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DATA FOR ELEMENTARY-PARTICLE PHYSICS

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Elementary-particle data and certain other reference information frequently are needed by research workers in high-energy physics in a compact and readily accessible form. For the use of students and staff members in the Radiation Laboratory we have attempted to meet this need. In this summary we have tried to employ units and concepts natural to this field, and to drop those that are irrelevant or obsolete. Slightly older versions of Tables I and Va have already appeared in Gell-Mann's and Rosenfeld's review of elementary particles.[1]

The tables and graphs are as follows:

Table I. The masses and mean lives of the elementary particles

Two international congresses have recently been held on elementary-particle physics: the 1957 Rochester Conference, and the Padova-Venezia Congress. At each, important new data on particle masses and mean lives were presented. In addition, the masses of many particles are better known because an accurate range-energy relation[2] for nuclear track emulsion has now been set forth, so that the errors in decay energies have been greatly reduced. Moreover, it appears that the existence of a single K particle and its antiparticle, with a common mass and decay lifetime, may be reasonably assumed. Bubble chambers and well-calibrated emulsion stacks have provided reliable new data on Λ- and Σ-hyperon decay energies and lifetimes.

All these considerations suggest that enough may now be known about the masses and lifetimes of most of the known elementary particles to warrant compilation.

The best values of the masses and mean lives of nucleons, leptons (e and μ), and pions have been computed recently by Cohen, Crowe, and DuMond;[3] we have used their values directly. We have also used their values

[1] M. Gell-Mann and A. H. Rosenfeld, Ann. Rev. Nuclear Sci. 7, 407 (1957).

[2] Barkas, Barrett, Cüer, Heckman, Smith, and Ticho, The Range-Energy Relation in Emulsion. Part 1. Range Measurements, UCRL-3768, April 1957;
Walter H. Barkas, The Range-Energy Relation in Emulsion. Part 2. The Theoretical Range, UCRL-3769, April 1957.

[3] Cohen, Crowe, and DuMond, Fundamental Constants of Physics (Interscience, New York, 1957).

for the masses of proton and pions in obtaining the masses (and uncertainty in mass) of strange particles from the experimental Q values. It is interesting to note that with the single exception of the mass differences in the Σ-hyperon triplet, it is now the uncertainties in the pion mass and the range-energy relation in emulsion that contribute almost all the uncertainty to the strange-particle masses. If there are theoretical questions that require a further reduction (by an order of magnitude) of the errors in the masses, methods other than the measurement of ranges in emulsion probably should be devised, both for determining strange-particle decay energies and for better determining the masses of π and μ mesons. Range straggling and uncertainties of the local density of even carefully calibrated emulsions limit the practically attainable accuracy of range measurements and the fundamental range-energy calibration curve itself.

Our recommended values of masses and mean lives are given for all the elementary particles on which data are available. The sources of the information are listed as references. When systematic as well as statistical errors appear to affect a measurement, we have been forced to exercise judgment, but this has in no case had a very important effect on the result. This table is not intended to take the place of the critical review by Henri, Shapiro, and Way[4] of all the experiments undertaken so far.

The observed particle spins suggest the following generalization: the particles listed as leptons and baryons have spin 1/2; the mesons have spin zero.

The Σ^- mass is derived entirely from the $\Sigma^- - \Sigma^+$ mass difference measured in emulsion.

To avoid skewed distributions in calculating weighted averages of lifetimes, we have always converted first to decay rates.

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[4]Henri, Shapiro, and Way, to be published in Revs. Modern Phys.

Table I

Masses and mean lives of elementary particles; November, 1957
(The antiparticles are assumed to have the same spins, masses, and mean lives as the particles listed)

	Particle	Spin	Mass (Errors represent standard deviation) (Mev)		Mass difference (Mev)		Mean life (sec)		Decay rate (number per second)
Photon	γ	1	0				stable		0
Leptons	ν	$\frac{1}{2}$	0				stable		0
	e^-	$\frac{1}{2}$	0.510976	(a)			stable		0
	μ^-	$\frac{1}{2}$	105.70 ± 0.06	(a)			$(2.22 \pm 0.02) \times 10^{-6}$		0.45×10^{6}
Mesons	π^+	0	139.63 ± 0.06	(a)	4.6 (a) (π^+, π^0)		$(2.56 \pm 0.05) \times 10^{-8}$	(a)	0.39×10^{8}
	π^0	0	135.04 ± 0.16	(a)			$< 4 \times 10^{-16}$	(d)	$> 2.5 \times 10^{15}$
	K^+	0	494.0 ± 0.2	(g)	0.4 ± 1.8 (K^+, K^0)		$(1.224 \pm 0.013) \times 10^{-8}$	(h)	0.815×10^{8}
	K^0	0	494.4 ± 1.8	(i)		K_1:	$(0.95 \pm 0.08) \times 10^{-10}$	(e)	1.05×10^{10}
						K_2:	$(4 < \tau < 13) \times 10^{-8}$	(c)	$(0.07 < \tau < 0.25) \times 10^{8}$
Baryons	p	$\frac{1}{2}$	938.213 ± 0.01	(a)			stable		0.0
	n	$\frac{1}{2}$	939.506 ± 0.01	(a)			$(1.04 \pm 0.13) \times 10^{+3}$	(a)	0.96×10^{-3}
	Λ	$\frac{1}{2}$	1115.2 ± 0.14	(j)			$(2.77 \pm 0.15) \times 10^{-10}$	(k)	0.36×10^{10}
	Σ^+	$\frac{1}{2}$	1189.4 ± 0.25	(l)	7.1 ± 0.4 (Σ^+, Σ^-)		$(0.83 {}^{+.06}_{-.05}) \times 10^{-10}$	(m)	1.21×10^{10}
	Σ^-	$\frac{1}{2}$	1196.5 ± 0.5	(n)	$6.0^{+1.4}_{-0.9}$ (Σ^-, Σ^0)		$(1.67 \pm 0.17) \times 10^{-10}$	(o)	0.60×10^{10}
	Σ^0	$\frac{1}{2}$	$1190.5^{+0.9}_{-1.4}$	(p)			$(< 0.1) \times 10^{-10}$ theoretically $\sim 10^{-19}$	(b)	$> 10 \times 10^{10}$ theoretically $\sim 10^{19}$
	Ξ	?	1320.4 ± 2.2	(q)			$(4.6 < \tau < 200) \times 10^{-10}$	(f)	$(> 0.005, < 0.2) \times 10^{10}$
	Ξ^0	?	?				?		

Footnotes for Table I

(a) From compilations by Cohen, Crowe, and DuMond, Nuovo cimento 5, 541 (1957), and Fundamental Constants of Physics, to be published by Interscience, New York, 1957. They include all data available before January 1, 1957.

(b) Alvarez, Bradner, Falk-Vairant, Gow, Rosenfeld, Solmitz, and Tripp, K^- Interactions in Hydrogen, UCRL-3775, May 1957.

(c) Landé, Lederman, Bardon, Tinlot, and Chinowsky (to be published).

(d) Orear, Harris, and Taylor, Phys. Rev. 106, 327 (1957).

(e) Eisler, Plano, Samios, Schwartz, and Steinberger, Nuovo cimento 5, 1700 (1957).

(f) G. H. Trilling and G. Neugebauer, Phys. Rev. 104, 1688 (1956).

(g) $M_{K^+} = 3m_{\pi^\pm} + Q_\tau$, where Q_τ is the weighted average of values reported by Heckman, Smith, and Barkas, Nuovo cimento 4, 51 (1956); Roy Haddock, Nuovo cimento 4, 240 (1956); and Bacchella, Berthelot, et al., Nuovo cimento 4, 1529 (1956). The uncertainty in m_π has of course been treated as common to all experiments. We have assumed that the K^- is the antiparticle of the K^+ and shares the same mass and lifetime. The present experimental mass of the K^- is consistent with this assumption, namely 493.4 ± 0.5 Mev (R.S. White, compilation of all emulsion data for 1957 Rochester Conference).

(h) τ_{K^+}, from weighted average of the decay rates corresponding to the following mean lives:
$1.227 \pm 0.015 \times 10^{-8}$ sec (Alvarez, Crawford, Good, and Stevenson, Phys. Rev. (to be published)).
$1.211 \pm 0.026 \times 10^{-8}$ sec (V. Fitch and R. Motley, Phys. Rev. 101, 496 (1956); Phys. Rev. 105, 265 (1957); and private communication.) The quoted errors are statistical only. We have assumed that the K^- is the antiparticle of the K^+ and shares the same mean life. The present experimental mean life is consistent with this assumption, namely $\tau_{K^-} = 1.25 \pm 0.11 \times 10^{-8}$ sec (W. H. Barkas, 1957 Rochester Conference).

(i) m_{K^0}, weighted average of the following Q values for $K^0 \rightarrow \pi^+ + \pi^- + Q$ (Mev):
214.0 ± 2.5 (Thompson, Burwell, and Huggett, Nuovo cimento 4, Suppl. 3, 286 (1956)),
212.0 ± 4 (Arnold, Martin, and Wyld, Phys. Rev. 100, 1545, (1955)),
217.0 ± 4 (R. Armenteros, 1957 Rochester Conference),
222.6 ± 5.3 (Fretter, Freisen, and Lagarrique, Nuovo cimento 4, Suppl. 3, 539 (1956)).

(j) m_Λ is the weighted average (in Mev) of:
1114.00 ± 0.39 (all cloud chamber work in review by Cohen et al.),
1115.74 ± 0.40 (R. Armenteros, 1957 Rochester Conference),
1115.30 ± 0.16 (W. H. Barkas, Padua-Venice Conference, 1957).
There is another value, $m_\Lambda = 1114.7 \pm 0.21$ Mev, reported by Friedlander et al. in Phil. Mag. 45, 533 (1957) and updated at the 1957 Padua-Venice conference. However, these authors are in process of re-evaluating their errors, therefore we have postponed folding in their value.

(k) τ_Λ, from weighted average of the decay rates corresponding to the following mean lives:
$1.9 \pm 0.4 \times 10^{-8}$ sec (Graves, Brown, Glaser, and Perl, Bull. Am. Phys. Soc. 2, 221 (1957)),
$2.77 \pm 0.2 \times 10^{-8}$ sec (e),
$3.1 \pm 0.5 \times 10^{-8}$ sec (b),
$3.25 \pm 0.33 \times 10^{-8}$ sec (a).

(l) m_{Σ^+}, weighted average (allowing for common systematic uncertainties) of
1189.28 ± 0.28 Mev (W.H.Barkas, 1957 Padua-Venice Conference),
1189.1 ± 0.4 Mev (Fry, Schneps, Snow, and Swami, Phys. Rev. (to be published)),
1190.3 ± 0.5 Mev (R. S. White, 1957 Rochester Conference).

(m) τ_{Σ^+} from weighted average of
$0.95 \pm 0.30 \times 10^{-10}$ sec (Graves et al., Bull. Am. Phys. Soc. 2, 221 (1957)),
$0.69 \pm 0.10 \times 10^{-10}$ sec (b),
$0.90^{+0.10}_{-0.08} \times 10^{-10}$ sec (average of emulsion data on the protonic decay mode only). The emulsion data include 15 decay events from Rochester and 14 from Wisconsin that were compiled by Dr. G. Snow for the 1957 Rochester Conference. Included also are 12 events by Glasser, Seeman, and Snow (private communication, Nov. 13, 1957) and 59 from the University of California Thesis of P.C.Giles, reported at the Padua-Venice Conference by W. H. Barkas.

(n) m_{Σ^-} from the following $m_{\Sigma^-} - m_{\Sigma^+}$ mass differences:
6.56 ± 0.66 Mev(Barkas, Giles, Heckman, Inman, Mason, and Smith, Hyperon and K^--Meson Masses, UCRL-3892, Sept. 1957),
7.10 ± 0.92 Mev(Chupp, Goldhaber, Goldhaber, and Webb),
8.12 ± 1.48 Mev(Fry, Schneps, Snow, Swami, and Wold, Phys. Rev. 104, 270 (1956)),
7.46 ± 0.72 Mev(K Collaboration-Presented by Prowse at Padua-Venice Conference, 1957).

(o) τ_{Σ^-}, weighted average of
$1.9^{+0.4}_{-0.3} \times 10^{-10}$ sec (Columbia, Bologna, Pisa propane chamber collaboration (Padua-Venice Conference, 1957))
$1.6 \pm 0.2 \times 10^{-10}$ sec (b)

(p) Σ^0 from weighted average of
$1186.9^{+3.8}_{-7.1}$ Alvarez et al. "Interactions of K^- Mesons in Hydrogen" UCRL-3775, (1957)
1192.6 ± 3.5 Eisler et al "Associated Production of Σ^0 and θ_2^0, Mass of the Σ^0" Nevis-60 Report R-198 (1957)
1191.6 ± 3.3 M. L. Stevenson "The Σ^0 Mass" UCRL-8199 (1958). This experiment was performed since Table V was prepared. The older Σ^0 mass of 1190.0 was used to calculate Table V.

(q) m_{Ξ^-} from 12 events. Six of these (from CalTech) are summarized by Trilling and Neugebauer, (f); six others are compiled from Tables 4-15 by Cohen, Crowe, and DuMond.

Table II. Atomic and nuclear properties of materials

Atomic and nuclear properties of materials often used as particle absorbers and detectors have been collected for ready reference. The densities given are subject to variations depending on the form in which the material has been prepared. This is an especially important variable for graphite. The radiation length, as is well known, depends on the approximations made in its calculation.

In Table II, for definiteness and consistency, we have preferred simply to take the values quoted by Bethe and Ashkin.[5] These have not been corrected for the failure of the Born approximation, and Wheeler's and Lamb's[6] calculation of the ζ was used (ζ is the efficiency for bremsstrahlung of electrons relative to nuclei in a screened field). Wheeler and Lamb calculated ζ on the basis of a Thomas-Fermi model of the atom and neglected electron exchange. The failure of the Born approximation is known to cause the tabulated radiation length to be about 10% too low for lead,[7] and the error varies approximately with the square of the atomic number, so that the effect in emulsion, for example, is about 3%. The effects of the other approximations are not well known. The calculated radiation length is particularly uncertain in liquid hydrogen. A rough formula useful when the atomic number, Z, exceeds 5 is

$$L_{rad} \approx 166\ Z^{-0.76}\ \mathrm{g/cm^2}.$$

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[5] H. Bethe and J. Ashkin, Part II of Experimental Nuclear Physics, E. Segrè, Ed. (Wiley, New York, 1953).
Professor W. K. H. Panofsky has kindly advised us regarding the various types of errors in the calculation of the radiation length, and if another edition of these tables is written, it may be possible to refine these numbers somewhat and to include suggested changes of other sorts.

[6] J. A. Wheeler and W. E. Lamb, Phys. Rev. 55, 858 (1939).

[7] Davies, Bethe, and Maximom, Phys. Rev. 93, 788 (1954).

Table II

Atomic and nuclear properties (dE/dx, collision mean free path, radiation length, etc.) of materials used as absorbers and detectors

Material	Z	A	Cross section σ [a] (barns)	$-\frac{dE}{dx}$ min [b] Mev g/cm^2	Collision[a] length, L_{coll} g/cm^2	Collision[a] length, L_{coll} cm	Radiation[c] length, L_{rad} g/cm^2	Radiation[c] length, L_{rad} cm	Density ρ (g/cm^3)
H_2	1	1.01	0.063	4.14	26.5	374	58	819.0	0.0708
Li	3	6.94	0.23	1.72	50.4	94.3	77.5	145	0.534
C	6	12.00	0.33	1.86	60.4	39.0	42.5	27.4	1.55 (variable)
Al	13	26.97	0.57	1.66	79.2	29.3	23.9	8.86	2.70
Cu	29	63.57	1.00	1.45	105.4	11.8	12.8	1.44	8.9
Sn	50	118.70	1.55	1.27	129.7	17.8	8.54	1.17	7.30
Pb	82	207.21	2.20	1.12	156.2	13.8	5.8	0.51	11.34
U	92	238.07	2.42	1.095	163.6	8.75	5.5	0.29	18.7
Hydrogen (bubble chamber, -27.6°K)				0.243 Mev/cm	26.5	452	58	990	0.0586
Propane (C_3H_8, bubble chamber)				0.935 Mev/cm	48.9	119.3	44.7	109.0	0.41
Polystyrene (CH scintillator)				2.14 Mev/cm	54.9	52.3	43.4	41.3	~ 1.05
Ilford emulsion				5.49 Mev/cm	103	27.0	11.2	2.91	3.815

[a] $\sigma_{natural} \equiv \pi \left(\frac{\hbar}{m_\pi c}\right)^2 \times A^{2/3} = 63 \text{ mb} \times A^{2/3}$; $L_{collision} \equiv \frac{A}{N_0 \sigma_{natural}} = \frac{A^{1/3}}{N_0 \pi \left(\frac{\hbar}{m_\pi c}\right)^2} = 26.4\, A^{1/3}$ g/cm^2.

[b] From range-energy tables of M. Rich and R. Madey, UCRL-2301, March 1954, and of Walter H. Barkas, UCRL-3769, April 1957.

[c] From Experimental Nuclear Physics, E. Segrè, Ed. (Wiley, New York, 1953), Table 8, p. 265. The radiation lengths have not been corrected for failure of the Born approximation and several additional small effects.

Table III. Particle scattering

An estimate of multiple Coulomb scattering is often made by assuming that the distribution is Gaussian, with a root-mean-square space angle

$$\theta_{rms} \approx (21.2/Pv)\sqrt{L/L_{rad}}, \qquad (1a)$$

where L is the thickness traversed in the scatterer, and L_{rad} is the radiation length of the scatterer.[8] The equivalent formula for the more useful projected rms angle is

$$\theta_{rms\text{-}p} \approx (15.0/Pv)\sqrt{L/L_{rad}}. \qquad (1b)$$

Although the formula above is convenient, it has the weakness that the true angular distribution is not strictly Gaussian but has an appreciable "tail" out in the region where a Gaussian distribution has fallen to a few percent of its maximum value.[9] This tail (due to single and plural scattering) causes Eq. (1) to be in error by ~20% for thicknesses ~1% of a radiation length (it was derived to give correct results for large thicknesses). This error is given in Table III and is discussed below.

Molière has calculated a distribution that fits the experimental facts.[10] Because of the large "tail" the root-mean-square angles θ_{rms} and $\theta_{rms\text{-}p}$ for the Molière distribution are not meaningful unless an arbitrary cutoff angle is introduced. The theory, however, does define a mean (absolute) projected angle of scattering θ_{mp}.

We have chosen the following way to display the results of Molière's theory. First we have rewritten the familiar Eq. (1) to give the mean projected scattering angle. This was still done on the assumption that the distribution is Gaussian, so that the mean deviation can be obtained from the standard deviation by using the relation $\pi(\theta_{rms\text{-}p})^2 = 2(\theta_{mp})^2$. Correcting the 15 in Eq. (1b) by $\sqrt{2/\pi}$, we then have

$$\theta_{mp} \approx (12/Pv)\sqrt{L/L_{rad}}. \qquad (2)$$

The Molière-theory results are then expressed as correction factors for the crude Eq. (2), i.e., we have expressed the Molière result in the form

$$\theta_{mp} = (12/Pv)\sqrt{L/L_{rad}}\,(1+\epsilon). \qquad (3)$$

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[8] See, for example, Reference 5, Eq. (79b).

[9] See, for example, the experimental work of Hansen, Lanzl, Lyman, and Scott, Phys. Rev. 84, 634 (1951).

[10] G. Z. Molière, Naturforsch. 3 (a), 18 (1948).

The values of the correction ϵ are compiled in Table III. The root-mean-square formulas, Eq. (1) will also be improved by introducing the factor $(1 + \epsilon)$. The estimates of ϵ in Table III are to be employed with values of L_{rad} taken from Table II.

The screening effect in the Molière theory is derived from the Thomas-Fermi model of the atom. The error introduced in applying these formulas to the scattering by molecular hydrogen is not known (at least to us).

When the thickness of the scatterer becomes comparable to the nuclear interaction free path in that material, the scattering calculated from Molière's theory will be completely wrong, because specific nuclear scattering will by then have become dominant. Also the high radiation probability makes the theory unusable for electrons except when the foil is thin. Only for muons, therefore, is the formula at all applicable when the absorber is thick.

Table III

Multiple scattering (Coulomb only) calculated from Molière theory.

θ_{mp} is the mean projected angle in radians between tangents to the particle trajectories:

$$|\theta|_{average} \equiv \theta_{mp} = z \frac{12(\text{Mev})}{pv(\text{Mev})} \sqrt{\frac{L}{L_{rad}}} (1 + \epsilon) \quad *$$

L is the thickness, and L_{rad} the radiation length (from Table II) for the absorber (atomic number Z).
For particles of charge ze and velocity βc, the following table for ϵ applies:

Z \ L/L_{rad}	10^{-3}	10^{-2}	10^{-1}	1	10	
1	-0.20	-0.14	-0.08	-0.03	+0.02	
6	-0.14	-0.07	-0.00	+0.06	+1.12	$\beta/z = 0.1$
29	-0.18	-0.10	-0.01	+0.06	+0.13	(4.7-Mev proton)
82	-0.27	-0.16	-0.07	+0.02	+0.10	
1	-0.26	-0.20	-0.14	-0.08	-0.03	
6	-0.20	-0.12	-0.05	+0.01	+0.07	$\beta/z = 0.3$
29	-0.20	-0.11	-0.03	+0.05	+0.12	(45-Mev proton)
82	-0.28	-0.17	-0.07	+0.08	+0.09	
1	-0.31	-0.24	-0.18	-0.12	-0.07	
6	-0.26	-0.18	-0.10	+0.03	+0.03	$\beta/z = 0.7$
29	-0.25	-0.15	-0.06	+0.02	+0.09	(380-Mev proton)
82	-0.29	-0.17	-0.08	-0.01	+0.09	
1	-0.34	-0.26	-0.20	-0.14	-0.08	
6	-0.29	-0.20	-0.12	-0.05	-0.01	$\beta/z = 1.0$
29	-0.34	-0.23	-0.13	-0.05	-0.03	
82	-0.31	-0.19	-0.09	-0.00	-0.08	

*Note that in the Gaussian approximation the root-mean-square projected angle is obtained from the formula above by substituting 15 for the coefficient 12.

Table IV. Atomic and nuclear constants

Atomic and nuclear constants in the directly applicable units of Mev, cm, and sec are tabulated. A few useful formulas and numerical constants are also included.

Table IV

Atomic and nuclear constants in units of Mev, cm, and sec[a]

GENERAL ATOMIC CONSTANTS

$N = 6.0249 \times 10^{23}$ molecules/gram mole

$c = 2.99793 \times 10^{10}$ cm/sec

$e = 4.80286 \times 10^{-10}$ esu $= 1.6021 \times 10^{-19}$ coulomb.

1 Mev $= 1.6021 \times 10^{-6}$ erg [1 ev = e(10^8/c)]

$\hbar = 6.5817 \times 10^{-22}$ Mev sec $= 1.054 \times 10^{-27}$ erg sec.

$\hbar c = 1.9732 \times 10^{-11}$ Mev cm [$= \lambda\!\!\!^{-}$ for p = 1Mev/c]

$k = 8.6167 \times 10^{-11}$ Mev/°C [Boltzmann constant]

$\alpha = \frac{e^2}{\hbar c} = 1/137.037$; $e^2 = 1.44 \times 10^{-13}$ Mev cm

QUANTITIES DERIVED FROM THE ELECTRON MASS, m

Mass and Energy

$m = 0.510976$ Mev $= 1/1836.12\ m_p = 1/273.26\ m_\pi$

Rydberg, $R_\infty = \frac{me^4}{2\hbar^2} = mc^2 \times \frac{\alpha^2}{2} = 13.605$ ev

Length (1 fermi = 10^{-13} cm; 1 Å = 10^{-8} cm)

$r_e = e^2/mc^2 = 2.81785$ fermi

$\lambda\!\!\!^{-}_{Compton} = \frac{\hbar}{mc} = r_e \alpha^{-1} = 3.8612 \times 10^{-11}$ cm

a_∞ Bohr $= \frac{\hbar^2}{me^2} = r_e \alpha^{-2} = 0.52917$ Å

Cross Section

$\sigma_{Thompson} = \frac{8}{3} \pi r_e^2 = 0.6652 \times 10^{-24}\ cm^2 = 0.6652$ barn

Magnetic Moment and Cyclotron Angular Frequency

$\mu_{Bohr} = \frac{e\hbar}{2mc} = 0.57883 \times 10^{-14}$ Mev/gauss

$\frac{1}{2}\omega_{cyclotron} = \frac{e}{2mc} = 8.7945 \times 10^{6}$ rad sec^{-1}/gauss

$g_{electron} = 2[1 + \frac{\alpha}{2\pi} + 0.328 (\frac{\alpha}{\pi})^2] = 2[1.001163]$[b]

$g_{muon} = 2[1 + \frac{\alpha}{2\pi} + 0.75 (\frac{\alpha}{\pi})^2] = 2[1.001172]$[b]

QUANTITIES DERIVED FROM THE PROTON MASS, m_p

Rest mass = 938.211 Mev/c^2 = 1836.12 m_e = 6.719 m_π

1.007593 m_1(m_1 = 1 amu = $\frac{1}{16}$ O^{16})

Magnetic Moment and Cyclotron Angular Frequency

$\mu_p = \frac{e\hbar}{2m_p c} = 3.1524 \times 10^{-18}$ Mev/gauss

$\frac{1}{2}\omega_{cyclotron} = \frac{e}{2m_p c} = 4.7896 \times 10^{3}$ rad sec^{-1}/gauss

$g_p \equiv \left.\frac{\mu}{\mu_p}\right)_{proton} = 2.79275$; $\quad g_n \equiv \left.\frac{\mu}{\mu_p}\right)_{neutron} = -1.9128$

Table IV (continued)

QUANTITIES DERIVED FROM THE MASS OF THE CHARGED PION, m_π

Rest mass = 139.63 Mev/c^2 = 273.26 m_e = 0.14882 m_p

Length

$\frac{\hbar}{m_\pi c}$ = 1.4132 fermi ($\sim\sqrt{2}$ fermi)

Natural (≈ "geometrical") Nucleon Cross Section

$\pi\left(\frac{\hbar}{m_\pi c}\right)^2$ = 62.7344 mb (1 mb = 10^{-27} cm^2)

(3/2, 3/2)πp Resonance

Center-of-mass momentum: p_π = 230 Mev/c

Lab-system momentum: P_π = 303 Mev/c (T_π = 194 Mev)

RADIOACTIVITY

1 curie = 3.7 × 10^{10} disintegrations/sec

1 r = 87.8 ergs/g air = 5.49×10^7 Mev/g air

Fluxes (per cm^2) to liberate 1 r in carbon:

3 ×10^7 minimum ionizing singly charged particles
0.9×10^9 photons of 1 Mev energy.

(These fluxes are are actually correct to within a factor of two for all materials.)

Natural background: 100 mr/year

"Tolerance" 100 millirem/week [Note, 1 r may produce up to 10 "rem" (r equivalent for man), depending on type of radiation.]

MISCELLANEOUS

Physical Constants

1 year = 3.1536×10^7 sec (≈ π×10^7 sec)

Density of air = 1.205 mg/cm^3 at 20°C

Acceleration by gravity = 980.67 cm/sec^2

1 calorie = 4.184 joules

1 atmosphere = 1033.2 g/cm^2

Numerical Constants

1 radian = 57.29578 deg; e = 2.71828
ln 2 = 0.69315; $\log_{10}$ e = 0.43429;
ln 10 = 2.30259; $\log_{10}$ 2 = 0.30103.

Stirling's approximation

$\sqrt{2\pi n}\,(\frac{n}{e})^n < n! < \sqrt{2\pi n}\,(\frac{n}{e})^n\,(1 + \frac{1}{12n-1})$

Gaussianlike Distributions

For n > -1 but not necessarily integral:

$$\int_0^\infty x^{2n+1} \exp\left[-\frac{x^2}{2\sigma^2}\right] dx = 2^n\, n!\, \sigma^{2n+2};\ (\tfrac{1}{2})! = \sqrt{\pi}/2$$

Relation between standard deviation σ and mean deviation α:

$2\sigma^2 = \pi\alpha^2$; σ = 1.4826 probable error.

Odds against exceeding one standard deviation = 2.15:1; two, 21:1; three, 370:1; four, 16,000:1; five, 1,700,000:1

[a] Based mainly on Cohen, Crowe, and Dumond, The Fundamental Constants of Physics (Interscience, New York, 1957).

[b] C. Sommerfield, Phys. Rev. 107, 328 (1957).

Table V. Particle decay and reaction dynamics

Energy and momentum conservation have been applied to the possible decay reactions of the unstable particles listed in Table I, and center-of-mass quantities of interest derived from the mass values listed are given in Table Va. Reactions of negative particles with protons and deuterons have also been analyzed and the results are given in Table Vb.

Coulomb binding energies have been neglected. The tables were prepared before the final estimate of the Σ^0 mass was made and the figure used for this mass was 1190.0 rather than 1190.5 Mev. The number of significant figures is correctly given for the particle masses, but other table entries may contain more than are experimentally justified.

Table Va

Dynamics of particle decays

For three-body decays (e.g. $\mu \to e + \nu + \bar{\nu}$) the quantities tabulated for each particle are the maximum values attainable. The masses are taken from Table I, with the exception of the deuteron mass, $(H^2)^+ = d = 1875.49$ Mev,[a] and $\Sigma^0 = 1190.0$.[b]

	Q (Mev)	Decay products	Mass (Mev/c^2)	Momentum p (Mev/c)	Total energy $w = T + mc^2$ (Mev)	$\eta = p/mc$	$\gamma = w/mc^2$	$\beta = pc/w$
$M_\mu = 105.70 \pm 0.06$ Mev								
$\mu^\pm \to e^\pm + \nu + \bar{\nu}$	105.189	$e^\pm$	0.5110	52.849	52.851	103.4271	103.4319	1.0000
$M_\pi = 139.63 \pm 0.06$ Mev								
$\pi^\pm \to \mu^\pm \pm \nu$	33.93	$\mu^\pm$	105.70	29.808	109.822	0.2820	1.0390	0.2714
$M_{K^\pm} = 494.0 \pm 0.2$ Mev								
$K^\pm \to \pi^\pm + \pi^0$	219.33	$\pi^\pm$	139.63	205.291	248.276	1.4703	1.7781	0.8269
		π^0	135.04	205.291	245.724	1.5202	1.8196	0.8355
$K^\pm \to \mu^\pm \pm \nu$	338.30	$\mu^\pm$	105.70	235.692	258.308	2.2298	2.4438	0.9124
$K^\pm \to \pi^+ + \pi^- + \pi^\pm$	75.11	$\pi^\pm$	139.63	125.588	187.800	0.8994	1.3450	0.6687
$K^\pm \to \pi^0 + \pi^0 + \pi^\pm$	84.29	$\pi^\pm$	139.63	133.099	192.904	0.9532	1.3815	0.6900
		π^0	135.04	132.371	189.097	0.9802	1.4003	0.7000
$K^\pm \to \pi^0 + \mu^\pm \pm \nu$	253.26	π^0	135.04	215.304	254.149	1.5944	1.8820	0.8472
		$\mu^\pm$	105.70	215.304	239.851	2.0369	2.2692	0.8977
$K^\pm \to \pi^0 + e^\pm \pm \nu$	358.449	π^0	135.04	228.542	265.457	1.6924	1.9658	0.8609
		$e^\pm$	0.5110	228.542	228.543	447.2664	447.2665	1.0000
$M_{K^0} = 494.4 \pm 1.8$ Mev								
$K^0 \to \pi^0 + \pi^0$	224.32	π^0	135.04	207.056	247.200	1.5333	1.8306	0.8376
$K^0 \to \pi^+ + \pi^-$	215.14	$\pi^\pm$	139.63	203.988	247.200	1.4609	1.7704	0.8252
$K^0 \to \pi^0 + \pi^0 + \pi^0$	89.28	π^0	135.04	136.306	191.873	1.0094	1.4209	0.7104
$K^0 \to \pi^+ + \pi^- + \pi^0$	80.10	$\pi^\pm$	139.63	129.766	190.619	0.9294	1.3652	0.6808
		π^0	135.04	129.028	186.773	0.9555	1.3831	0.6908
$K^0 \to \pi^0 + \mu^\pm \pm \nu$	249.07	π^0	135.04	214.113	255.618	1.5334	1.8307	0.8376
		$\mu^\pm$	105.70	214.113	238.782	2.0257	2.2591	0.8967
$K^0 \to \pi^0 + e^\pm \pm \nu$	354.259	π^0	135.04	227.482	266.917	1.6292	1.9116	0.8523
		$e^\pm$	0.5110	227.482	227.483	445.1918	445.1929	1.0000
$M_\Lambda = 1115.2 \pm 0.14$ Mev								
$\Lambda \to p + \pi^-$	37.356	p	938.214	99.892	943.517	0.1065	1.0057	0.1059
		π^-	139.63	99.892	171.683	0.7154	1.2296	0.5818
$\Lambda \to n + \pi^0$	40.652	n	939.508	103.314	945.172	0.1100	1.0060	0.1093
		π^0	135.04	103.314	170.028	0.7651	1.2591	0.6076
$\Lambda \to p + \mu^- + \bar{\nu}$	71.286	p	938.214	130.518	947.249	0.1391	1.0096	0.1378
		μ^-	105.70	130.518	167.951	1.2348	1.5889	0.7771
$\Lambda \to p + e^- + \bar{\nu}$	176.475	p	938.214	162.941	952.258	0.1737	1.0150	0.1711
		e^-	0.5110	162.941	162.942	318.8823	318.8838	1.0000
$M_{\Sigma^+} = 1189.4 \pm 0.25$ Mev								
$\Sigma^+ \to p + \pi^0$	116.146	p	938.214	189.052	957.072	0.2015	1.0201	0.1975
		π^0	135.04	189.052	232.328	1.4000	1.7204	0.8137
$\Sigma^+ \to n + \pi^+$	110.262	n	939.508	185.072	957.563	0.1970	1.0192	0.1933
		π^+	135.04	185.072	231.837	1.3254	1.6604	0.7983
$\Sigma^+ \to n + \mu^+ + \nu$	144.192	n	939.508	202.400	961.062	0.2154	1.0229	0.2106
		μ^+	105.70	202.400	228.338	1.9148	2.1602	0.8864
$\Sigma^+ \to n + e^+ + \nu$	249.381	n	939.508	223.640	965.759	0.2380	1.0279	0.2316
		e^+	0.5110	223.640	223.641	437.6731	437.6743	1.0000
$M_{\Sigma^0} = 1190.0^{+1.2}_{-2.0}$ Mev								
$\Sigma^0 \to \Lambda + \gamma$	74.8	Λ	1115.2	72.449	1117.551	0.0650	1.0021	0.0648
$M_{\Sigma^-} = 1196.5 \pm 0.5$ Mev								
$\Sigma^- \to n + \pi^-$	117.362	n	939.508	192.168	958.960	0.2045	1.0207	0.2004
		π^-	139.63	192.168	237.540	1.3763	1.7012	0.8090
$\Sigma^- \to n + \mu^- + \bar{\nu}$	151.292	n	939.508	208.836	962.438	0.2223	1.0244	0.2170
		μ^-	139.63	208.836	234.062	1.9757	2.2144	0.8929
$\Sigma^- \to n + e^- + \bar{\nu}$	256.481	n	939.508	229.392	967.107	0.2442	1.0294	0.2372
		e^-	0.5110	229.392	229.393	448.9298	448.9309	1.0000
$M_{\Xi^-} = 1320.4 \pm 2.2$ Mev								
$\Xi^- \to \Lambda + \pi^-$	65.57	Λ	1115.2	138.455	1123.762	0.1242	1.0077	0.1232
		π^-	139.63	138.455	196.638	0.9916	1.4083	0.7041
$\Xi^- \to n + \pi^-$	241.3	n	939.51	302.66	987.06	0.3221	1.0506	0.3066
		π^-	139.63	302.66	333.34	2.1676	2.3873	0.9080

[a] American Institute of Physics, Handbook (McGraw-Hill, New York, 1957).

[b] See Ref. (p) of Table I.

Table Vb

Dynamics of particle absorption by H and D

The hyperfragments (Λn), ($\Sigma^- n$), etc., are assumed to have zero binding energy.[a]

	Q (Mev)	Decay Products	Mass (Mev/c^2)	Momentum p (Mev/c)	Total energy $w = T + mc^2$ (Mev)	$\eta = p/mc$	$\gamma = w/mc^2$	$\beta = pc/w$
$M_{\pi^- + p} = 1077.844$ Mev i.e. $M_{\pi^-} + M_p$; (binding energies ignored)								
$\pi^- + p \to n + \pi^0$ $\to n + \gamma$	3.296	n	939.284	28.028	939.926	0.0298	1.0004	0.0298
		π^0	135.04	28.028	139.918	0.2076	1.0213	0.2032
$M_{K^- + p} = 1432.214$ Mev (binding energy ignored)								
$K^- + p \to \Lambda + \pi^0$	181.974	Λ	1115.2	254.712	1143.918	0.2284	1.0258	0.2227
		π^0	135.04	254.712	288.296	1.8862	2.1349	0.8835
$K^- + p \to \Sigma^+ + \pi^-$	103.184	Σ^+	1189.4	181.553	1203.177	0.1526	1.0116	0.1509
		π^-	139.63	181.553	229.037	1.3002	1.6403	0.7927
$K^- + p \to \Sigma^0 + \pi^0$	107.174	Σ^0	1190.0	183.829	1204.115	0.1545	1.0119	0.1527
		π^0	135.04	183.829	228.099	1.3613	1.6891	0.8059
$K^- + p \to \Sigma^- + \pi^+$	96.084	Σ^-	1196.5	174.033	1209.090	0.1455	1.0105	0.1439
		π^+	139.63	174.033	223.124	1.2464	1.5980	0.7800
$K^- + p \to \Lambda^0 + \pi^0 + \pi^0$	46.934	Λ	1115.2	146.793	1124.820	0.1316	1.0086	0.1305
		π^0	135.04	114.084	176.780	0.8448	1.3091	0.6453
$K^- + p \to \Lambda^0 + \pi^+ + \pi^-$	37.754	Λ	1115.2	132.629	1123.059	0.1189	1.0070	0.1181
		$\pi^\pm$	135.04	102.487	173.206	0.7340	1.2405	0.5917
$M_{\Sigma^- + p} = 2134.714$ Mev (binding energy ignored)								
$\Sigma^- + p \to \Lambda + n$	80.006	Λ	1115.2	288.491	1151.911	0.2587	1.0329	0.2504
		n	939.508	288.491	982.803	0.3071	1.0461	0.2935
$\Sigma^- + p \to \Sigma^0 + n$	5.206	Σ^0	1190.0	73.983	1192.982	0.0622	1.0019	0.0621
		n	939.508	73.983	942.416	0.0787	1.0031	0.0785
$M_{\pi^- + d} = 2015.12$ Mev (binding energy ignored)								
$\pi^- + d \to n + n$	136.104	n	939.508	364.008	1007.56	0.3874	1.0724	0.3613
$M_{K^- + d} = 2369.49$ Mev (binding energy ignored)								
$K^- + d \to \Lambda + n$	314.782	Λ	1115.2	588.430	1260.921	0.5276	1.1307	0.4667
		n	939.508	588.430	1108.569	0.6263	1.1799	0.5308
$K^- + d \to \Sigma^0 + n$	239.982	Σ^0	1190.0	516.626	1297.306	0.4341	1.0902	0.3982
		n	939.508	516.626	1072.184	0.5499	1.1412	0.4818
$K^- + d \to \Sigma^- + p$	234.776	Σ^-	1196.5	511.105	1301.092	0.4272	1.0874	0.3928
		p	938.214	511.105	1068.398	0.5448	1.1388	0.4784
$K^- + d \to \Lambda + p + \pi^-$	176.446	(Λp)	2053.414	264.517	2070.381	0.1288	1.0083	0.1278
		Λ	1115.2	448.564	1202.032	0.4022	1.0779	0.3732
		p	938.214	444.597	1038.226	0.4739	1.1066	0.4283
		π^-	139.63	264.517	299.109	1.8944	2.1422	0.8844
$K^- + d \to \Lambda + n + \pi^0$	179.742	($\Lambda^0 n$)	2054.708	265.332	2071.769	0.1291	1.0083	0.1281
		Λ	1115.2	452.561	1203.529	0.4058	1.0792	0.3760
		n	939.508	448.742	1041.165	0.4776	1.1082	0.4310
		π^0	135.04	265.332	297.721	1.9648	2.2047	0.8912
$K^- + d \to \Sigma^- + n + \pi^+$	93.852	($\Sigma^- n$)	2136.008	177.823	2143.397	0.0833	1.0035	0.0830
		Σ^-	1196.5	329.729	1241.102	0.2756	1.0373	0.2657
		n	939.508	325.476	994.289	0.3464	1.0583	0.3273
		π^+	139.63	177.823	226.093	1.2735	1.6192	0.7865
$K^- + d \to \Sigma^- + p + \pi^0$	99.736	Σ^-	1196.5	339.649	1243.774	0.2839	1.0395	0.2731
		p	939.214	335.391	996.360	0.3575	1.0620	0.3366
		π^0	139.63	182.454	226.993	1.3511	1.6809	0.8038
$K^- + d \to \Sigma^0 + n + \pi^0$	104.942	Σ^0	1190.0	348.264	1239.914	0.2927	1.0419	0.2809
		n	939.508	344.031	1000.516	0.3662	1.0649	0.3439
		π^0	135.04	188.249	231.677	1.3940	1.7156	0.8125
$K^- + d \to \Sigma^0 + p + \pi^-$	101.646	Σ^0	1190.0	342.896	1238.417	0.2881	1.0407	0.2769
		p	938.214	338.564	997.432	0.3609	1.0631	0.3394
		π^-	139.63	186.659	233.106	1.3368	1.6695	0.8007
$K^- + d \to \Sigma^+ + n + \pi^-$	100.952	($\Sigma^+ n$)	2128.908	185.880	2137.007	0.0873	1.0038	0.0870
		Σ^+	1189.4	341.761	1237.527	0.2873	1.0405	0.2762
		n	939.508	337.477	998.282	0.3592	1.0626	0.3381
		π^-	139.63	185.880	232.483	1.3312	1.6650	0.7995
$K^- + d \to \Lambda^0 + n + \pi^0 + \pi^0$	44.702	Λ	1115.2	288.862	1138.441	0.2052	1.0208	0.2010
		n	939.508	224.953	966.064	0.2394	1.0283	0.2329
		π^0	135.04	114.070	176.773	0.8447	1.3090	0.6453
$K^- + d \to \Lambda^0 + n + \pi^+ + \pi^-$	35.552	Λ	1115.2	204.179	1133.737	0.1831	1.0166	0.1801
		n	939.508	200.572	960.679	0.2135	1.0225	0.2088
		$\pi^\pm$	139.63	101.784	172.972	0.7290	1.2375	0.5891
$K^- + d \to \Lambda^0 + p + \pi^- + \pi^0$	41.406	Λ	1115.2	220.327	1136.756	0.1976	1.0193	0.1938
		p	938.214	216.472	962.863	0.2307	1.0263	0.2248
		π^-	139.63	110.772	178.234	0.7933	1.2765	0.6215
		π^0	135.04	109.286	173.724	0.8093	1.2865	0.6291
$M_{\Sigma^- + d} = 3071.99$ Mev (binding energy ignored)								
$\Sigma^- + d \to \Lambda^0 + n + n$	77.774	(Λn)	2054.708	320.007	2079.478	0.1557	1.0121	0.1539
		Λ^0	1115.2	332.651	1163.756	0.2983	1.0435	0.2858
		n	939.508	320.007	992.512	0.3406	1.0564	0.3224
$\Sigma^- + d \to \Sigma^0 + n + n$	2.974	Σ^0	1190.0	65.848	1191.821	0.0553	1.0015	0.0553
		n	939.508	62.289	941.571	0.0663	1.0022	0.0662

[a]Note that the Σ^0 mass was assumed to be 1190.0 Mev for this table. See ref. (p) of Table I.

Figure 1. Range and energy-loss rate

The curves labeled R_α, R_p, etc., are the ranges of alpha particles, protons, etc., in g/cm^2 of Ilford emulsion plotted vs kinetic energy. The energy-loss rate dE/dx for protons has also been included. Provided thicknesses are measured in g/cm^2, the range curves also apply for all other materials (except H_2) with an error usually not exceeding 30%. The conversion from cm of emulsion to g/cm^2 was made on the assumption of a standard emulsion density of 3.815 g/cm^3.

The electron "range" curve becomes meaningless as the "critical energy" is approached. The critical energy is defined as that energy at which radiation and ionization are equally important; for example, this occurs at about 15 Mev in emulsion. The electron range curve is not drawn above this energy. Where drawn, it is taken from experimental data, so that radiation is crudely taken into account. These ranges apply "along the track" (i.e., correcting for Coulomb scattering). In practice (for example, for low-energy electrons) the projected range may be much smaller than given by the curve.

The mean free path ("$L_{collision}$") has been indicated, because, except for R_μ, the range is not very meaningful when it is large in comparison with this distance.

The equality of ranges of singly charged particles at a common energy of about 3 Bev is to be noted.

A simple analytical expression for the range in g/cm^2 for a particle of charge ze, mass number A, and kinetic energy T in a stopping material of atomic number Z (excluding hydrogen) is

$$R = \frac{Z^{0.26}\, T^{1.7}}{500\, z^2\, A^{0.7}} \quad g/cm^2;$$

this is correct to within about 10% for T/A from 1 Mev to 400 Mev. For protons it is simply

$$R = \frac{Z^{0.26}\, T^{1.7}}{500} \quad g/cm^2.$$

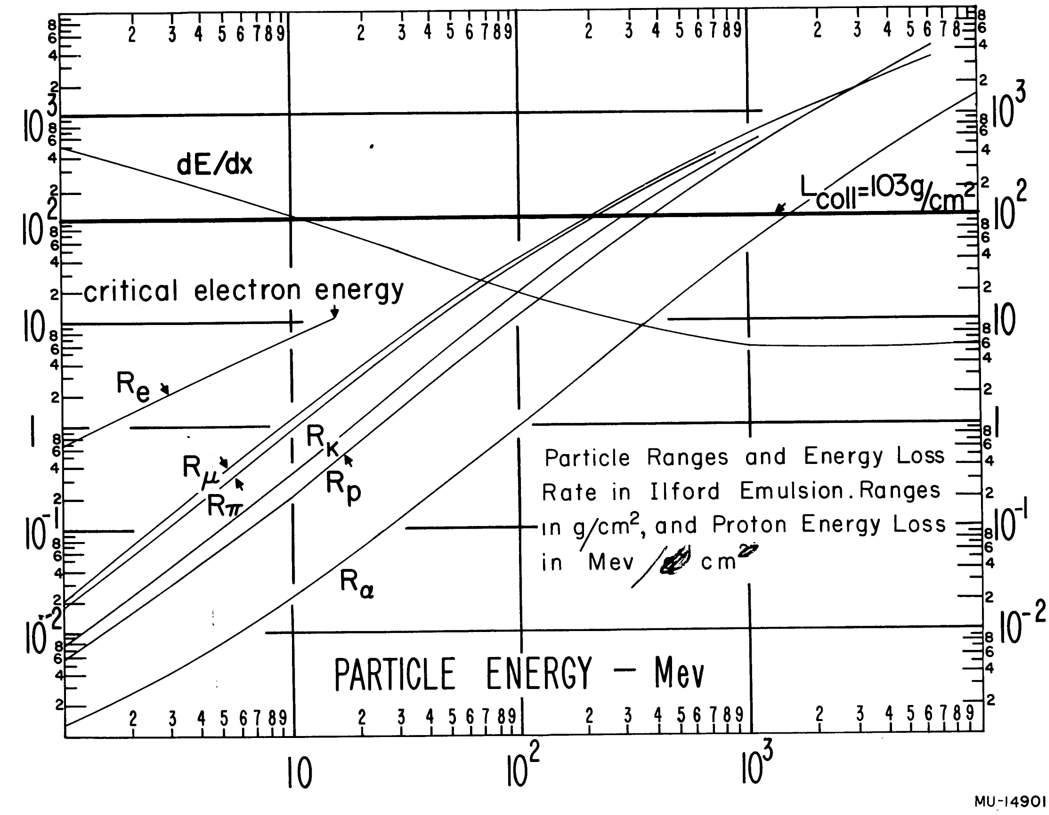
dE/dx
critical electron energy
R_e
R_μ
R_π
R_K
R_p
R_α
L_{coll}=103g/cm²
Particle Ranges and Energy Loss Rate in Ilford Emulsion. Ranges in g/cm², and Proton Energy Loss in Mev / cm²
PARTICLE ENERGY — Mev
10
10²
10³
MU-14901

Fig. 1

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There may remain errors and oversights in the tables or text. We should be most grateful to have such faults called to our attention, and to receive suggestions for improving the usefulness of the tables.

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