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Translated by N. M. Queen

Installations for the investigation of free neutrinos

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Usp. Fiz. Nauk **119**, 633–639 (August 1976)

PACS numbers: 29.90.+r, 92.80.+r

Neutrino physics and its applications to astrophysics constitute an independent branch of a blossoming science. In the course of preparing a review lecture on neutrino physics and astrophysics, I searched for a compact exposition form capable of giving the listeners an idea of the scales and the progress of the branch of physics in question. For this purpose I prepared several tables of existing installations for free-neutrino research. The tables, in the opinion of the editors of this journal, can be of interest to its readers and are presented below.

The table includes most installations for which means have been allocated, i.e., installations either already in operation or actually under construction (an exception is the DUMAND installation, the actual construction of which is still in doubt, but is reported here because of its exotic character).

Four tables are presented in accordance with the following arbitrary subdivision:

I. Installations for manmade neutrinos of "low" energies.

II. Installations for the investigation of manmade neutrinos of high energies.

III. Installations for the investigation of "low"-energy cosmic neutrinos.

IV. Installations for the investigation of high-energy cosmic neutrinos.

The information contained in the tables is frequently tentative for objective reasons, for subjective reasons (insufficient information available to the author of the tables), and for reasons connected with limiting volume of the tables themselves. The bibliography, of course, is far from complete and is chosen mainly to include the latest data on the given group.

TABLE I. Installations for the investigation of "low" energy manmade neutrinos.

Research group or laboratory	Neutrino energy	Source of neutrinos	Flux of neutrinos near detector; number of events	Distance between detector and source, m	Investigations	Type of detector
Los Alamos[1]	Several MeV ($\tilde{\nu}_e$)	Fission products in "Savannah River" reactor	$\sim 10^{13}$ cm^{-2} sec^{-1}	~13 m	Observation of free neutrinos in inverse β-decay reactions	Scintillation counters
University of California[2]	Several MeV ($\tilde{\nu}_e$)	Fission products in "Savannah River" reactor	$\sim 2 \cdot 10^{13}$ cm^{-2} sec^{-1}; $\leqslant 1$ events/day	~13 m	Search for the processes $\tilde{\nu}_e + e \to \tilde{\nu}_e + e$	Scintillation counters
LAMPF (projected, but many parts already completed)[3]	10–50 MeV ($\nu_e, \nu_\mu, \tilde{\nu}_\mu$)	Stopped pions and muons in meson factories	~1 event of $\nu_e - e$ scattering per day	~7	$\nu_e - e$ scattering; $\nu_\mu - e$ scattering; conservation of lepton charge, etc.	Electronic and radiochemical methods
Nuclear Physics Institute, USSR Academy of Sciences (projected)[4]	10–300 MeV ($\nu_e, \tilde{\nu}_e, \nu_\mu, \tilde{\nu}_\mu$)	Muons accumulated in a superconducting trap and decaying in flight	~10 events of $\nu_e - e$ scattering per day with accelerator of the LAMPF type	~7	$\mu_e - e$ scattering; neutral currents (excitation of nuclei)	Electronic registration methods; detector weighing several tons

TABLE II. Installations for the investigation of high-energy manmade neutrinos.

Research group or laboratory	Neutrino energy	Source of neutrinos	Flux of neutrinos near detector; number of events	Distance between detector and source, m	Investigations	Type of detector
Argonne[5]	0.5–2 GeV (ν_μ, $\tilde{\nu}_\mu$)	Pions decaying in flight	$\sim 2 \cdot 10^4$ cm^{-2} sec^{-1}	~30	Comparison of charged neutral currents, particularly reactions of the type $\nu + N \to \begin{cases} \mu + N + \pi \\ \nu + N + \pi \end{cases}$	Hydrogen-deuterium bubble chamber (26 m^3)
CERN[6]	1–10 GeV (ν_μ, $\tilde{\nu}_\mu$, ν_e)	Pions, kaons, and muons decaying in flight	$\sim 2 \cdot 10^5$ cm^{-2} sec^{-1}; one event per ~20 counts	~40	Neutral currents; nucleon structure; lepton charge; ν_μ–e scattering; μ–e symmetry; search for charmed particles	"Gargamelle" propane-freon bubble chamber (~10 m^3)
Brookhaven[7]	1–10 GeV (ν_μ, $\tilde{\nu}_\mu$)	Pions and kaons decaying in flight	$\sim 2 \cdot 10^5$ cm^{-2} sec^{-1}	~40	$\nu_\mu \neq \nu_e$; single production of pions; investigation of ν_μ–p elastic scattering	Electronic methods, large-volume hydrogen chamber (6 m^3)
Institute of High Energy Physics (IHEP)–Institute of Theoretical and Experimental Physics (ITEP), USSR[8]	4–20 GeV (ν_μ, $\tilde{\nu}_\mu$)	Pions and kaons decaying in flight	$\sim 10^5$ cm^{-2} sec^{-1}; one event per ~3 counts in 100-ton detector	~200	Search for dimuon events; neutral currents; ν_μ–e scattering; direct neutrino production	Electronic detectors
IHEP	4–20 GeV (ν_μ, $\tilde{\nu}_\mu$)	Pions and kaons decaying in flight	$\sim 10^5$ cm^{-2} sec^{-1}; one event per 20 counts	~250	Neutral currents; structure of nucleon; ν_μ–e scattering; search for new quantum numbers	SKAT propane-freon bubble chamber (9 m^3)
Harvard, Pennsylvania, Wisconsin, Fermilab[9]	20–200 GeV (ν_μ, $\tilde{\nu}_\mu$, ν_e)	Pions, kaons, and muons decaying in flight	$\sim 10^5$ cm^{-2} sec^{-1}	~1100	Dimuon events and charm; neutral currents; nucleon structure; direct predictions of neutrons; μ–e symmetry	Calorimeter target 3×3 m^2 (60 tons of scintillator) and magnet with iron core (60 tons). It is planned to increase the magnet diameter from 4 to 8 m.
California Institute of Technology, Fermilab[10]	Beam with the maxima at 50 and 150 GeV (ν_μ, $\tilde{\nu}_\mu$)	Monochromatic pions and kaons decaying in flight	$\sim 2 \cdot 10^3$ cm^{-2} sec^{-1}	~700	Neutral currents; dimuon events; searches for heavy leptons and W boson	Calorimeter 1.5 ×1.5 m^2 with iron liners (150 tons); it is planned to increase the area to 3×3 m^2
Fermilab[11]	20–200 GeV (ν_μ, $\tilde{\nu}_\mu$, ν_e)	Pions, kaons, and muons decaying in flight	$\sim 10^5$ cm^{-2} sec^{-1}; one event in ~10 counts in ν_μ beam (20% Ne)	~1100	Neutral currents; charm; strange particle; direct neutrino production	Large hydrogen (+20% Ne) bubble chamber (30 m^2)
CERN (planned)[12]	20–200 GeV (ν_μ, $\tilde{\nu}_\mu$, ν_e)	Pions, kaons, and muons decaying in flight	$\sim 10^5$ cm^{-2} sec^{-1}	~500		"Gargamelle" and BEBC (30 m^3 H and D) bubble chambers; 150-ton electron detector

TABLE III. Installations for the investigation of "low" energy cosmic neutrinos.

Research group or laboratory	Neutrino energy	Source of neutrinos	Flux of neutrinos near detector; number of events	Distance between detector and source, m	Investigations	Type of detector
Brookhaven[13]	Several MeV (ν_e)	Thermonuclear reactions in the sun, especially B^8 decay	$\leqslant 10^6$ cm^{-2} sec^{-1}; $\leqslant 0.2$ events/day	$\sim 150 \cdot 10^6$	Astrophysics of the sun; neutrino physics	Cl–Ar method, C_2Cl_4 (800 tons) at a depth of 4500 m w.e.
Nuclear Research Institute, USSR Academy of Sciences (planned)[14]	Several MeV (ν_e)	Thermonuclear reactions in the sun, especially B^8 decay	$\leqslant 10^6$ cm^{-2} sec^{-1}	$\sim 150 \cdot 10^6$	Astrophysics of the sun; neutrino physics	C_2Cl_4 (300 tons at a depth of 4500 m w.e.) (Baksan Station)
Nuclear Research Institute, USSR Academy of Sciences (planned)[15]	More than several hundred keV (ν_e)	Thermonuclear reactions in the sun, especially $p+p \to d+e^++\nu_e$	$\sim 10^{11}$ cm^{-2} sec^{-1}	$\sim 150 \cdot 10^6$	Physics of the sun; neutrino physics; neutrino oscillations	Radiochemical Ga–Ge method ($\geqslant 20$ tons Ga) (Baksan Station)
University of Pennsylvania (planned)	More than several hundred keV (ν_e)	Thermonuclear reactions in the sun, especially $p+p \to d+e^++\nu_e$	$\sim 10^{11}$ cm^{-2} sec^{-1}	$\sim 150 \cdot 10^6$	Physics of the sun; neutrino physics; neutrino oscillations	Radiochemical Ga–Ge method ($\geqslant 20$ tons Ga) (Baksan Station)
University of Pennsylvania[16]	Several dozen MeV ($\bar\nu_e$)	Collapsing star	Flash from ~ 10 events per ton of detector matter	$\sim 10^{17}$	Fundamental astrophysics	Cerenkov detectors, weight 1.828 tons of water (reaction $\bar\nu_e+p \to n+e^+$); detectors weighing 400 and 2000 tons are planned
Nuclear Physics Institute, USSR Academy of Sciences (planned)[17]	Several dozen MeV ($\bar\nu_e$)	Collapsing star	Flash from ~ 10 events per ton of detector matter	$\sim 10^{17}$	Fundamental astrophysics	Two scintillation installations weighing 100 and 600 tons, located at the Artem and Baksan Stations

TABLE IV. Installations for the investigation of high-energy cosmic neutrinos.

Research group or laboratory	Neutrino energy	Source of neutrinos	Flux of neutrinos near detector; number of events	Distance between detector and source, m	Investigations	Type of detector
University of California[18]	10–1000 GeV ($\nu_\mu, \bar\nu_\mu$)	Pions and kaons produced in the atmosphere by cosmic rays	~ 10 events/year	Several dozen kilometers	Horizontal neutrinos	Scintillation counters of area ~ 100 m^2 at a depth 7500 m w.e. in South Africa
Bombay-Osaka[19]	10–100 GeV ($\nu_\mu, \bar\nu_\mu$)	Pions and kaons produced in the atmosphere by cosmic rays	~ 20 events/several years	Several dozen kilometers	Horizontal neutrinos; searches for heavy leptons	Hodoscopic counters of area ~ 50 m^2 at a depth 7100 m w.e. in India
Nuclear Physics Institute, USSR Academy of Sciences (planned, but much is finished)	10–100 GeV ($\nu_\mu, \bar\nu_\mu$)	Pions and kaons produced in the atmosphere by cosmic rays	~ 50 events/year	$\sim 10\,000$	Neutrinos passing through the earth; unexpected events; measurement accuracy 2°	Scintillation counters of 300 m^2 area, weight 300 tons at a depth 800 m w.e.
Proposed international experiment (project DUMAND)[20]	1000 GeV ($\nu_\mu, \bar\nu_\mu$); dozens of MeV ($\bar\nu_e$)	Pions and kaons produced in the atmosphere by cosmic rays; collapsing star	~ 1000 events/year	$\sim 10\,000$ $\geqslant 10^{17}$	Neutrino physics at very high energies; fundamental astrophysics	Cerenkov water detector of volume $\sim 10^8$ m^3 in the Pacific (5 km deep)

In conclusion, I wish to point out that an investigation of free neutrinos has already led to a number of major discoveries in the field of elementary-particle physics. There is no doubt that this will continue. The role of neutrinos in astrophysics is already theoretically well founded. There is no doubt also that the construction of the large installations listed in the tables will also yield its own fruit.

It is my pleasure to thank V. S. Kaftanov for help in the discussions.

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Translated by J. G. Adashko