conservation

$$P = \sum_i p_i$$

P: four-momentum of the initial particle of mass M
p_i: four-momenta of decay products of masses m_i

$$M^2 = P^2 = P \cdot \sum_i p_i = M \sum_i E_i^{\mathrm{CM}} \geq M \sum_i m_i$$

CM: rest frame of initial particle
$(E_i^{\mathrm{CM}})^2 = m_i^2 + (\vec{p}^{\mathrm{CM}})^2 \geq m_i^2$

Sum of masses of decay products cannot exceed mass of initial particle

Dynamical constraints depend on details the interaction responsible for the process, lead to conservation laws (e.g.: conservation of electric charge, baryon number, lepton, lepton family number – approximate)

Elementary processes of particle physics: scattering

Elementary processes are of two types: decays and **scattering processes**

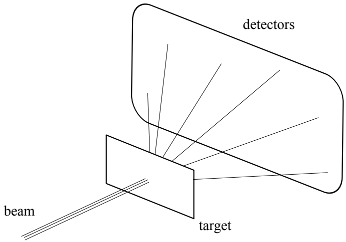
Q. If unstable particles decay, how are we even able to know about their existence?

Look at a decay, and imagine reversing time: you would see a set of particles getting closer, colliding, and building up the unstable particle

A. To see unstable particles we have to create them by means of *scattering processes*, in which particles are thrown at each other, collide, and the products of the collision are studied: if an unstable particle is created it leaves its footprint in the final products

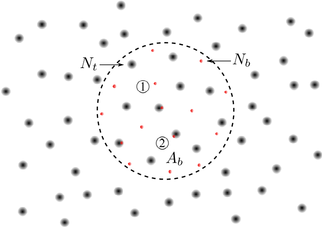
Scattering processes reveal more about interactions than just the spectrum of unstable particles, and are the main type of experiment in particle physics

Fixed target experiments



- Bunch of particles accelerated and focussed into a *beam*, directed against a target (e.g., thin foil of metal), at rest in the lab
- What comes out of the collision is analysed by means of detectors placed behind (or around) the target
- Beam: N_b particles (projectiles) of velocity v, over cross-sectional area A_b
- Target: N_t particles (scatterers) in the part "seen" by the beam (typically target much wider than the beam)

Fixed target experiments (contd.)



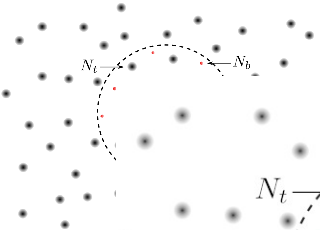
- interactions typically short-ranged
- projectiles (red) and scatterers (black) interact only if close: proj. should pass in a small region in the plane perpendicular to the beam around scat. (grey area)

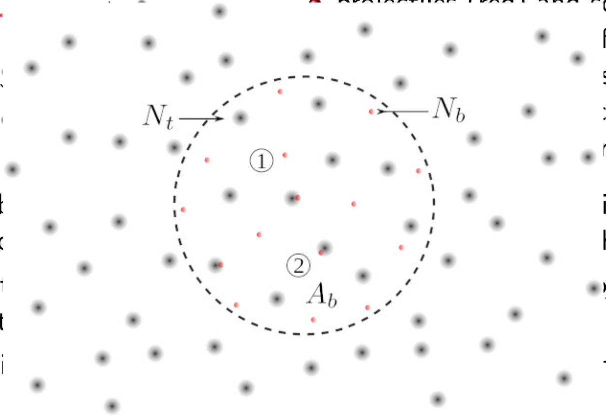
- To the beam, target looks like two-dimensional surface with "active" areas, scattering takes place if projectile passes through them
- For dilute beams and targets, interactions involve one projectile and one scatterer $\rightarrow$ independent scattering events $N_{\text{events}} \propto N_t N_b$
- Proportionality factor = active/total area of the target under beam

(thin targets $\rightarrow$ no multiple events)

$$\boxed{N_{\text{events}} = N_t N_b \frac{\sigma}{A_b}}$$

Fixed target experiments (contd.)





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- To the b… ith "active" areas, sc… hem
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- Proporti… nder beam … multiple events)

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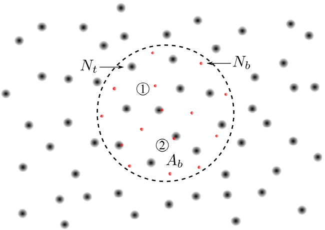
Fixed target experiments (contd.)



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References

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