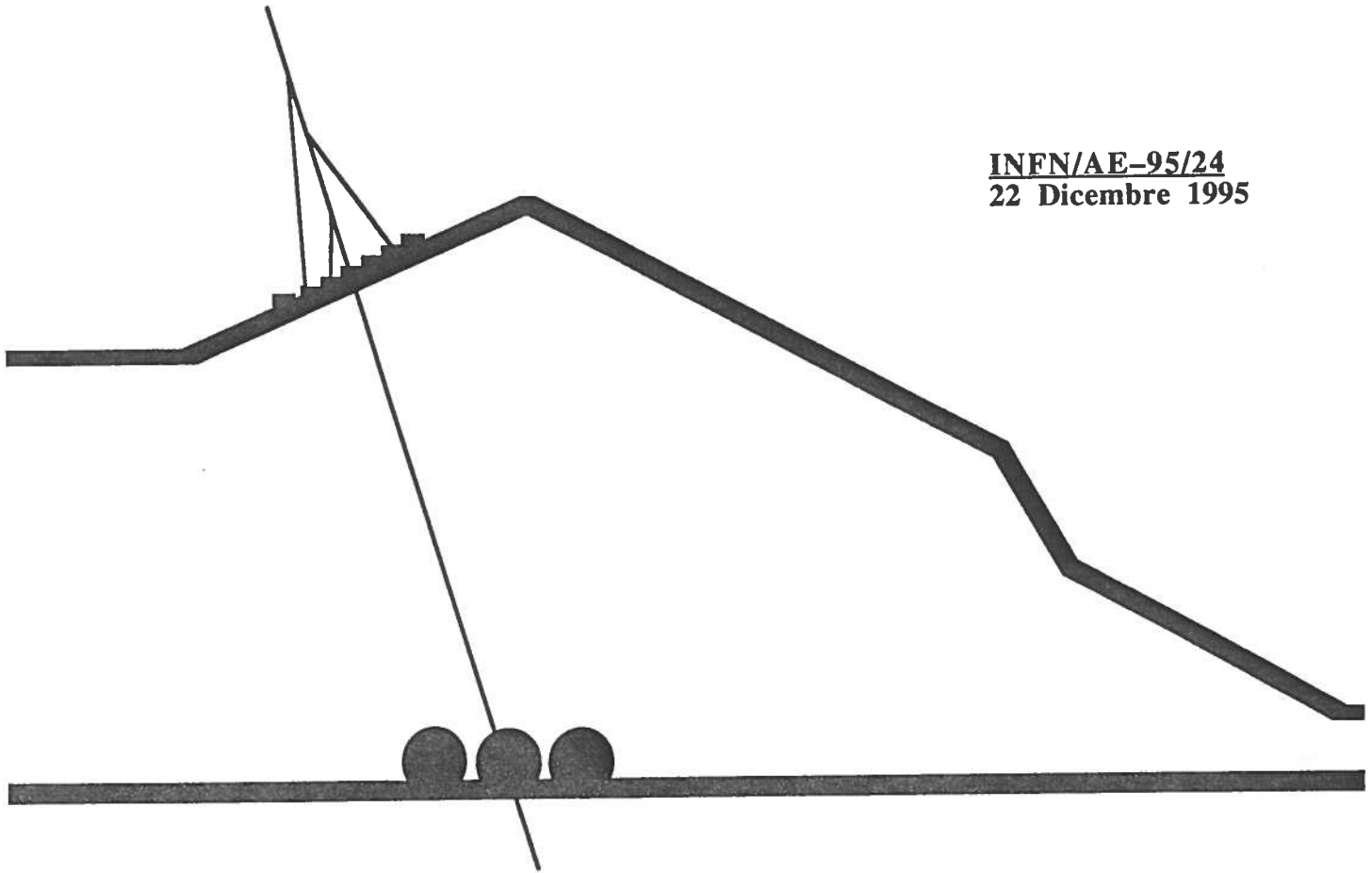


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WITH AN ARTIFICIAL SOURCE AND NaI(Tl)
SCINTILLATORS DEEP UNDERGROUND

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ABSTRACT

We present here a project to search for a neutrino magnetic moment in the range 10^{-10} - 10^{-11} μ_B by using a ^{147}Pm antineutrino source and a large mass high radiopurity NaI(Tl) set-up deep underground.

1. - INTRODUCTION

The Solar Neutrino Problem (SNP) - i.e. the observed deficit of the solar neutrino flux from the four experiments: Homestake, Kamiokande, GALLEX and SAGE, with respect to the predictions of the Standard Solar Model - remains one of the major unsolved puzzles of modern physics and astrophysics (1). Although an astrophysical solution of the problem is not completely ruled out (2), it is very unlikely to be the explanation, provided that all the experimental data are considered fully reliable, with proper error estimates.

There are several possible neutrino physics solution for the SNP, such as the resonant neutrino oscillation in the matter of the Sun (MSW effect) (3)- the most widely discussed at present - and the possible existence of a large magnetic moment of the neutrino (4).

In the last case, neutrino spin precession or spin-flavour precession in the magnetic field of the Sun can convert a fraction of solar neutrinos, ν_e , into other types of neutrinos (such as ν_{eR} , $\nu_{\mu R}$, $\overline{\nu_{\mu R}}$, $\overline{\nu_{\tau R}}$) which cannot be detected at all or have much smaller cross-sections with detectors. It has been shown that these processes are able to account for all the solar neutrino data including their possible (anti)correlation with solar activity, for which R. Davis suggests there is some indication in the Homestake results. In this case the neutrino would have a magnetic moment in the range of 10^{-10} - $10^{-11} \mu_B$ (where μ_B is the Bohr magneton) (4). Furthermore, regardless of the SNP, an investigation of the electromagnetic properties of the neutrino is of obvious interest and importance for particle physics.

The only direct experimental constraint on μ_ν comes from the reactor experiments by means of the $\overline{\nu}_e e^-$ scattering measurements (5,6): $\mu_\nu < 3 \times 10^{-10} \mu_B$. In these reactor experiments, the threshold on recoil electron was rather high (1.5 - 3 MeV) and the signal, estimated by comparing reactor on and reactor off measurements, was marginal compared to the background.

Analysis of stellar evolution (7) gives more severe limits: from white dwarfs $\mu_\nu < 10^{-11} \mu_B$ and from red giant $\mu_\nu < 3 \times 10^{-11} \mu_B$; but these limits are based on concepts of stellar evolution and, to varying degrees, they are model-dependent.

A still more stringent limit, $\sim 10^{-12} \mu_B$, comes from SN1987A (8), but it has been demonstrated that this limit would increase up to $\sim 10^{-10} \mu_B$ if the possibility of a thermalization inside the star is taken into account (9).

We therefore think that investigation of the $\mu_\nu < 3 \times 10^{-10} \mu_B$ is interesting. Direct experiments are in any case necessary .

We discuss here an experiment to search for a magnetic moment of the neutrino in the range of 10^{-10} - $10^{-11} \mu_B$, which is about an order of magnitude lower than existing limits from reactor experiments.

2. - THE PROPOSED EXPERIMENT

2.1 - DETECTION PRINCIPLE

The principle of such an experiment is similar to the reactor experiments. If the neutrino has a large magnetic moment, this significantly contributes to neutrino electron scattering:

$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e' + e^-' \quad (1).$$

But instead of a reactor, we plan to use a β -decaying isotope of large activity (1-5 MCi) with low maximal energy of decay (100-500 keV). Measurements with sources of a comparable strength have been successfully performed by the GALLEX experiment in the Gran Sasso Laboratory and by the SAGE experiment in the Baksan Laboratory.

The low-background NaI(Tl) installation, used by the BPRS collaboration, has a mass of about 100 kg and a threshold of a few keV ⁽¹⁰⁾. The low radioactive background, the low energy threshold and the fully automatic calibration system used in that installation offer the most sensitive detector for the measurement of recoil electrons. It is possible to use the existing set-up without major change of its parameters; only some rearrangement of the detector modules will be needed.

2.2 - CROSS-SECTION DUE TO THE MAGNETIC MOMENT IN ANTINEUTRINO-ELECTRON INTERACTION

The cross-section of magnetic moment $\bar{\nu}_e$ e^- scattering was calculated by Bethe and corrected by Domogatsky ⁽¹¹⁾. The differential cross-section is:

$$d\sigma_{MM} = \mu_\nu^2 \pi r_0^2 (1/w - 1/E_\nu) dw \quad (2)$$

where E_ν - antineutrino energy, w - kinetic energy of recoil electron, r_0 - classical radius of electron, μ_ν - in Bohr magneton units.

The total cross-section is:

$$\sigma_{MM}(w > w_0) = \mu_\nu^2 \pi r_0^2 \{ \ln[(2E_\nu^2)/(w_0(m_e c^2 + 2E_\nu))] - (2E_\nu)/(m_e c^2 + 2E_\nu) + w_0/E_\nu \} \quad (3)$$

where w_0 is the detection threshold energy .

There is another contribution to the σ_{MM} from an interference term with electroweak interaction - due to the W or Z exchange - but for the energy region under consideration it is negligible ⁽¹¹⁾.

The numerical values of σ_{MM} at different $\bar{\nu}_e$ energies and different electron energy threshold are shown in table 1 for $\mu_\nu = 10^{-10} \mu_B$. In the last column the cross-section of weak interaction - evaluated from zero to the maximum electron energy - is given for comparison. A small correction to the values quoted for $w_0=2, 3$ keV is expected because of the uncertainties on

the cross sections for atomic shell electrons. However, Table 1 clearly shows the importance of using low energy antineutrinos and detection threshold as low as possible.

TABLE 1

Values of the cross-section σ_{MM} at different $\bar{\nu}_e$ energies and different electron energy thresholds for $\mu_\nu = 10^{-10} \mu_B$. For comparison the weak cross-section, σ_w - evaluated from zero to the maximum electron energy - is given in the last column. Cross-section are given in units of 10^{-45} cm^2 .

$E_\nu \setminus w_0$ (keV)	2	3	5	10	15	20	25	30	σ_w
60	3.80	2.85	1.79	0.27	--	--	--	--	0.09
80	5.08	4.11	2.86	1.33	0.47	--	--	--	0.11
100	5.93	4.48	3.72	2.12	1.24	0.65	0.22	--	0.15
120	6.60	5.61	4.38	2.76	1.85	1.24	0.79	0.44	0.20
140	7.14	6.16	4.95	3.28	2.36	1.73	1.26	0.90	0.26
160	7.61	6.61	5.37	3.72	2.79	2.15	1.68	1.30	0.31
180	8.00	7.00	5.76	4.11	3.17	2.51	2.03	1.64	0.37
200	8.35	7.35	6.10	4.40	3.50	2.8	2.35	1.95	0.43
210	8.51	7.51	6.26	4.60	3.64	3.00	2.49	2.09	0.46
220	8.65	7.65	6.40	4.74	3.79	3.13	2.63	2.23	0.49
300	9.61	8.61	7.35	5.67	4.70	4.03	3.52	3.10	0.74
500	11.1	10.1	8.82	7.12	6.13	5.35	4.91	4.48	1.40
1000	12.9	11.9	10.6	8.94	7.94	7.24	6.70	6.26	3.19
2000	14.7	13.7	12.4	10.7	9.68	8.98	8.43	7.99	6.68

2.3 - THE ANTINEUTRINO SOURCE

The use of an artificial antineutrino source has a number of advantages respect to the use of a reactor for the same kind of experiment:

- a) In a reactor experiment, the antineutrino and recoil electrons are in the energy range $E > 0.5 \text{ MeV}$. In this energy region, the weak interaction cross-section of $\bar{\nu}_e e^-$ scattering is larger than the cross-section due to the magnetic moment of the neutrino, for values of $\mu_\nu < 2 \times 10^{-10} \mu_B$. That puts a limitation to further improvements of the reactor experimental results.

In case of an artificial low energy source installed in an ultra low background environment of a few keV detection capability, the situation is opposite: ratio of σ_{MM}/σ_w is at least an order of magnitude larger for the same values of μ_ν .

b) The effect of reaction (1) for values of μ_ν under consideration is relatively small so that the background of the detector must be extremely low. The continuous activation of the detector materials by cosmic rays and neutrons sets a basic background limitation in the case of detectors operating in a poorly shielded environment and, therefore, further improvements in the background parameters of the detector can be achieved only by using deep underground laboratories.

The central question of the project is the right choice of antineutrino source. The main requirements on the antineutrino source are listed in the following.

a) Antineutrino energy: The best energy region for the antineutrino source is 100-500 keV; in fact, in this region the ratio σ_{MM}/σ_w is the largest. At higher energies σ_w steeply increases and the ratio σ_{MM}/σ_w falls down. At energies less than 100 keV the absolute value of σ_{MM} becomes too small and the main part of the recoil electron energy spectrum transfers into region $E_e < \text{a few keV}$, which is difficult to detect.

b) Absence of accompanying γ -rays: A high flux of γ -rays from the isotope or unavoidable admixtures would require a thick shielding. That would increase the distance between source and detector and lower the effect.

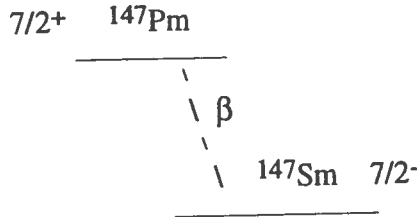
c) Activity and production of the isotope: The isotope activity should be rather large: $\sim 1-5$ MCi, and it must be easy enough to produce either by (n, γ) activation or by extraction from used reactor fuel.

d) Half-life of the isotope: It should be longer than 10-12 days to produce, transport and allow a measurement in the underground laboratory. A number of possible isotopes has been considered for such kind of experiments ⁽¹²⁾; some of them are listed in Table 2.

TABLE 2
Isotopes considered for the experiment.

Isotope	max [anti]neutrino energy (keV)	$T_{1/2}$
^{125}I	142	60 days
^{181}W	182	121.2 days
^{159}Dy	366	144.4 days
^{147}Pm	235	2.6234 years

We have chosen ^{147}Pm , which satisfies best the requirements quoted above. The decay schema of ^{147}Pm is:



with $E_{\beta\text{max}} = 234.7 \text{ keV}$ and $T_{1/2} = 2.6234 \text{ years}$.

The physical parameters of ^{147}Pm are rather convenient from an experimental point of view. In fact, its long half-life offers the possibility to produce the required quantity of isotope in a few months and to wait for a time sufficient for the decay of radioactive admixtures with short half-life. Furthermore, at the end of the experiment, the isotope could be used for other experiments or applications (considering that f.i. it is widely used in medicine).

The β -spectrum of ^{147}Pm is well known from experimental measurements and the antineutrino energy spectrum can be easily calculated from it. This is shown in fig. 1; the energy region 120 - 230 keV includes 80% of all antineutrinos.

The total cross-section due to the magnetic moment in the antineutrino interaction, averaged over the ^{147}Pm antineutrino spectrum, is calculated from (2,3) for $\mu_\nu = 10^{-10} \mu_B$:

$$\begin{array}{ll}
 \sigma_{\text{MM}}(^{147}\text{Pm}) = 5.54 \times 10^{-45} \text{ cm}^2 & \text{for } w_0 = 5 \text{ keV} \\
 = 6.64 \times 10^{-45} \text{ cm}^2 & \text{for } w_0 = 3 \text{ keV} \\
 = 8.35 \times 10^{-45} \text{ cm}^2 & \text{for } w_0 = 2 \text{ keV}
 \end{array}$$

For other μ_ν values, the cross-section can be easily derived by taking into account its dependence on μ_ν^2 .

The weak cross-section is, for comparison: $\sigma_w(^{147}\text{Pm}) = 0.32 \times 10^{-45} \text{ cm}^2$. We point out, once more, the importance of using a low energy antineutrino source and a low detection threshold.

Finally, the energy spectrum of the recoil electron (w) from magnetic moment interaction of ^{147}Pm antineutrinos (fig. 1), given as $d\sigma/dw$ [$10^{-45} \text{ cm}^2/10 \text{ keV}$] versus w , has been calculated by using the differential cross-section in eq. (2). This is shown in fig. 2, where the spectrum corresponding to the weak interaction is also shown for comparison. The energy region 5-25 keV includes 68% of all events, whereas for weak interaction only 39%. This gives an additional factor 1.74 that could even increase if the threshold would be lowered

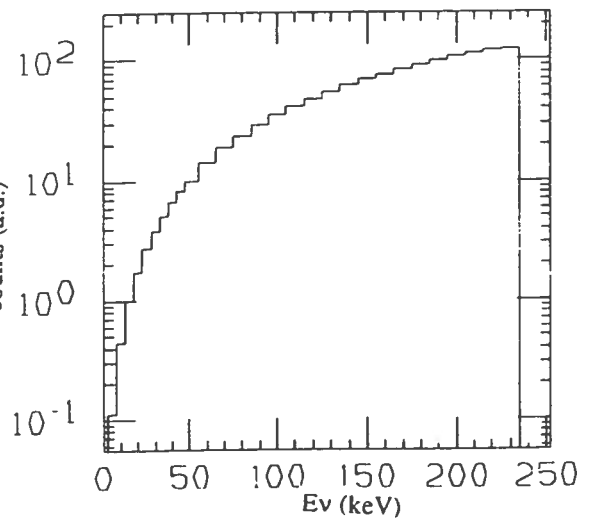


Fig 1 - Antineutrino energy spectrum of ^{147}Pm

down to 2-3 keV as it is the case for the best NaI(Tl) detectors used by the BPRS collaboration.

2.4 - NaI(Tl) AS DETECTOR

Instead of (or together with) NaI(Tl), other kinds of low-background detectors could be used (Ge detectors, liquid or plastic organic scintillators, thermal detectors). NaI(Tl) is however the most adequate for the problem under consideration and it offers a number of important advantages.

First of all the energy threshold reachable with NaI(Tl) is interestingly low: down to 2 keV ⁽¹⁰⁾, i.e. approximately the same as for small Ge detectors and order of magnitude lower than for organic scintillation detectors. A low energy threshold is very convenient because the spectrum of recoil electron from the magnetic moment of antineutrino interaction steeply increases in the low energy region. The mass of the set-up used by the BPRS collaboration consists - at present - of about 100 kg of NaI(Tl) and there is plan to increase it in the context of future improvements of the detector radiopurity ⁽¹³⁾. It offers a mass an order of magnitude larger than the experiments with Ge detectors under way and insures a better signal/background ratio than experiments with organic scintillators, due to the higher density of NaI(Tl).

Concerning the internal sources of the detector background, Na and I can be purified, if necessary, by chemical or physical-chemical procedures to obtain an extreme radiopurity. This is not the case for Ge and organic scintillator which include long lived isotopes (such as ⁷⁶Ge with $2\beta 2\nu$ decay - $T_{1/2} \sim 10^{21}$ years - for Ge detectors and ¹⁴C for organic scintillator), limiting the background reduction in these types of detectors. The latest results of BPRS collaboration have shown that the U and Th content in NaI(Tl) can be as low as 10^{-12} - 10^{-14} g/g and ^{nat}K less than $\sim 10^{-9}$ g/g, which sets up the basis for a development of ultra-low-background detectors. Furthermore, long time measurements to search for Dark Matter candidates will allow a good knowledge of the internal background behaviour in the interesting energy region before the source insertion for a $\mu\nu$ measurement.

For all these advantages, NaI(Tl) is the most preferable kind of detector for our proposed source.

3. - EXPERIMENTAL PARAMETERS

The expected rate of events from the magnetic moment of antineutrino interaction strongly depends on the geometry of the experiment, which is mainly determined by the passive shielding of the source.

The ¹⁴⁷Pm isotope is a pure β -emitter and low energy γ -rays arise only from bremsstrahlung. They do not present a problem and can be absorbed by 10 cm of tungsten (W).

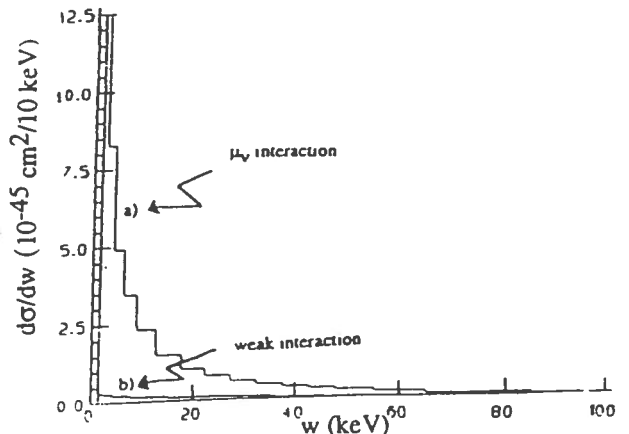


Fig. 2 - a) Energy spectrum of the recoil electron from magnetic moment interaction of ¹⁴⁷Pm antineutrinos given as $d\sigma/dw$ [10^{-45} $\text{cm}^2/10$ keV] versus w , according to eq. (2); b) the spectrum corresponding to the weak interaction is also shown for comparison.

However, in a real condition, the required amount of ^{147}Pm can only be produced by extraction from used reactor fuel (see table 4) and in this case an admixture of other long-lived Pm isotopes must be taken into consideration. The most dangerous isotope is ^{146}Pm with a half-life of 5.53 years; its abundance in used reactor fuel is 10^8 times less than that of ^{147}Pm , but it produces γ -rays with an energy $E = 750$ keV. If an isotope separation technique has not been used, the shielding must be increased to 20 cm of W. To be on the safe side and taking into account a possible admixture of other γ -emitters, the finite size of source and the necessity to shield the detector from γ -rays of natural radioactive isotopes in W, we plan to use at maximum a shield of 25 cm of W and 5 cm of pure Cu. The questions of γ -rays intensity and their energy spectrum for a commercially produced ^{147}Pm together with the W radiopurity are of first priority; however, the γ -ray flux of the source will be at list 5-6 orders of magnitude lower than in the case of the ^{51}Cr source which has been twice successfully used for the calibration of the GALLEX experiment at the Gran Sasso Laboratory.

3.1 - THE EXPECTED NUMBER OF EVENTS

As a first approximation of the geometry of the experiment, we consider a point source surrounded by 30 cm of shield and a NaI(Tl) detector with a mass of 100 kg homogeneously distributed around the shield. Using the cross-section quoted above, the total number of events from the magnetic moment of antineutrino interaction - considering a ^{147}Pm $\bar{\nu}_e$ source activity of 5 MCi and a magnetic moment $\mu_\nu = 10^{-10} \mu_B$ - has been calculated (see table 3) ⁺⁾ . The number of expected events - for μ_ν in the $10^{-10} \mu_B$ range - is quite large and a high statistical accuracy can be achieved - about 1% during 1 to 2 months of acquisition - so that the effect will be well distinguishable. In the case of a lower value of μ_ν , the expected rates are correspondingly reduced and exposures up to 2 years have to be considered.

TABLE 3
Total number of events from antineutrino magnetic moment interaction
in case of a 5 MCi ^{147}Pm $\bar{\nu}_e$ source and $\mu_\nu = 10^{-10} \mu_B$.

Total events/day/100 kg	Events/day/100 kg with energy $E < 25$ keV	w_0 (keV)
230	173	5
276	229	3
347	290	2

The best background achieved so far - during detector developments - by the BPRS collaboration in the low energy region is of the order of 1 cpd/kg/keV. In this case, the σ_{MM} effect in the energy region below 25 keV is $\sim 10\%$ and would be easily demonstrated. Taking

⁺⁾ For comparison we recall that the expected event rate for the MUNU experiment - to be realized at the Bugey reactor - is 8 events/day for $\mu_\nu = 10^{-10} \mu_B$ and recoil electron energy between 0.5 and 1 MeV. The detector mass is ~ 18.7 kg ⁽¹⁴⁾.

into account that the number of expected events is quite large and that the ~ 100 kg set up - now installed at Gran Sasso Laboratory - is expected to have background well reduced compared with previously used detectors, we consider that at least the limit $\mu_\nu < 4-5 \times 10^{-11} \mu_B$ can be achieved with the existing installation. This limit is about 10 times better than the ones obtained from existing reactor experiments.

For $\mu_\nu = 10^{-11} \mu_B$ the effect would be still detectable $N(\mu_\nu = 10^{-11} \mu_B) \sim 3$ events/day/100kg at same level than reactor experiments. Furthermore, a work is under way for a better understanding and reduction of the background at energies less than a few keV and there are some hopes that as result of this work the threshold could be lowered down to 1 keV; this would increase further (about 30%) the effect/background ratio. In addition, a larger detector mass: up to ~ 250 kg NaI(Tl), can be accommodated in the present installation without modifying the general layout of the experiment. However, further efforts are already in progress to improve the background parameters of the set-up used by BPRS collaboration, considering f.i. the possible purification of NaI in liquid phase; a success in these efforts could imply both a lower background rate and a higher detector mass to explore this μ_ν region with the highest sensitivity.

In the case that μ_ν would be less than $10^{-11} \mu_B$, not only an important limit will be set, but weak $\bar{\nu}_e$ e scattering will be investigated and the predictions of the electroweak theory checked with a high accuracy in the low energy region for the first time.

Finally, we want to point out that measurements of delayed coincidences to identify and reject events coming from standard contaminant chains and proper subtraction of the low energy spectrum collected for ~ 3 years during the source preparation ++) can further increase the experimental sensitivity.

3.2 - THE PRODUCTION OF THE ^{147}Pm SOURCE.

The yield of ^{147}Pm from used reactor fuel is among the largest ones (see table 4). This isotope is widely used for medical applications and the methods for extraction and purification are well worked out. The long half-life of ^{147}Pm gives the possibility to produce the required activity in a few months with the help of relatively inexpensive techniques and allows also to wait some time for the decay of short-life isotopes.

The ^{147}Pm source is planned to be produced in Russia by a factory specialized in REE-production from used reactor fuel. To produce 1 MCi of ^{147}Pm it is necessary to treat 100 kg of REE from used fuel. The technology of fine Pm purification from other REE isotopes has been developed at Fiziko-Chimicheski Institut Ras. It gives the possibility to purify one of REE element from others at level of 10^{-9} g/g. However, the question of extremely high purification of

++) This method will be similar to the one used in the reactor experiments when comparing data collected with reactor-on and reactor-off.

Promethium from other lanthanides, which can include long lived γ -emitters, has to be fully investigated as first.

The source activity will be measured by the factory with a standard calorimetry method with an accuracy of 3-5%. A more accurate method has been developed at Vserossiiskiy Institut Metrologii Im. Mendeleeva (San Peterburg) for the SAGE calibration experiment and guarantees an accuracy of 2%.

The heating of the source is ~ 400 W/MCi; this is not expected to be a serious problem both considering the metallic properties of Pm and the contact with the massive W/Cu shield as well as the possibility to realize a refrigeration system similar to the one used for the ^{51}Cr source in the GALLEX experiment.

After this experiment, the isotope could be used for other experiments and applications.

TABLE 4.

a) Prometium properties

	Pm - metal	Pm ₂ O ₃
Density (g/cm ³)	7.31	6.48
Specific activity (Ci/g)	882	759
Melting point (°C)	1160	2310

b) Activity per 1 ton of fuel, Bq

¹⁴⁶ Pm (5.53 y)	1.32×10^7
¹⁴⁷ Pm (2.62 y)	2.69×10^{15}
^{148m} Pm (40.9 d)	1.20×10^7
¹⁴⁸ Pm (5.37 d)	6.35×10^5

4. - CONCLUSIONS

An experiment with an artificial ¹⁴⁷Pm antineutrino source is proposed to look for the existence of an $\bar{\nu}_e$ magnetic moment in the range of $10^{-11} \mu_B < \mu_{\nu} < 10^{-10} \mu_B$, interesting to solve the SNP. The use of a low energy (<235 keV) antineutrino source and a low background installation in underground laboratory offers the possibility to seriously improve existing limits.

A new limit of at least $\mu_{\nu} < 4-5 \times 10^{-11} \mu_B$ (10 times better than modern reactor limit) can be achieved with an already existing NaI(Tl) low background installation. Improved limits in the range $\mu_{\nu} < 10^{-11} \mu_B$ are expected to be reachable as a by-product of the further background reduction techniques already under study for the Dark Matter experiment.

Furthermore, the proposed experiment will allow to investigate antineutrino-electron scattering with high statistical accuracy and to check predictions of electroweak theory at low energy.

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