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Spectrometers for compact neutron sources

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ABSTRACT

We discuss the potential for neutron spectrometers at novel accelerator driven compact neutron sources. Such a High Brilliance Source (HBS) relies on low energy nuclear reactions, which enable cryogenic moderators in very close proximity to the target and neutron optics at comparably short distances from the moderator compared to existing sources. While the first effect aims at increasing the phase space density of a moderator, the second allows the extraction of a large phase space volume, which is typically requested for spectrometer applications. We find that competitive spectrometers can be realized if (a) the neutron production rate can be synchronized with the experiment repetition rate and (b) the emission characteristics of the moderator can be matched to the phase space requirements of the experiment. MCNP simulations for protons or deuterons on a Beryllium target with a suitable target/moderator design yield a source brightness, from which we calculate the sample fluxes by phase space considerations for different types of spectrometers. These match closely the figures of todays spectrometers at medium flux sources. Hence we conclude that compact neutron sources might be a viable option for next generation neutron sources.

1. Introduction

Neutron scattering has proven to be one of the most powerful methods for the study of dynamics in condensed matter. This is due to the fact that the neutron energy in cold and thermal moderators matches the energy scale of atomic and molecular motions and of spin excitations, whereas the neutron wavelength is of the same order of magnitude as the typical length scales in condensed matter. Therefore, to resolve atomic, molecular and spin correlations in space from sub-Å to μm range and in time from the ps to the μs range requires only a modest resolving power from 10 to 1000 as compared, e.g., to X-ray methods.

However, many applications of neutron spectroscopy are flux limited and therefore any new generation of neutron sources has boosted the development of new instrumentation. With the latest development of MW spallation sources the source brightness has reached a new level, exceeding the brightness of the formerly most intense research reactors by more than one order of magnitude. Accompanying these brightness gains with an optimized transport and analysis systems, the new instruments at the MW spallation sources promise efficiency gains between two and three orders of magnitude as compared to existing instruments and therefore will enable completely new science. Beside these new bright opportunities, many of today's applications will still be requested by the users. As many research reactors face the end of their operational time, the demand for future medium flux sources is hence pressing. Recently we have suggested a pulsed source based on low energy nuclear reactions [1], driven by accelerators in the energy range below 50 MeV, called High Brilliance Source (HBS). The operation of such accelerators is more flexible compared to high energy accelerators used for spallation sources. In particular different source repetition rates can be realized, tailored to the needs of an individual instrument. The low particle energy allows a more compact target-moderator–reflector assembly, bringing a larger fraction of the produced neutrons to thermal or cold energies. Using low dimensional neutron moderators [2], the moderator geometry can also be optimized to emit preferentially into a narrow solid angle, thus increasing the brightness along these directions. Last but not least, the lower nuclear energies involved require significantly less bulky shielding, not only saving cost, but also allowing optical components such as guides or choppers to be located closer to the moderator so that larger phase space volumes can be extracted.

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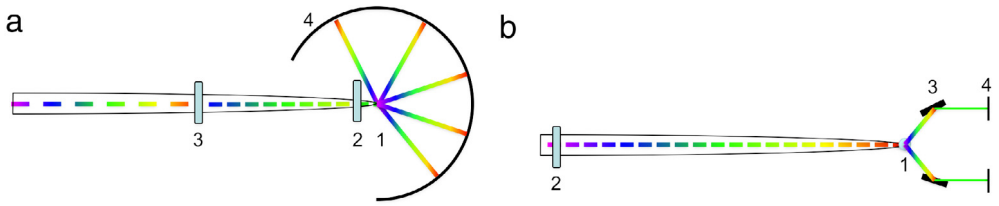

Fig. 1. Sketch to elucidate the working principle of direct (a) and indirect (b) time-of-flight spectrometers. The instrument components are (1) sample, (2) chopper, (3) initial (direct) or final (indirect) energy filter, (4) detector.

Here we will discuss the potential for time-of-flight spectrometers at such sources. We will show that despite the less efficient neutron production the special features, namely the optimization of the instrument from the neutron source on, enable instrument performance that is comparable or even superior to existing instruments focusing the same science.

We distinguish between the two cases of direct and indirect time-of-flight spectrometers, which are sketched in Fig. 1. In the direct geometry, the sample is illuminated by a short monochromatic pulse. A broad range of final neutron energies arrives a different times at the detector and the neutron energy resolution is then determined by the length of the illuminating pulse. The initial neutron energy can be defined in two ways. Using the time-of-flight between a pulsed source or an additional chopper, the pulse length of the source/choppers controls the initial neutron energy resolution. Alternatively, Bragg scattering from a single crystal can be used to select a narrow band of initial energies from the source spectrum.

The indirect spectrometer filters a narrow spectral range of final neutron energies by means of e.g. a monochromatic analyser or a Be transmission filter. The initial neutron beam, which has a broad spectral range, is pulsed at a rather large distance from the sample, so initial neutron energy is distinguished by the arrival time at the detector.

2. Dynamic range requirements

The dynamic range probed by a spectrometer is related to the repetition rate of the instrument and the geometry. For the direct geometry instrument, the range of scattered neutron wavelengths that can be recorded without frame overlap is given by

$$0\ \text{Å} < \lambda' < \frac{h}{m_n}\left(L_{\text{SD}} f_{\text{rep}}\right)^{-1} = \lambda'_{\text{max}} \tag{1}$$

and the corresponding dynamic range

$$-\infty < \hbar\omega = E_i - E_f < \frac{h^2}{2m_n}\left(\lambda^{-2} - \lambda'^{-2}_{\text{max}}\right) \tag{2}$$

assuming a monochromatic sample illumination with the repetition rate f_{rep} and a detector at a distance L_{SD} from the sample. To give an example, a repetition rate of 100 Hz and $L_{\text{SD}} = 3$ m yields $\lambda'_{\text{max}} = 13.2$ Å. The dynamic range is then set by the choice of the initial neutron wavelength λ. For thermal neutrons one can still cover a large energy transfer range at high repetition rate yielding a rather small λ'_{max}, while for long wavelength neutrons the repetition rate is limited to cover a sufficiently large range in energy transfer.

For an inverse instrument, the bandwidth for the initial neutron wavelength $\Delta\lambda$ is defined by the distance of the sample from the moderator or in the case of pulse shaping from the resolution defining chopper L_{S}:

$$\Delta\lambda = \frac{h}{m_n}\left(L_{\text{S}} f_{\text{rep}}\right)^{-1}, \tag{3}$$

giving a continuous range of the initial neutron energy. The final neutron energy after scattering from the sample is fixed by a suitable analyzer, e.g. a monochromator crystal or a Be filter. With these, the energy transfer range can be calculated from the initial band and the analyzer wavelength λ'_{Bragg} for an inverted geometry instrument. The inverse instrument has typically a fixed dynamic range, e.g. several hundred μeV for time-of-flight backscattering instruments or several hundred meV for vibrational spectrometers. Fig. 2 shows the repetition rate, which provides a given dynamic range centered around the wavelength fixed by the backscattering condition for the (002) reflection of pyrolitic graphite. It is clear, that for this narrow dynamic range a repetition rate well above 100 Hz is suitable for a moderate instrument length between 15 and 30 m.

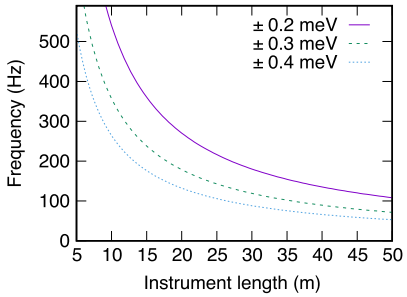

Fig. 2. Repetition rate as function of the instrument length to cover a given dynamical range using backscattering from pyrolitic graphite (002) reflection as analyzer.

3. Energy resolution requirements

Considering the different pulsed sources existing or in construction today, different routes have been exploited to optimize the energy resolution of a spectrometer. At short pulse spallation sources moderators have been designed with very short emission times by decoupling of the moderator from the reflector and poisoning of the moderator, which provide an extremely good energy resolution already for rather compact instruments [3]. Such 'poisoning' requires on the other hand, that neutron absorbers inside the moderator reduce the overall number of free neutrons.

For the long pulse source ESS, the energy resolution is controlled by choppers for most instruments. The accelerator pulse length provides an initial wavelength λ resolution, which is not sufficient to resolve the energy transfer $\hbar\omega$ with the required precision for many applications. Therefore choppers are employed to vary the pulse length by the chopper speed or the use of different windows to trade resolution for flux or in other words to enlarge or reduce the phase space volume of the neutrons probing the excitations of the sample. As they have certain technical limitations in particular for large beams, the instruments are typically longer than their counterparts at short pulse sources.

For the HBS, it is envisioned to match the neutron production time, i.e. the accelerator pulse length, with the moderation time of the spectral transformer, which ranges from several ten μs to a few hundred μs for thermal or cold moderators, respectively. For most spectrometer applications using cold and thermal neutrons, the phase space can be constrained sufficiently by choppers also for a modest instrument length, see Fig. 3. So the moderator pulse lengths should be long enough to allow the relaxation of the resolution by the choppers within a range defined by a specific instrument design.