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Energy deposition on nuclear emulsion by recoil ions for directional dark matter searches

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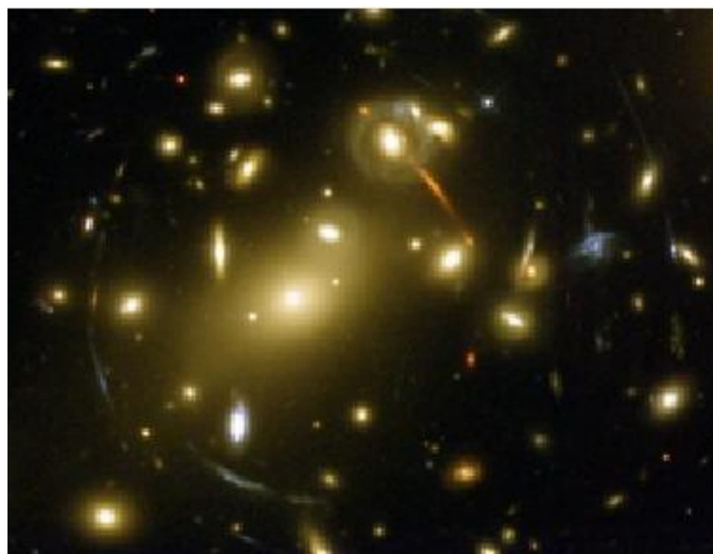
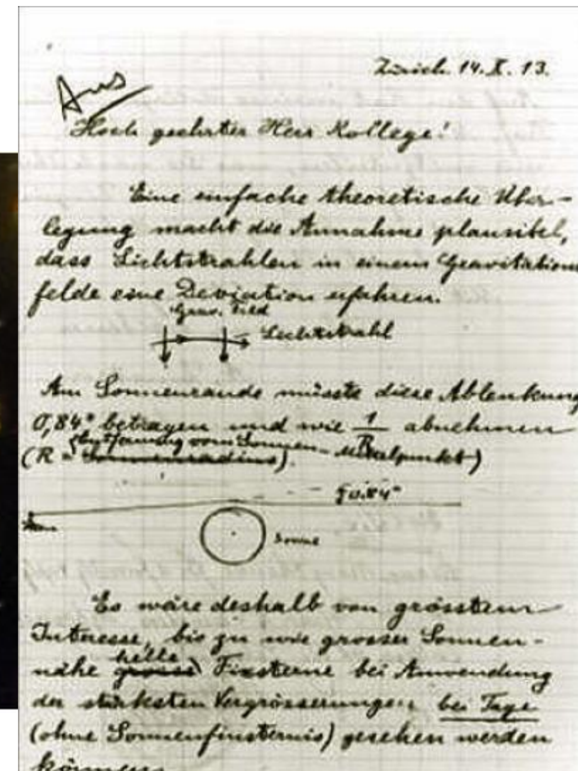


Gravitational lens   The Hubble Deep Field



Zürich. 14. X. 13.

Hoch geehrter Herr Kollege!

Eine einfache theoretische Überlegung macht die Annahme plausibel, dass Lichtstrahlen in einem Gravitationsfelde eine Deviation erfahren.

Am Sonnenrande müsste diese Ablenkung 0,84" betragen und wie 1/R abnehmen (R = Abstand des Strahles vom Sonnen-Mittelpunkt).

Es wäre deshalb von grösstem Interesse, bis zu wie grosser Sonnennähe helle Fixsterne bei Anwendung der stärksten Vergrösserungen bei Tage (ohne Sonnenfinsternis) gesehen werden können.

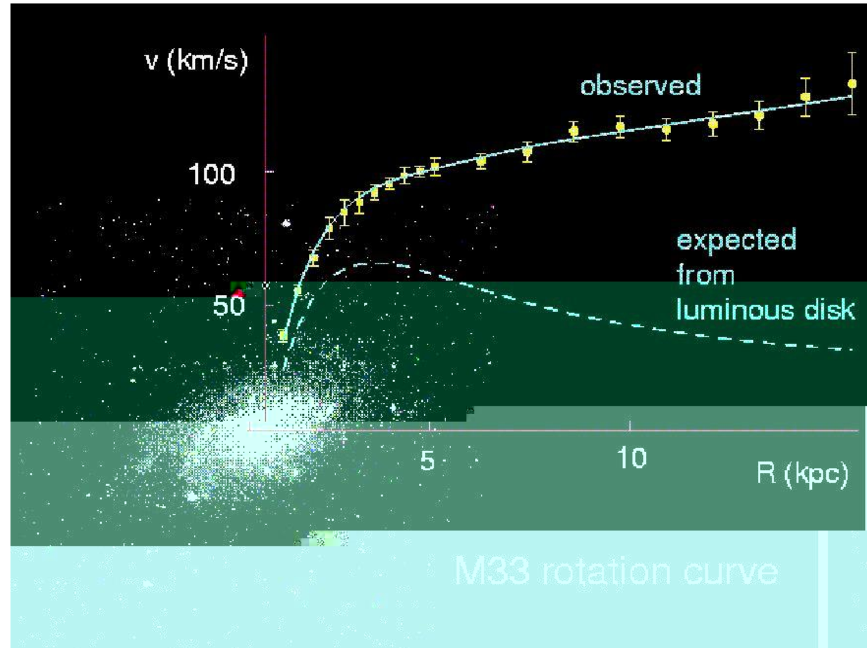
Einstein

Dark Matter

In 1933, F. Zwicky
The rotational velocity of galaxies in the Coma cluster is greater than that expected from the virial theorem, the universe contain more matter then is inferred from optical observation

$$\overline{T} \qquad \frac{1}{2}\overline{V}$$

V. Rubin and K. Ford
The rotational velocity does not decrease as *R* increases.
⇒ dark matter is something different from ordinary matter.



Univ. Sheffield HP

Constituent of universe

ordinary matter	4 %	(0.5%：visible light, 0.5%：X-rays)
dark matter	23 %	
dark energy	73 %	

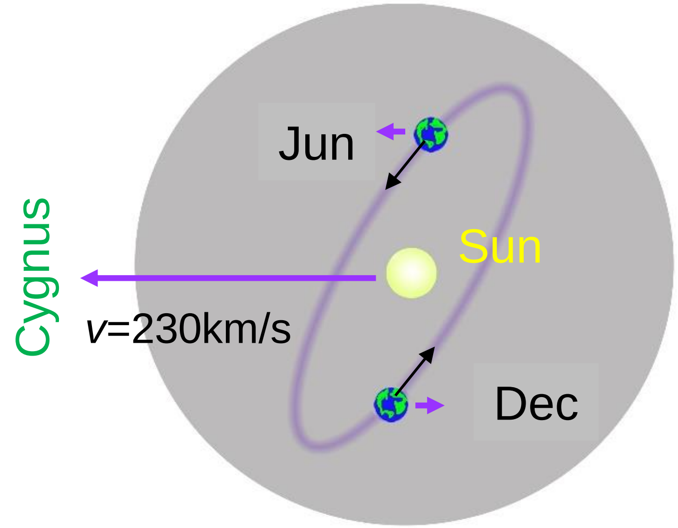
the leading candidates for galactic dark matter:

WIMPs (Weakly Interacting Massive Particles)
SUSY (neutralino predicted by supersymmetry)

Direct detection of dark matter

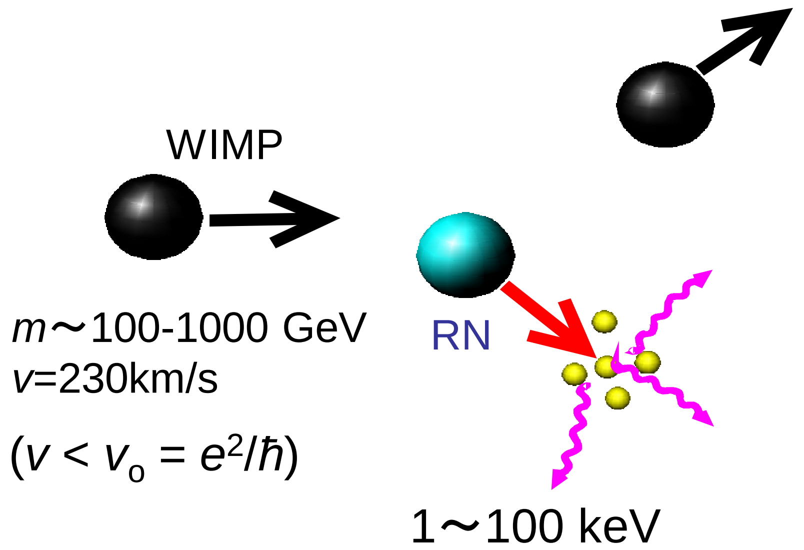
The Galaxy is surrounded by dark matter. The solar system is traveling at 230 km/s towards Cygnus.

The detection of WIMPs (Weakly Interacting Massive Particles) observes the ionization, excitation and chemical reactions caused by recoil ions of ~ 1-100 keV energy, produced by elastic scattering with WIMPs



~ 10 - 1000 GeV/c^2

~ 10^{-40} - 10^{-41} cm^{-2} (< 10^{-2} -10^{-4} /kg/day)



Energy sharing in low energy

For slow ions, $v < v_0 = e^2/\hbar$, S_e and S_n are similar in magnitude.
the energy of the incident particle E is given to atomic motion

E

atomic, ⇒

heat T — Bolometer

charge Q — SSD, gas TPC

LXe

scinti. S — Scintillator

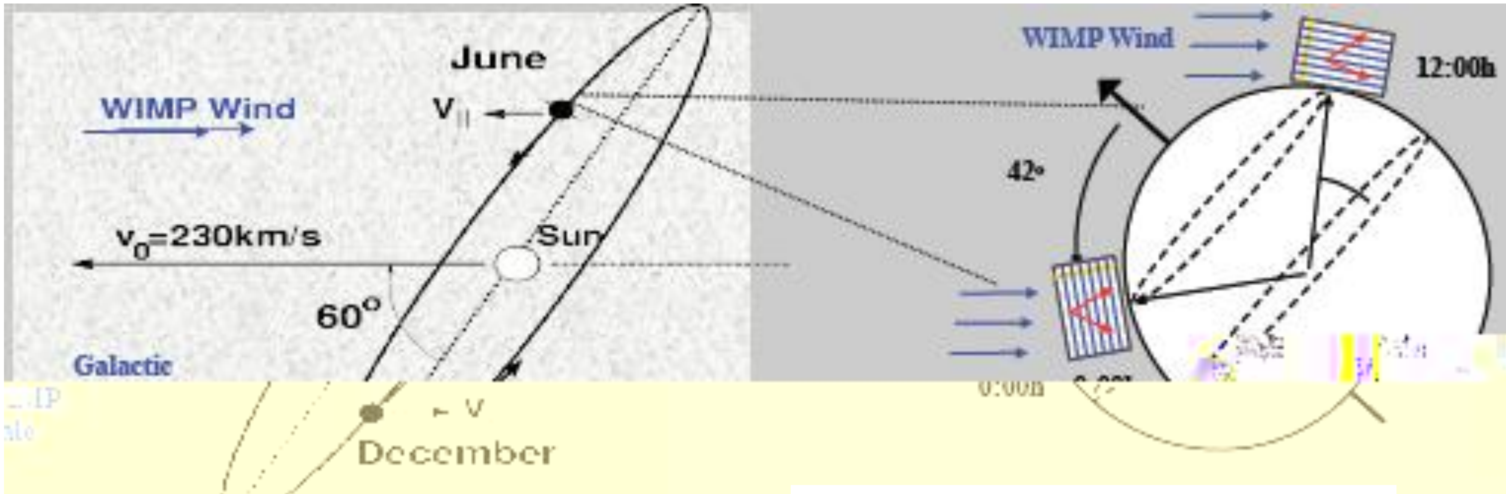
chem. C — Emulsion

The ratios ,Q,S,C,T, depend on particle, energy etc. can be used for particle discrimination

Nuclear quenching factor (the Lindhard factor) $q_{nc} = \dfrac{\text{Electronic energy}}{\text{Ion energy}}$ E

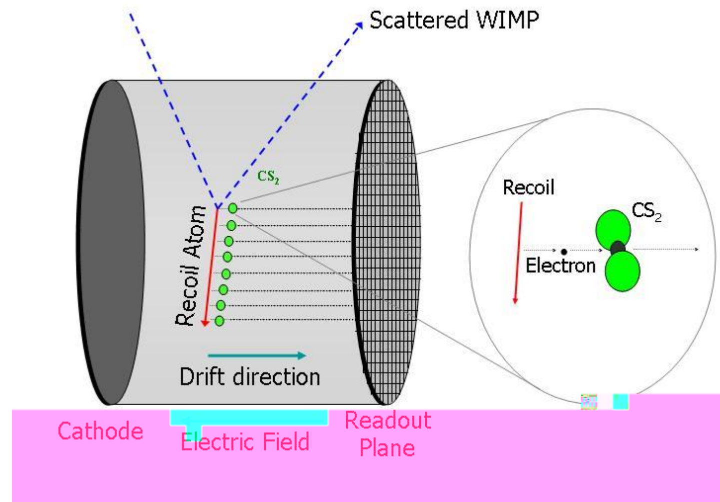
Head-tail or direction detection

The directional detection of low-energy recoil ions can provide strong possibility for observation of dark matter in the Galaxy.



DRIFT, NEWAGE

Detectors with directional capabilities can observe daily modulations.

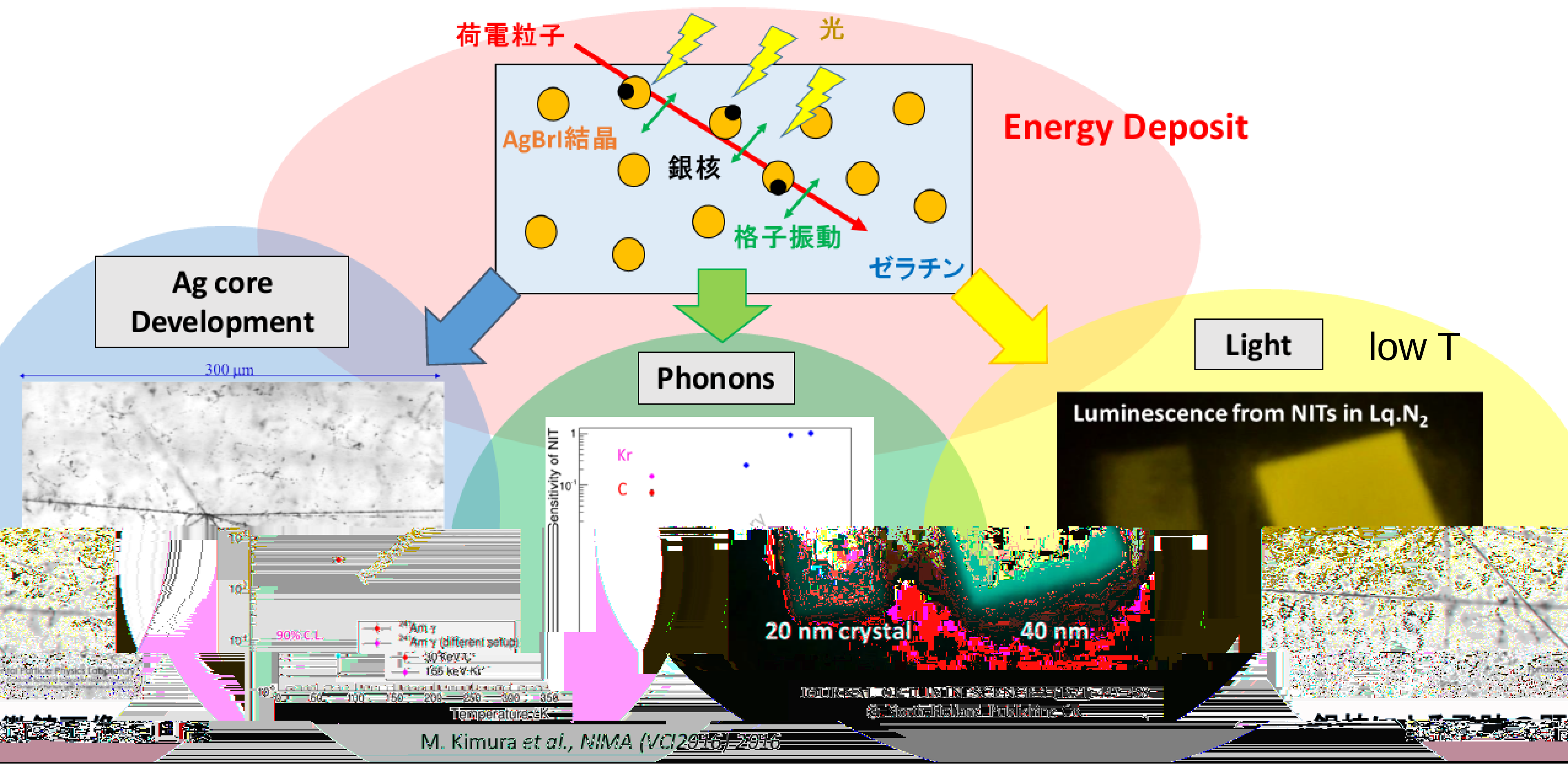


gas TPC (Time Projection Chamber)

electronegative gas such as CS_2, low diffusion

fine grain emulsions

Nuclear emulsion



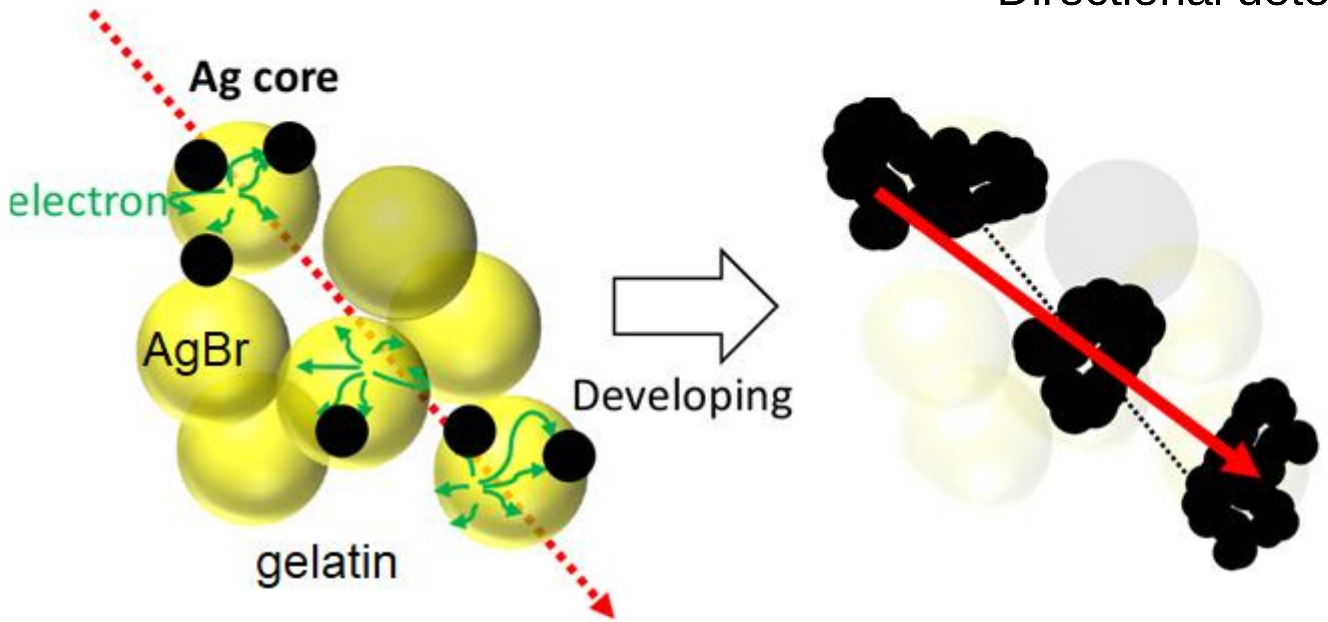
fine grain
⇒ direction detection

Shiraishi_jps2017_12pS34-10

NEWSdm

Nuclear Emulsion

Directional detection



T. Naka, NEWdm (2017), modified

$$e^- + Ag^+ \rightarrow Ag$$

$$e^- + Ag^+ + Ag \rightarrow Ag_2 \cdots Ag_n$$

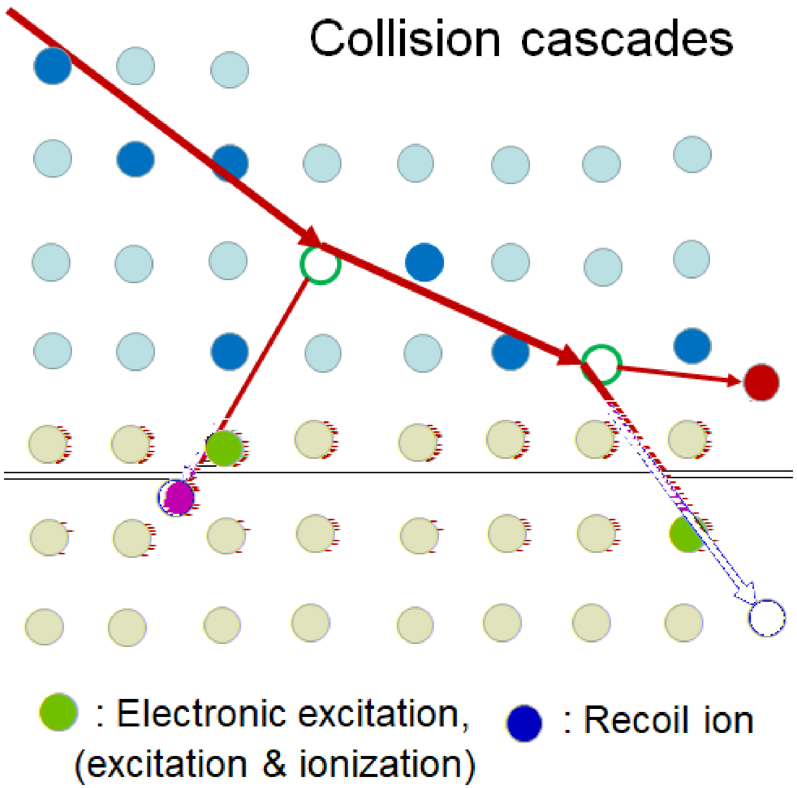
Ag:Br:C(N,O) = 9:7:2. (weight)
= 3.2 g/cm^3 (AgBr 6.5 g/cm^3)
grain size 18-100 nm

Ag filament structure
depends on LET_{el} and track structure
controlled by development treatment

Stopping power and Linear energy transfer, LET

Stopping power:
energy lost by a charged particle

Linear energy transfer, LET:
energy loss along the track of charged particle (-d*E*/dx)



Low energy

$S_T = S_e + S_n$

Energy sharing between electronic excitation and nuclear motion

E = E + E

Electronic LET: LET_{el}
electronic energy absorbed by

$$LET_{el} \quad \frac{dE}{dx} \quad \frac{dE}{dE} S_T \quad \frac{E}{E} S_T$$

$$LET_{el} \quad E \; / R \quad q_{nc} E / R$$

The secondaries, recoil atoms, may again go to the collision process and transfer the energy to new particles and so on.

Nuclear quenching factor, $q_{nc} = E\ /E$

We take a simple model to obtain some idea of response of emulsion to recoil ions because composition, structure and chemical reactions in nuclear emulsion are quite complicated.

Stopping power calculation:
Ag:Br:C(N,O) = 0.4:0.4:2 (no.)
Ag, Br ⇒ Kr
C, N,O ⇒ C

q_{nc} calculation:
$Z_1 = Z_2$ given by Lindhard
Ag, Br in AgBr ⇒ Kr in Kr

C,N,O in AgBr ⇒ C in C
The S_e/S_T ratio for C ions in C differs less than 5% from that for C ions in Br for E keV.

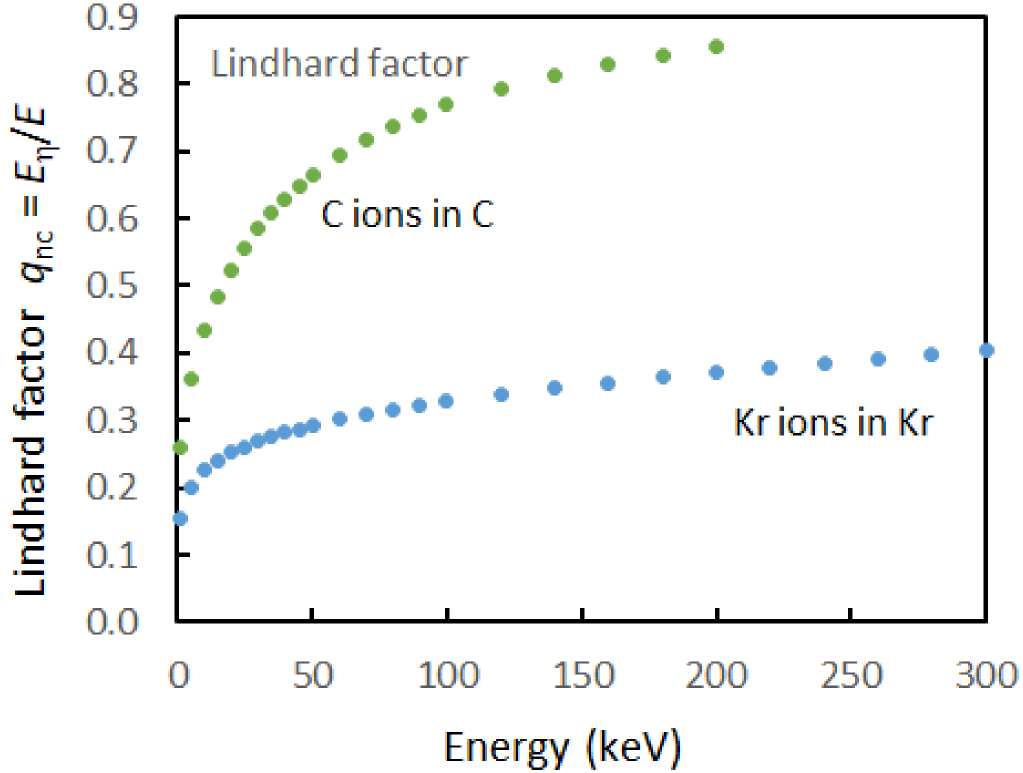


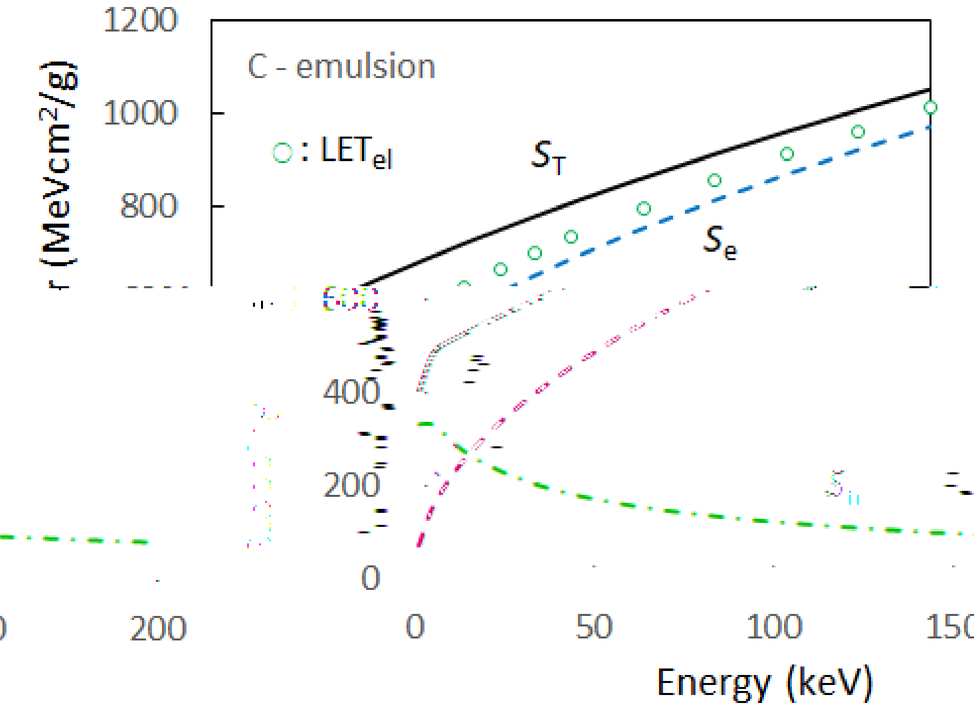
Fig. The nuclear quenching factor (Lindhard factor, $q_{nc} = E\ /E$) for C ions in C and Kr ions in Kr as functions of energy.

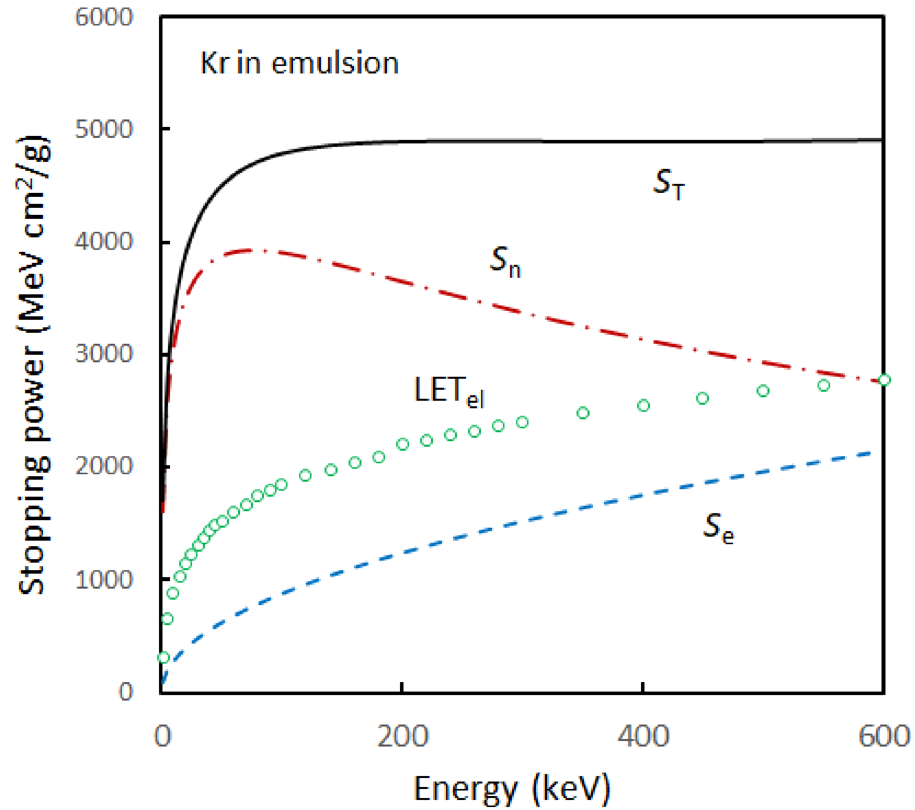
Stopping powers and LET_{el}

$$LET_{el} \quad \frac{dE}{dx} \quad \frac{dE}{dE}\frac{dE}{dx} \quad \frac{dE}{dE} S_T \quad \frac{E}{E} S_T$$

Stopping power
LSS theory

$$LET_{el} \quad E \; / R \quad q_{nc}E / R$$





Figs. The stopping powers, S_T, S_n, S_e and LET_{el} (=-dE /dx) for C and Kr ions in emulsion as functions of energy.

Mean hit density

Hit density: $(n\text{-}1)/R_{PRJ}$
R_{PRJ}: the projected range
n : the no. of the filaments

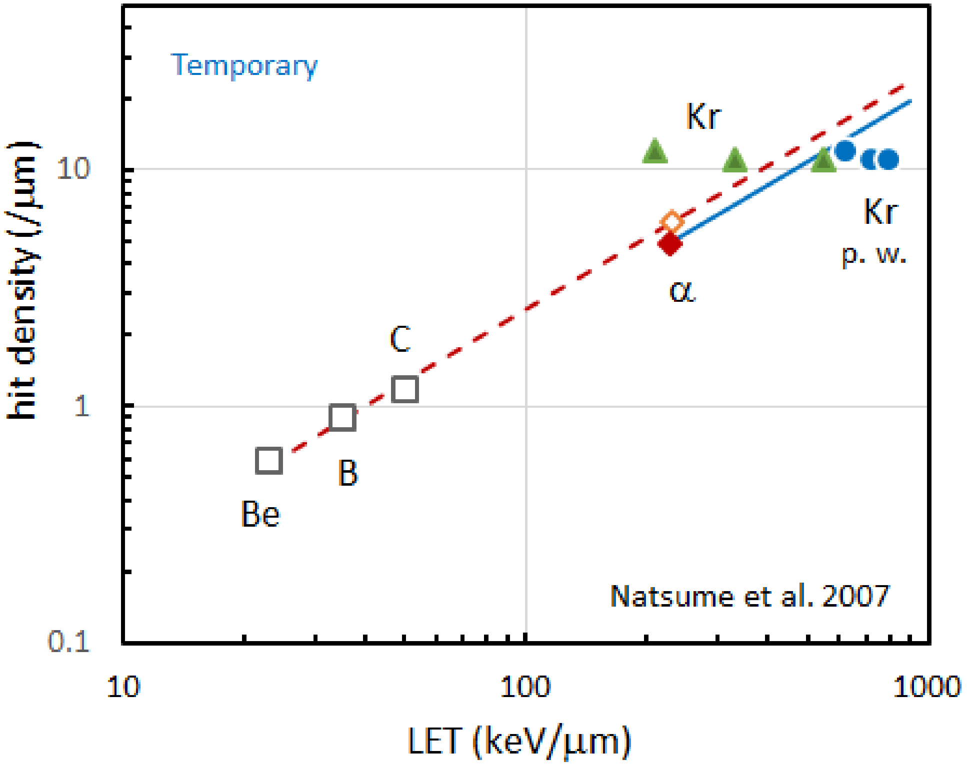


Figure Mean hit density for 5.3 MeV -particles, 290 MeV/n Be, B and C ions, and 200, 400 and 600 keV Kr ions in fine grain nuclear emulsion as a function of LET. The electronic stopping power at incident energy were used for Kr ions (▲). Circles for Kr are replotted at averaged LET_{el} (● present work).
Open and closed symbols show the difference in developer.

Heavy ion track

Microscopic structure

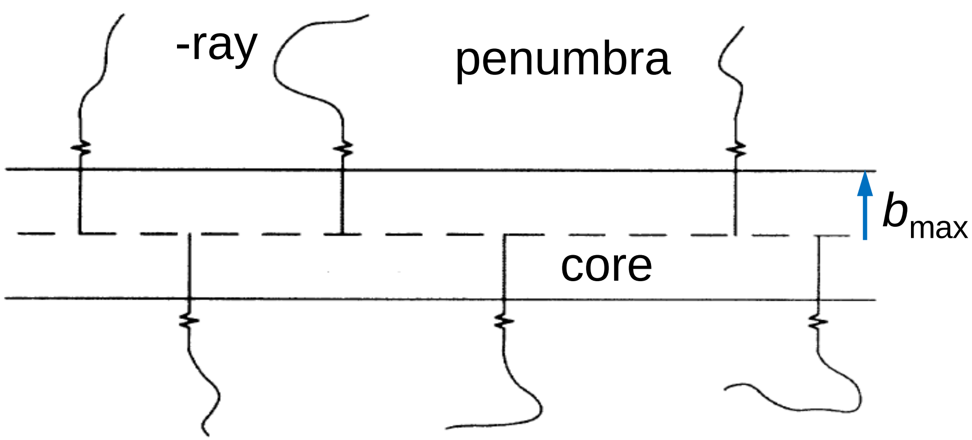
The track for heavy ions can be regarded as cylindrical geometry, consists of the high-density core and surrounding less dense penumbra

The core radius b_{max} is given by

$$\frac{2b_{max}}{v} \quad E_1 \quad \hbar \qquad\qquad (\ \ <<1)$$

v: the incident ion velocity

E_1 : the lowest excitation energy.



Quenching occurs in the core.

The energy T_s available for scintillation is

$$T_s \quad qT \quad q_c T_c \quad T_p$$

For   -particle, $T_c/T = 0.72$

the experimental $q = 0.71$ in LAr,

$$T_s / T \quad 0.71 \quad 0.72 q_c \quad 0.28$$

$$q_c \quad 0.6$$

For relativistic ions, $T_c/T \quad 0.5$

For recoil ions,

$T_c/T = 1$

$b_{max} \quad a_0$: atom distance

Stopping power theory tells equipartition of glancing and distant collisions

Core and penumbra of heavy-ion track structure

Cylindrical geometry

The stopping power theory supports the equipartition of the total energy loss between the glancing

$$D_g \quad \frac{LET/2}{a_0^2}\exp(\quad r^2/a_0^2)$$

and close collisions (-rays).

$$D_k \quad \frac{LET/2}{2 \quad r_c^2 \ln(\sqrt{e}r_p/r_c)} \qquad r \quad r_c$$

$$D_k \quad \frac{LET/2}{2 \quad r^2 \ln(\sqrt{e}r_p/r_c)} \qquad r_c \quad r \quad r_p$$

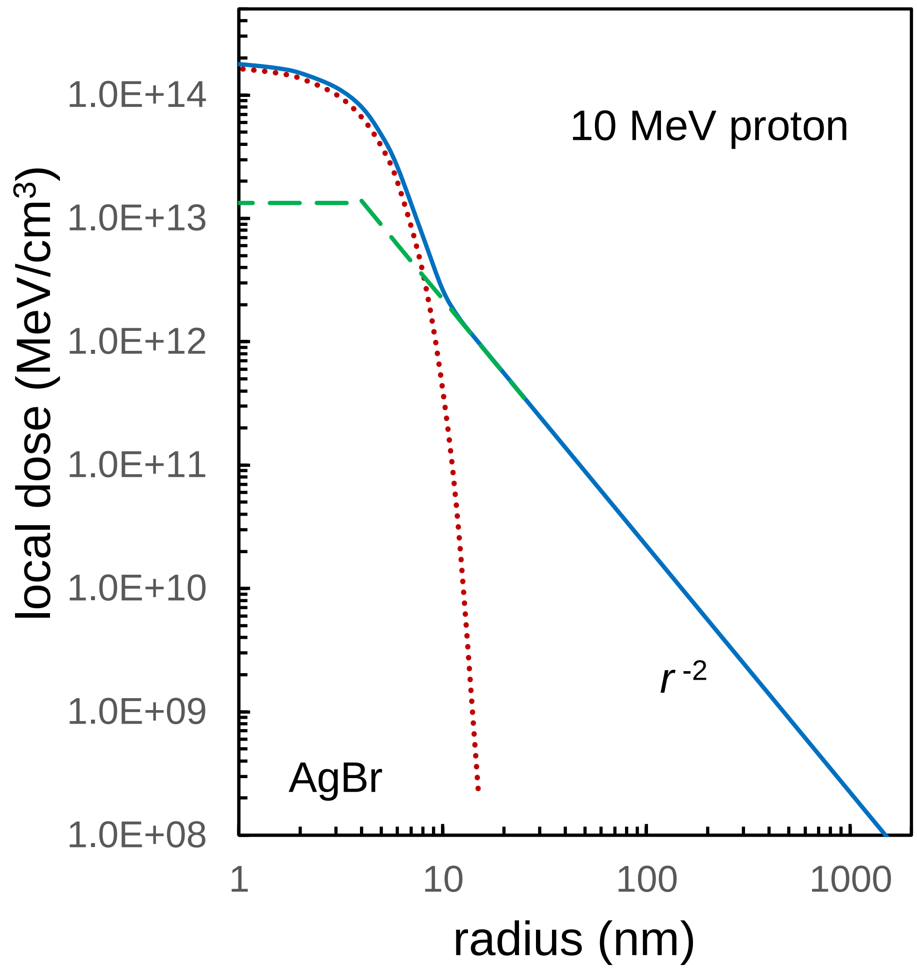
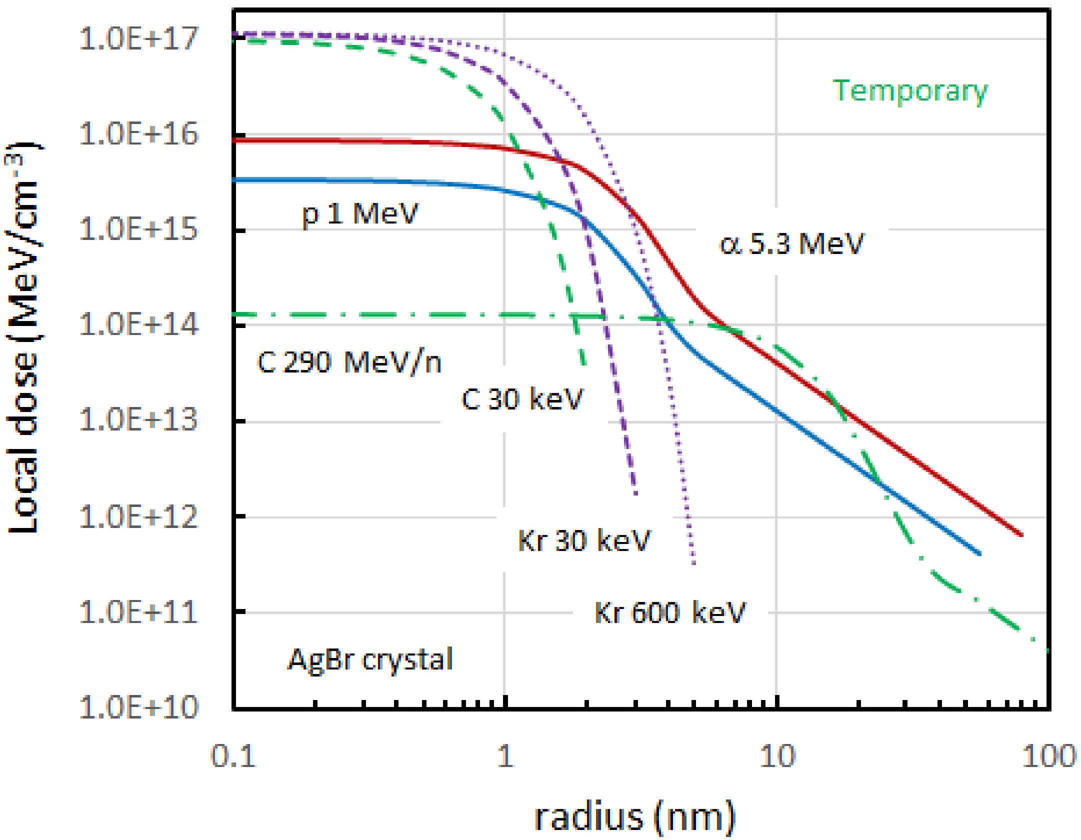


Fig. 1. The so-called core and penumbra of heavy-ion track structure shown for 10 MeV protons in AgBr crystal. red: the glancing, green & blue: knock-on (-rays)

Initial radial distribution of dose



Microscopic structure

A basic factor for
quenching
chemical reactions
charge collection

a_0 is determined so that the no. density of ionization n_i does not exceed that of AgBr n_0.

Figure. Initial radial distribution of dose in AgBr crystal due to various ions showing the core and penumbra of heavy-ion track structure. A part of penumbra is shown for 290 MeV/n C ions. Curves for slow C and Kr ions have only undifferentiated core.

Table I. Data for various particle tracks in AgBr crystal. Values for r_c and r_p are at the initial energy E. r_c values for C and Kr ions show expanded core radii, see the text. (temporary)

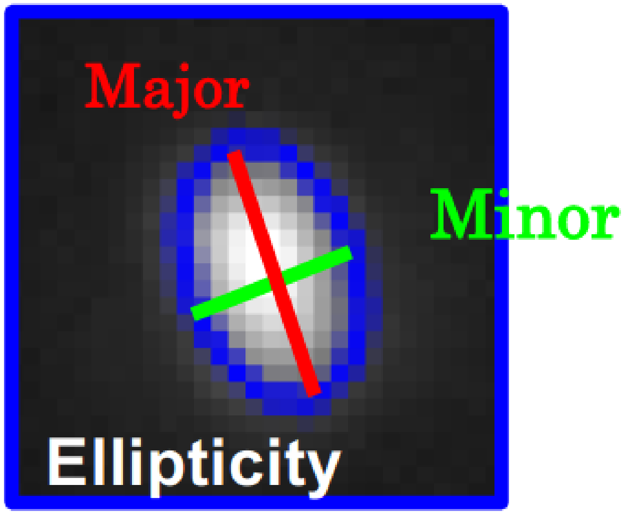
particles	energy keV	velocity = v/c	range m	$q_{nc} = E\ /E$	$<\mathrm{LET}_{el}>$ keV/ m	$E_{\ max}$ keV	r_c nm	r_p nm
protons	1,000	0.046	16	1.0	63	2.2	1.8	55
protons	10,000	0.145	550	1.0	18	22	5.7	2,670
alphas	5,300	0.053	24	1.0	220	2.9	2.1	89
C	30	0.0023	0.100	0.58	150	-	0.7	-
C	100	0.0042	0.310	0.77	250			
Kr	30	0.0009	0.025	0.27	320	-	0.9	-
Kr	200	0.0023	0.120	0.37	620			
Kr	600	0.0039	0.360	0.47	800	-	1.4	-

Parameters used in the calculation

E_g = 2.5 eV

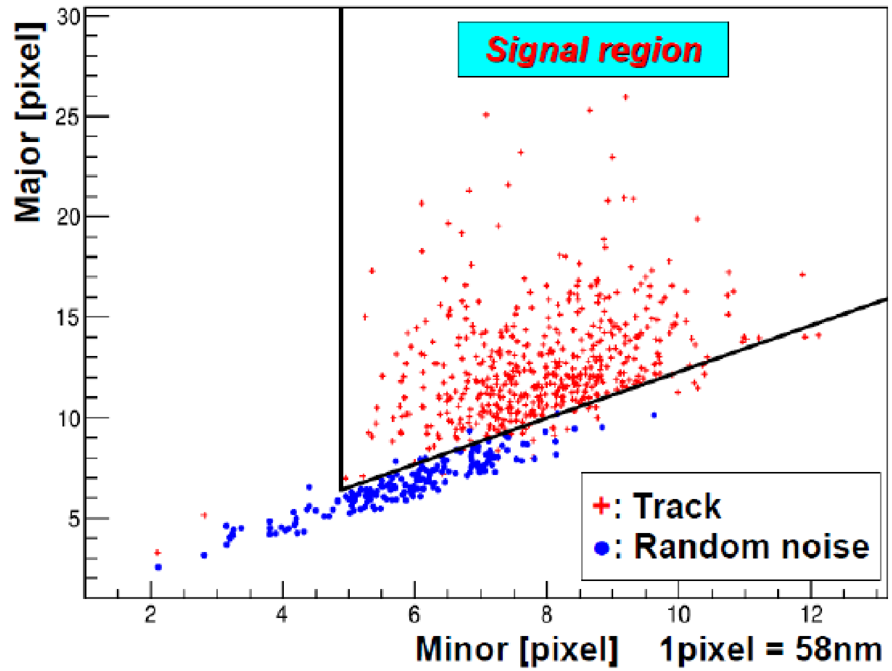
(W) = 5.8 eV

Directional detection　nuclear emulsion



.... Brightness ,Angle,
and number of pixel

Macroscopic structure

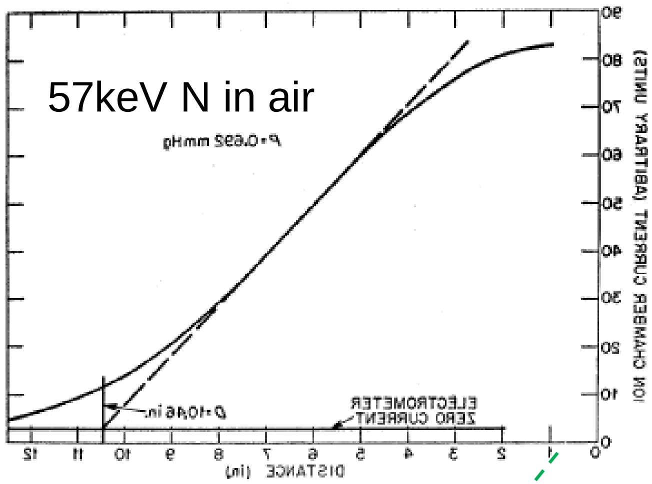


umemoto_jps2017

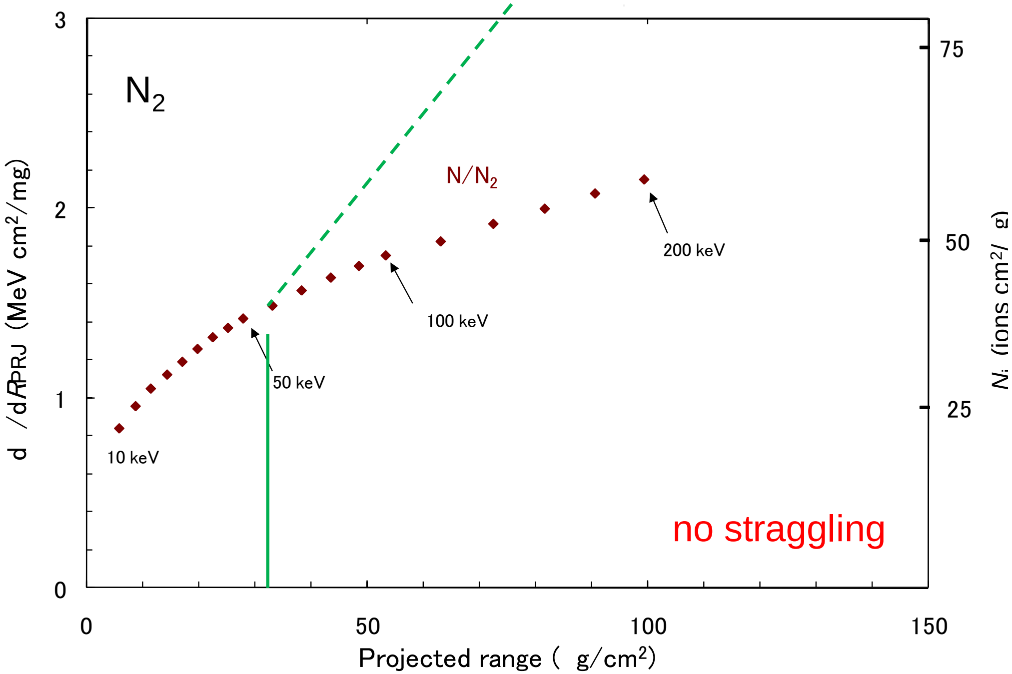
Katsuragawa_JPhys CS 469 (2013) 012004

Minor axis is determined by not only the resolution (grain size etc.) but also the shape of the recoil ion track.

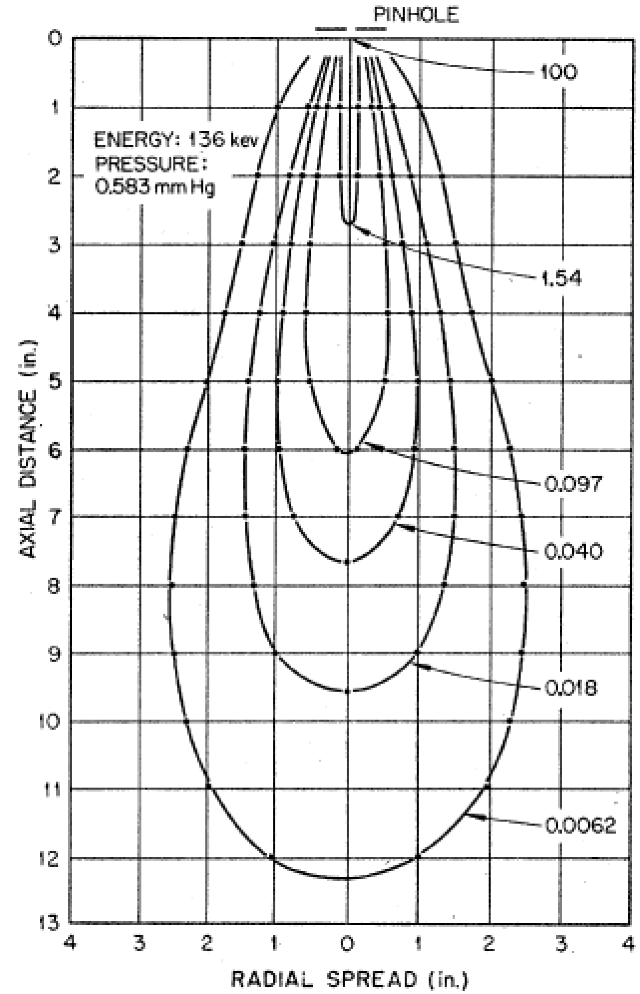
Bragg-like curve dE /dR_{PRJ}



ions



136keV Ar in Ar



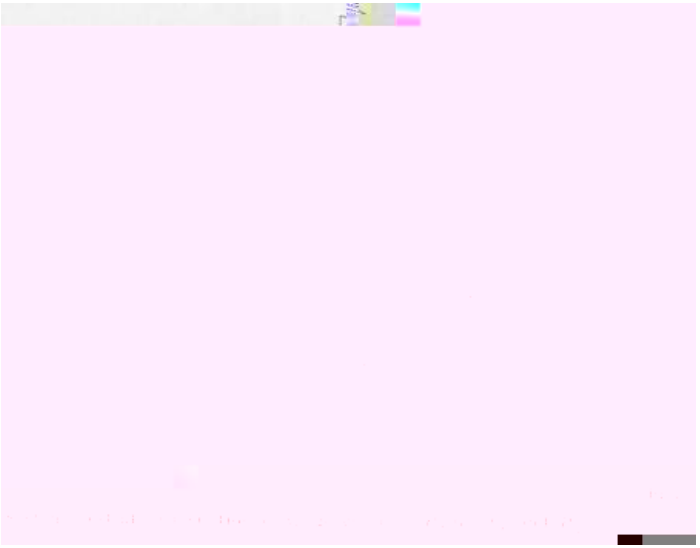
Evans, PR 90, 825 (1953)

R ⇒ bell shape

R & $R_{//}$ ⇒ drop-shape

Hitachi, Rad. Phys. Chem. 77, 1311-1317 (2008)

Range concepts



Lindhard, no.14

Range concepts
R: range along path
R_{PRJ}: projected range

Nuclear process is basically dealt with a screened Rutherford scattering.

LET$_{el}$: dE /dR

The Bragg-like curve : E / R_{PRJ} for head-tail detection.
The distribution of the electronic energy E deposited as a function of the ion depth.

Both are an averaged one dimensional presentation.

The track detours and has branches

Transversal spreads have to be considered.

Summary

a) The electronic LET (LET_{el} =-d*E* /d*x*) plays important role in the evaluation of scintillation quenching, chemical reactions, charge collection, etc..

b) The Bragg-like curve is useful for estimation of track shape and head-tail detection. However, the distribution in x, y, perpendicular to the initial direction, have to be evaluated.

c) Transversal spreads of the track have to be considered.

d) Refinement of stopping theory for low energy ions is required.

Acknowledgements

Dr. A. Mozumder for valuable comments.

Dr. T. Naka for providing information on nuclear emulsion.

Refs.

A. Hitachi, Rad. Phys. Chem. 77, 1311-1317 (2008).

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J. Lindhard and M. Scharff, Phys. Rev. 124 (1961) 128.

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A. Mozumder, "Fundamentals of Radiation Chemistry" (Academic, San Diego, 1999)

Backup

Stopping power for heavy ions Classical Theory

The charged particle gives energy Q for the target atom by collision.

Stopping is given as d the differential cross section

$$\frac{dE}{dx} \quad N \boxed{Qd} \quad S$$

[eV/Å²/atom]

N : atom/volume

the momentum transferred to the electron

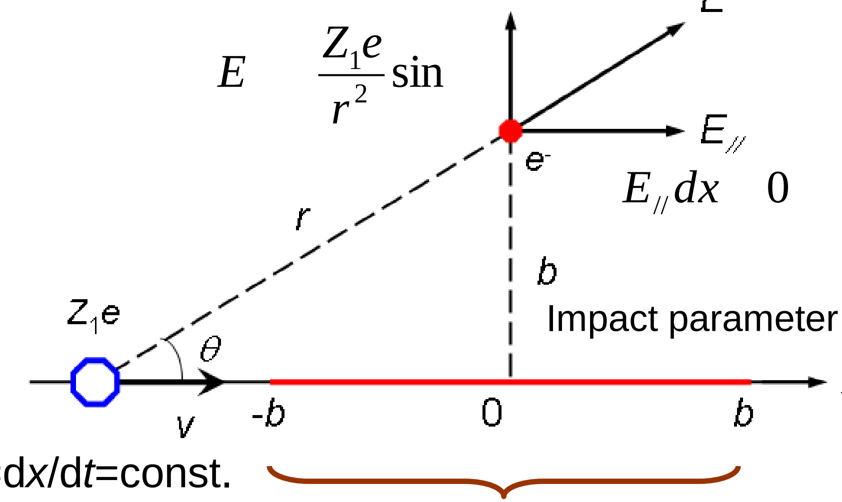
$$p \quad F\ dt \quad \frac{e}{v} \quad E\ dx$$

$$\frac{Z_1 e^2 b}{v} \quad \frac{dx}{(x^2 \quad b^2)^{3/2}} \quad \frac{2Z_1 e^2}{vb}$$

$$Q \quad \frac{p^2}{2m_e} \quad \frac{2Z_1{}^2 e^4}{m_e v^2 b^2}$$

$$E \quad \frac{Z_1 e}{r^2} \sin$$

$$E_{//} dx \quad 0$$



v=dx/dt=const.

Collision occurs this region

$$\mathrm{d} \quad 2 \ b(\mathrm{d}b/\mathrm{d}Q)\mathrm{d}Q$$

Impact parameter method

$$2 \quad {}_0 \quad P(b,v)b\mathrm{d}b$$

$$\boxed{\mathrm{d} \quad \frac{2 \ Z_1{}^2 e^4}{m_e v^2} \frac{\mathrm{d}Q}{Q^2}}$$

the Rutherford cross section for scattering of free charge.
the same form for QM

$$S \quad \frac{2 \ Z_1{}^2 e^4}{m_e v^2} NZ_2 \ln \frac{Q_{\max}}{Q_{\min}}$$

$Q_{max} = 2m_e v^2$

$$\boxed{\frac{2b_{\max}}{v} \quad E_1 \quad \hbar}$$

Q_{min}

$$\boxed{S \quad \frac{4 \ Z_1{}^2 e^4}{m_e v^2} NZ_2 \ln \frac{2m_e v^2}{E_1} \frac{\hbar v}{4Z_1 e^2}}$$

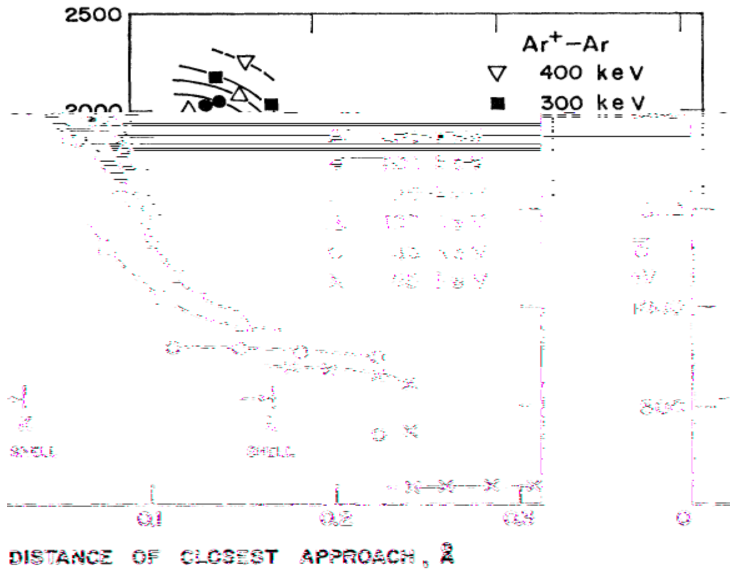
E_1: a typical atomic transition energy

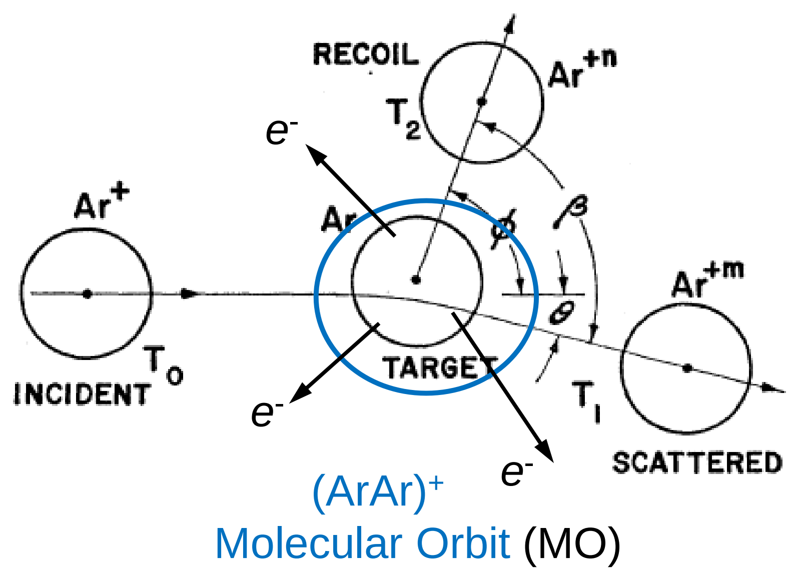
Heavy-particle collisions at low energy

When atomic projectile goes hard (wide deflection angle small impact parameter) collision with atom, the large inelastic energy losses occur at characteristic internuclear distances. Showers of fast-electrons are thrown out.

Inelastic energy losses Q for Ar^+-Ar collision

T_0,θ	m,n	$\bar{Q}_{mn}$ (eV)	m,n	$\bar{Q}_{mn}$ (eV)
6 keV, 8°	T,T	57±3	1,1	55±3
	0,1	36±3	2,1	79±4
	1,0	30±4		
25 keV, 16°	T,T^a	90±17	$2,2^b$	353±7
	T,T^b	379±10	$2,3^b$	362±9
	T,T^c	613±14	$2,3^c$	636±14
	$1,1^a$	62±6	$3,3^b$	468±6
	$2,2^a$	160±7	$3,3^c$	647±10



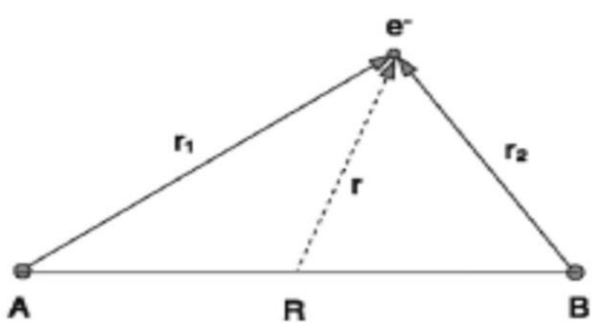


Kessel & Everhart, PR146 (1965)

Molecular orbital (MO) collision theory

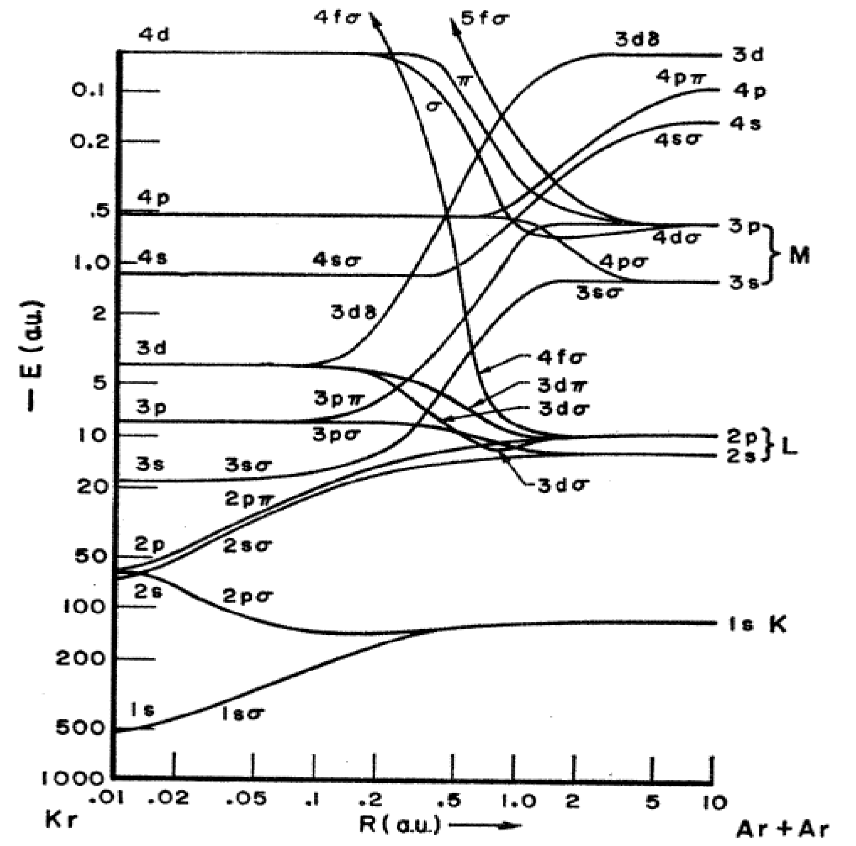
$v_c << v_e$, the electronic motion of the system is expected to adjust adiabatically to the changing position of colliding nuclei.

occupies a MO and become excited during the collision to a higher energy at smaller separation. It contains vacancies after the collision.



Coordinate system for a quasimolecule composed of an electron e^- and two nuclei *A* and *B*.

J. Eichler, Lectures on ion-atom collisions



Energy levels of diabatic (H_2^+-like) molecular orbitals of the Ar-Ar system.