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A CERN-PS EXPERIMENTAL CAMPAIGN TO MEASURE NEUTRON CROSS SECTIONS FROM 1 eV TO 250 MeV WITH HIGH RESOLUTION.

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Abstract.

We consider a spallation driven TOF facility at the PS with an unprecedented neutron flux (1000 times the existing ones) in the broad energy range between 1 eV and 250 MeV and with very high energy resolution. These novel features provide great potentials in Nuclear Physics, Nuclear Astrophysics, Nuclear Medicine and Nuclear Waste Incineration (TARC). It will attract many physicists from a broader community with different scientific interests and experience. The results obtained will allow to compile more reliable and accurate nuclear level data and neutron induced cross section evaluation relevant to many fields of science. The facility, initially using existing beam dump configuration, TOF tunnel and experimental area of the old ISR, would be compatible with the normal operation of the PS complex within the foreseen CERN programme.

We request the set-up of a preliminary test facility and make use of the experience and of the qualified collaboration of the GELINA group in order to fully evaluate the potentialities of the method. Technically it would be possible to set up such a test during the course of 1999.

In parallel, a Joint CERN, GEDEON (CEA+CNRS+EDF) and NEA (OCDE) Workshop will be organised during September 1998 at CERN inviting many already interested experimental groups to elaborate the detailed proposal on the physics programme, to be submitted to the SPSC. Substantial funding will be also requested from the 5th EC Framework Programme, from which we have received a preliminary, but favourable indication.

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I. INTRODUCTION.

Evaluations performed on neutron induced reaction cross sections for neutron data libraries presently in use [1] are based on differential measurements. However, they rely to a large extent on theoretical model codes to complement the databases where data are lacking or inconsistent. Such model predictions are benchmarked against crucial integral experiments and the available differential data, that are obtained under different conditions and in different neutron energy domains. Nevertheless, data files often show substantial differences amongst them in the case of Minor Actinides, Fission Fragments, and other poorly measured nuclei [App. 1]. This is due, on the one hand, to the lack of measurements and on the other hand to differences in fitting procedures and the use of different nuclear models.

A special situation of poor data availability is met in the “intermediate energy” domain ($20MeV<E_n<1GeV$), because this region is beyond the energy range of interest for classical nuclear energy systems. Presently theoretical codes that predict, on average, the poorly available experimental data within a factor of up to two in the case of double differential cross sections for example, are considered good [2,3,4]. The precise reason for this large discrepancy in the theoretical predictions is not yet known, although it is clear that the effects of different optical models, level densities and mechanisms like high-energy fission and multiple pre-equilibrium emission have a significant influence on these predictions. These large discrepancies have led in USA and Europe [5] to further research recommendations and clearly the precise measurement of essentially all neutron-induced reaction cross sections is mandatory for the different domains of Nuclear Physics.

The experimental determination of neutron cross section data has always been of primary importance in Nuclear Physics. Many of the salient features of nuclear levels and densities can be determined from the resonant structure of such cross sections and of their decay scheme. An associated importance of precise neutron induced reaction cross sections has resulted from the worldwide, enormous interest in Accelerator Driven Systems (ADS) that has emerged at CERN [6] and elsewhere. Many applications, such as accelerator-based transmutation of nuclear waste, energy amplification, medical research, astrophysical applications and also fusion research, require nuclear data that quantitatively and qualitatively go beyond the presently available traditional evaluation.

Cross sections of neutron induced reactions are best measured from the attenuation or scattering of the neutrons or from the intensity of the secondary radiation as functions of the energy of monochromatic neutrons. A precise neutron energy is required for the determination of the resonant structure of such cross sections and the parametrisation of such resonances. The most suitable method to achieve such good energy resolutions is the use of short neutron pulses with a broad energy distribution, where neutrons are sorted out of the continuous energy distribution on the basis of their time-of-flight (TOF). The present neutron TOF spectrometers are based on Electron Linacs with average energies and intensities of around 100 MeV and 70 μA respectively, providing 800 - 1000 neutron pulses per second of small (down to 1 ns) width combined with TOF paths of length up to a few 100 m. However, the currently achieved average neutron fluxes are limited by the low neutron yield (~0.05 neutrons per electron) to a level of few 10^{13} neutrons per second. Moreover, the neutron spectra of electron linac based neutron sources are limited to below about 20 MeV. At higher energies, quasi-monoenergetic neutrons are available using the ^{7}Li(p,n) reaction e.g. at the Uppsala cyclotron, at PSI and in Japan.

The present concept [7] for an intense neutron source makes use of both: the specifically high flux of neutrons attainable using the spallation process in the many GeV range for the incoming proton and the remarkable beam density of the CERN-PS, which can generate high intensities of the order of $2 \div 3 \infty 10^{13}$ ppp (protons per pulse) of 24 GeV (kinetic energy) protons — high enough to produce the vast number of $2x10^{16}$ neutrons per pulse — in the form of short (_ 13.5 ns) pulses with a repetition time of more than 2.4 seconds. With the 24 GeV proton energy at the CERN-PS, the number of produced neutrons varies between 360 to 760 per each proton, depending from the spallation target geometry. An additional factor of 2.5 in the neutron density is due to the strong, forward peaking of the neutron flux (see Fig. 15 of App.1). This huge factor in neutron yield per incident particle, namely $2.5 \infty 760/0.05 = 3.8 \infty 10^{4}$, can only be partially off-set by the higher, time averaged current of the LINAC e.g. 100 μA vs. 2 μA of the CERN-PS. Therefore the useful, initial neutron rate at the CERN-PS is about three orders of magnitude higher than in the most performing electron LINAC's, GELINA in Belgium [8,9] and ORELA [10] in the US, amounting up to 10^5 /L^2(km) [neutrons/cm^2/pulse], where L is the corresponding TOF distance.

The time duration of the PS pulse is presently $\Delta t|_{r.m.s}$=13.5 ns and we believe it could, if necessary, be potentially reduced further to $\Delta t|_{r.m.s}$=6.75 ns. The electron LINAC has much shorter pulses $\Delta t|_{r.m.s}$ _ 1 ns, to which however the resolution of the counters has to be added. But for neutron energy _ 1 MeV, $\Delta t|_{r.m.s}$ is not affecting the actual TOF energy resolution [App. 2], dominated by the fluctuations of moderation. Since the time fluctuations of the moderation process are largely independent of the chosen mechanism to produce the initial neutrons, the initial flux difference between the two methods, e.g. electrons vs. protons, reflects, at neutron energies below a few keV, directly the counting rate - for a given TOF resolution - at the measuring station. In the higher keV region, the large spatial extension of the primary neutron source in the spallation target adds to the flight path uncertainty, and in the MeV region the time resolution of any realistic detector and the time duration of the proton pulse also contributes to the TOF resolution. Finally, at energies above ~10 MeV, the neutron flux obtained from electron linac based neutron sources drops quickly, and the proposed new facility would be unique in Europe, the only competitor being the LANSCE/WNR facility in Los Alamos [11].

The extra flux offered by the prolific spallation mechanism and the remarkable features of the CERN-PS can be used either to improve the resolution for a given flux, or, alternatively to increase the flux for a given energy resolution. This new approach allowing for high precision measurements of neutron induced reactions is unique and almost inconceivable at other accelerators.

II. THE RELEVANCE OF NEUTRON INDUCED REACTION CROSS SECTIONS.

For neutron energies exceeding the nucleon binding energies of target nuclides a systematic comparison [12] shows significant discrepancies between the measurements of double differential cross sections and the evaluations. For the understanding of nuclear reaction mechanisms, like the multibody direct break-up processes for the light elements (Li, Be, C, O, F, etc.) and like the precoumpound and compound processes for the medium to heavier elements, more and better experimental data are required extending to the “missing range” between 7 and 14 MeV and to higher energies, even above 20 MeV. The lack of complete experimental data for (n,xn) cross sections above 10 MeV hinders the accurate systematic study of such cross sections, which indicate the existence of shell effects and are important in the studies of fission and fusion reactions. The systematic of giant resonance formation studied in fast neutron and proton capture reactions requires more experimental data in different neutron energies. For instance, experimental work [13] has revealed large discrepancies in $^{12}C(n,\gamma_0)^{13}C$ reaction cross sections in the neutron energy range from 7 to 14 MeV, and comparison with theoretical calculations questions the isospin invariance. The fission processes induced by high energy neutrons, combined with a high resolution, permit the detailed study of the spin and the formation of isomers in the fission fragments. The level density of the first well is well known but this is hardly the case for the second well. Theoretical models predict even the existence of a third well in the fission processes. For instance, Blons et al [14] claim to have experimentally established a triple-humped fission barrier in the case of $^{231,233}Th$. High quality measurements are needed for the unambiguous determination of such intermediate structures.

An increased concern for the environmental impact of nuclear fission energy, as well as the green house effect and the foreseen limits in fossil fuel have triggered active fields of research looking at innovative options. In the field of nuclear energy, transmutation of long-lived nuclear wastes, i.e. minor actinides (MA) and long-lived fission products (LLFP), reduced waste production and long term sustainability have led to a new interest in the ADS: waste burners, the energy amplifier and accelerator assisted thorium fuel cycle [6,15]. Both in the design, test and production phases, an accurate and complete set of neutron data are essential for proper evaluation of these options and the need for them. This is especially true since data for MA, LLFP and the thorium fuel cycle are in a comparatively poor shape, certainly at energies above 20 MeV and even below this energy in the case of highly radioactive materials and for materials that do not find applications in conventional reactor types [5]. In the recent EC meeting on Nuclear Safety [16], the priority to the ADS was clearly stated and the requirement from the European Nuclear Industry for more compete and precise Nuclear Data was generally adopted. The required data of neutron induced reactions are the total, capture, fission, (n,xn), (n,p), (n,α) etc. cross sections including all resonance parameters. These data are of relevance to the determination of the transmutation rates, to the inventories in PWRs, PWR-MOX, PWR-MOX with multiple recycling, to the design and inventories of waste burners and to the calculations of k_{eff}, of radiation damages and of the gas-production in such systems.

Nuclear astrophysics involves study of the synthesis of elements and the evolution of cosmic sites where such syntheses occur. Systems as diverse as the early universe, the interstellar medium, red giant stars, and supernova explosions are currently the focus of intense studies utilizing sophisticated computer models -- models which require large quantities of nuclear data as input. There is a strong need to produce and disseminate high-quality measurements of nuclear data for nuclear astrophysics. One of the primary goals of Nuclear Astrophysics is to obtain a detailed understanding of the stellar nucleosynthesis of all the elements which make up our world. The dominant process in the formation of the elements with $A<60$ is charged particle reactions, primarily those induced by protons and α particles. In contrast, the synthesis of all heavy elements with $A > 60$ has been attributed primarily to a combination of two very different reaction processes, the slow (s-) and the rapid (r-) neutron-capture processes. The advances in our understanding of the astrophysical sites where they occur -- red giants and (most likely) supernovae, respectively -- and the crucial input for astrophysical models of heavy element nucleosynthesis have gone hand-in-hand with laboratory measurements of neutron cross sections. Recent work has focused on more realistic stellar models - for example, low mass asymptotic giant branch (AGB) stars - suggesting that a substantial amount of s-process nucleosynthesis occurs at kT = 8 - 10 keV, significantly lower than the 30 keV value used in classical model studies. This is an important motivation for new neutron cross section measurements in the energy domain of neutron capture resonances : many old measurements need to be extended to lower energies (below an old 2 keV cut-off) to enable the reaction rate (the thermal average of the cross section over the Maxwell-Boltzmann temperature distribution) to be determined to the new lower temperatures. Moreover, precise r-process studies require precise s-process studies, and the precision of these studies rely on accurate (n,γ) cross section measurements. Measurements made from 20 eV to above 500 keV, covering all of the relevant range, integrated with other programs in Nuclear Astrophysics, such as the GANIL, GSI, RIKEN, ORNL, HRIBF and ISOLDE programs, would provide an important input in modelling these processes and to understand not only the detailed way in which heavy elements are synthesised, but also the conditions of the astrophysical sites where these syntheses occur. This is especially true for a new generation of sophisticated models attempting to explain observations ranging from precision abundance measurements in meteorites to spectacular images from the Hubble Space Telescope and the Compton Gamma Ray Observatory.

Nuclear data are also fundamental to our understanding of dosimetry in radiological protection (assessment of doses to aircraft crews for instance) and radiation therapy when energetic neutrons are used. Neutron therapy dosimetry and more importantly neutron transport calculations for dosimetry demand detailed microscopic charged particle production information for prediction and interpretation of absorbed dose to the patient. The same need exists for advanced proton therapy facilities, where secondary neutrons are produced with energies as high as 250 MeV. As data above few MeV are sparse, presently, nuclear model calculations only can provide some of the needed information.

The problems related to the future availability of existing nuclear reactors suitable for the production of medical radioisotopes, for research and clinical applications, have prompted a renewed interest on alternative, accelerator based methods of neutron production. Such systems are characterised by increased production efficiency, since they make use of the TARC method [17] fully exploiting the huge cross section contributions from the resonances. The high performances of the TARC method in the production of radiopharmaceuticals is clearly demonstrated in reference [18]. The optimal material configuration and dose for each produced radiopharmaceutical has to be calculated with neutron transport codes where, due to the significant self-shielding effect the resonance parameters are important to the resulting precision. The experimentally accurate determination of the corresponding cross sections in the energy domain of the resonances ($<10^4$ eV) will allow such transport codes to reach the required medical precisions.

The required data are the neutron total, elastic and inelastic scattering, double differential (n,xn) and (n,xp), (n,γ), (n,f), (n,x) and $(n,x\gamma)$ cross sections. Double differential cross sections with heavy products (α, etc.) would be also very useful for nuclear reaction modelling, while data on $(n, x\pi^{\pm 0})$ at 600-1000

MeV even with a moderate resolution are very interesting since very scarce relevant data exist in this region.

In view of these new large requests for neutron data a new facility is needed that can measure these neutron data on small quantities of material and in an energy range that covers the full range of interest. As described in [7, App. 1] this can be realised at the CERN PS with relatively minor modifications to the existing beam dump, with the additional means of providing neutrons in the traditional range of thermal to 10 keV with up to three orders of magnitude higher intensity than state-of-the-art electron accelerators and with high energy resolution. The latter allows the determination of resonance parameters for small quantities of material.

III. THE PROPOSED SPALLATION NEUTRON FACILITY.

The detailed description, the concept and the parameters of the proposed Spallation Neutron Source in comparison with those of existing facilities can be found in the two attached main papers [App. 1 and 2] and only a brief outline will be presented for clarity and completeness.

We intent to perform precise cross section measurements from neutron induced reactions with an intense neutron source based on the spallation of Lead nuclei by high energy protons extracted in short time pulses (<13.5 ns) through the proton beam line TT2 from the CERN-PS (see Figure 6 of App. 1). This proton beam is generated in the form of several short pulses, approximately fifty milliseconds apart, repeated several times during the flat top, providing a total of 2-3x10^{13} protons per PS super cycle and without significant interferences with the remainder of the CERN experimental programmes.

Such a high intensity neutron source can be practically achieved by simply replacing the concrete block, at present used as beam dump, with the TARC Lead Target, still maintaining the full functionality of fundamental beam dump facility. All magnets and all beam optics elements are already operational in situ, as well as the shielding necessary for the radioprotection safety. The Target Station requires no access and no specific instrumentation. The tunnel TT2A line connects in a straight line of 230 m length, the beam dump area with the experimental area of the former ISR. The TT2A tunnel construction is sufficient for the radioprotection shielding from the neutron flux. The large surface area in the ISR ring at the end of the TT2A tunnel provides all necessary infrastructure and services required for the running of various experiments.

Since the neutron mean free path in air amounts to 25 m, a beam pipe evacuated to 10^{-3} bar allows the interaction-free neutron transmission for TOF distances up to ~ 1000 m. A beam pipe equipped with a series of primary vacuum pumps, represents the TOF tube to be installed inside the TT2A ISR tunnel. The diameter of the TOF tube is decreased and collimated in order to finally provide a neutron beam at the experimental area, with the requested size from each measurement. Neutrons hitting the walls of the TOF tube may, in principle, reach the experimental sample after several scatterings. We studied by means of the TARC Montecarlo programme [19] the effect of these neutrons scattered on the wall of the TOF tube and evaluated that the only significant contribution arises from neutrons scattered in less than 30 m from the detection station. In order to suppress this effect, the radius of the TOF tube will be substantially increased over the last 30 m before the experimental area. With such a geometry and with the collimation and shielding techniques presently used at the other facilities, the scattered neutron background contribution to the main flux can be reduced for all neutron energies to a negligible level (_ 10^{-4}). Moreover, we have studied a proper neutron beam dump at the exit of the TOF tunnel, such as to eliminate neutrons scattered on the walls.

The charged particles will be removed completely by the use of a simple sweeping magnet, beam-downstream after the spallation target. Sufficient shielding of concret is foreseen between the spallation target and the TT2A tunnel, so that neutrons come only within the flight path. The contributions of other particles to the detected signals are evaluated to be either negligibly small or can be eliminated by the experimental method, as is the case of photons. Although the photons are the major contamination of the beam, 0.04 γ/neutron ($<E_{\gamma}>$ _ 1.2 MeV), their amount is very reduced, since Lead is strongly absorbing them in contrast with neutrons. The γ-prompt “flash” is by two orders of magnitude smaller for a proton machine than in the case of an electron LINAC and no γ-filters are required. The fastest neutrons, having an energy of 250 (100) MeV are delayed by TOF by as much as 484 (1029) ns at the 230 m detection station. Any background interaction from these photons belongs to the t = 0 bin and is completely eliminated (>30σ). Therefore the neutron beam can be considered as essentially free of contamination by other particles.

In conclusion, the CERN-PS accelerator complex appears to be the most suitable and immediate host to operate such a neutron spallation source, characterised by five main, practically unique features:

1) High neutron flux, $10^5/L^2$(km) neutrons/cm^2/pulse, for the standard CERN-PS intensity, allowing very modest mass targets.
2) An excellent energy resolution in the neutron energy determination by TOF, namely $\Delta E/E = 3.5 \infty 10^{-5}/L(km)$.
3) A very wide energy spectrum, covering simultaneously the whole energy domain of over eight orders of magnitude, from 1 eV to 250 MeV.
4) The much smaller repetition rate of the CERN PS (< 1/2.4 sec^{-1}) as compared to the LINAC (800 sec^{-1}) eliminates the problems of time overlaps at the Measuring Station due to successive bunches.
5) The much smaller repetition rate implies also a significant reduction to the accidental background due to radioactive targets.

The experimental area will be equipped with all necessary infrastructure to provide flexible operation in the running of individual experiments. Different targets and different detectors may be used in a variety of configurations according to the requirements of each specific measurement.

Some of the measurements will be essential for exploiting new ideas in nuclear technology with emphasis to ADS but also for providing data relevant to other domains of physics. But such high energy spallation facility, combining prolific rates with high resolution, will undoubtedly open up also novel avenues in Nuclear Physics with a careful and systematic study of many neutron driven reactions over an energy domain of more than eight orders of magnitude, from thermal energies up to 250 MeV.

IV. BEAM REQUEST.

In the future, the CERN-PS will be mostly used as injector for the SPS and therefore spare time is generally available for additional physics at 24

GeV. The proposed neutron source would be thus compatible with the normal operation of the PS complex within the foreseen CERN program. The results obtained will allow to compile the most reliable and accurate nuclear level data and neutron induced cross section evaluation.

Since the uniqueness of the proposed neutron beam will attract many physicists from a broader community with different scientific interests, we propose a graded strategy for the implementation, namely the installation of the Lead target and the TOF tube in the available ISR tunnel already during the 1999 shut-down, followed by test measurements during the year 1999 related to the determination of the neutron and photon fluxes, the neutron energy spectrum and the overall performances of the neutron beam.

We intend to perform these measurements with the available neutron detectors and Data Acquisition System, already successfully used for the neutron flux measurements at CERN in the experiment PS211 (TARC [17] and FEAT [20]) and in the experimental program at the GELINA Facility [8,9]. In the neutron energy domain between 1 eV to few 100 keV , we intend to take advantage from the well known fission cross sections of ^{235}U, ^{233}U and ^{239}Pu using fission gas detectors by directly counting the Fission Fragments, as well as gas scintillation detectors based on the well-known cross section of the (n,p) reaction in ^{3}He. The prompt gamma detection technique with C_6F_6 or C_6D_6 gamma counters, standardly used at GEEL, will allow to exploit the neutron capture cross sections of well-known elements, for instance ^{197}Au, ^{181}Ta and ^{107,109}Ag. The neutron flux at the higher energies will be explored by the standard liquid scintillation GEEL detectors (NE-213) and the CERN ^{232}Th, ^{237}Np and ^{238}U fission gas detectors.

In conclusion, we ask for parasitic test beam time during 1999, preferably distributed in periods of two weeks.

In parallel, a Joint Workshop between CERN, GEDEON and NEA will be organised the 21st and 22nd of September 1998 at CERN inviting all interested experimental groups to elaborate a detailed proposal, to be submitted to the SPSC, on the physics program and the priorities of the various measurements to be performed at the proposed neutron beam.

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