An approach to the spatial-temporal analysis of the n-n collision rate in the YAGUAR experiment

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Abstract Monte Carlo modeling of transient neutron fluxes in the YAGUAR moderator was performed for neutron pulses of different shapes and durations. Subsequent calculations were carried out for the thermal neutron *nn*-collision count rate with account of space-time variation of the spectral neutron density. These calculations led to the establishment of a generic expression connecting the *nn*-detector response with the YAGUAR thermal neutron burst fluence, the pulse duration and the *nn*-cross section.

1 Introduction

Values of the neutron-neutron and the proton-proton scattering lengths are of importance to the ongoing study of charge symmetry breaking in the nuclear force. A first direct measurement of the *nn* scattering length with a final goal of 3% accuracy (0.5 fm) is presently under preparation at the pulsed reactor YAGUAR [1]. This project was initially proposed at the Dubna ISINN-VIII meeting [2]. The idea is that free neutrons will collide inside the YAGUAR through channel, and that the scattered neutrons should be detected outside the channel by the time-of-flight (TOF) method. Such an idea has been discussed in several laboratories since the 1960's. In particular, the late Prof. F.L. Shapiro, to whose memory we dedicate this report in appreciation of his impact on neutron physics, proposed the nn-measurement for the JINR Neutron Laboratory pulsed reactor IBR-2 [3]. Other proposals are referenced by Furman *et al.* [4], none of them have been implemented though. The great advantage of the reactor YAGUAR is a central through channel with a very high ($\sim 10^{18}/\mathrm{cm}^2\mathrm{s}$) thermal neutron flux density in its moderator. The reactor has recently been equipped with an underground 12-m flight path, making it a working facility for a direct measurement of the *nn* scattering length.

In the direct *nn* experiment, the neutron "target" and neutron "beam" are produced by the same source. The *nn* scattering intensity is thus proportional to the square of the neutron flux density. For a steady-state regime the *nn* collision rate R_{nn} (integrated over the thermal part of the TOF spectrum) per time interval Δt is related to the space-averaged neutron density n_{av} (or to the space-averaged time-instantaneous flux density $\Phi_{av}(t)$), the average relative velocity of colliding neutrons v_{rel}, the *nn* scattering cross section σ_{nn} and the *nn* cavity volume V by the relationship

$$R_{nn} = n_{av}^2 \frac{v_{rel}}{2} \sigma_{nn} \Delta t V = \frac{\pi}{4} c_{av} \frac{\Phi_{av}^2(t)}{v_0} \sigma_{nn} \Delta t V , \tag{1}$$

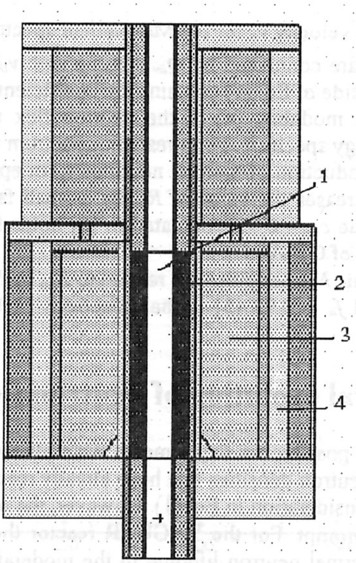

Figure 1: Input geometry for the MCNP modeling of the YAGUAR reactor neutron flux: 1 − the *nn* cavity, 2 − moderator, 3 − active core, 4 − air space.

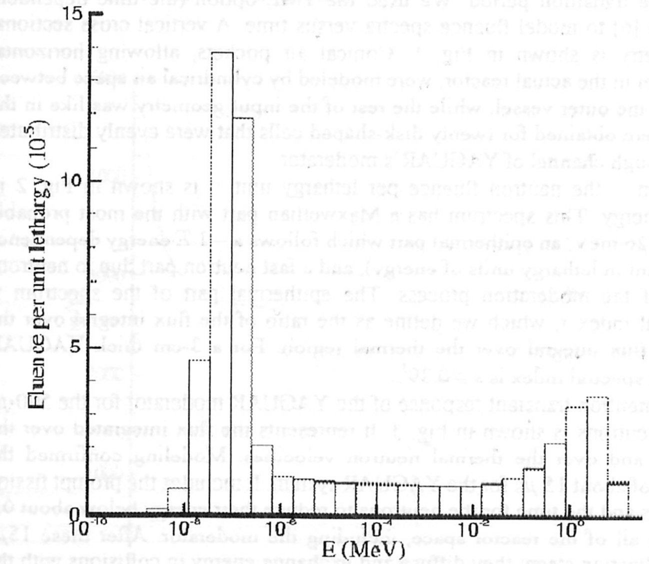

Figure 2: Modeled energy spectrum − the neutron flux per lethargy unit.

where the most probable velocity v_0 for the Maxwellian spectrum is $v_0 = v_{th}\sqrt{\pi}/2$ and the flux and the neutron density are connected by $\Phi_{av} = n_{av}v_{th}$ with v_{th} as the thermal neutron average velocity. The right hand side of Eq. (1) contains the coefficient $c_{av} = v_{rel}/2$. Its value was initially obtained from extensive modeling [4] of the neutron flux under the assumption of a pure Maxwellian neutron energy spectrum. For a realistic spectrum with an additional 1/E epithermal tail it was shown that production of thermal neutrons from epithermal-thermal and epithermal-epithermal collisions increases the value of R_{nn} by a small factor depending on the detection threshold. The latest value $c_{av} = 0.92$ calculated in [5] holds for the realistic spectrum and the neutron energy threshold of 0.2 eV.

The *nn* detector counts N_{nn} per pulse are related to R_{nn} by $N_{nn} = 2R_{nn}f_a\Omega_{eff}$, where Ω_{eff} is the detector solid angle and $f_a = 0.98$ [5] is the anisotropy factor for scattering in the detector direction.

2 Spatial-temporal evolution of neutron flux

Previous analyses of possible *nn*-experiments were always performed using a steady-state approach with thermal neutron densities that have already reached asymptotic values before the time interval Δt under consideration in Eq. (1). However, the moderator response to an insertion of fast neutrons is not prompt. For the YAGUAR reactor the neutron thermalization scale is about 15 μs, and the thermal neutron lifetime in the moderator is about 100 μs. This is large enough to make a possible influence on the *nn* collision rate in the *nn* experiment. Therefore we performed calculations of transient effects, specifically the spatial and temporal changes of neutron spectra during the transition period. We used the TME option (the time dependent source) in MCNP- 4 code [6] to model fluence spectra versus time. A vertical cross sectional view of the input geometry is shown in Fig. 1. Conical air pockets, allowing horizontal expansion of the liquid fuel in the actual reactor, were modeled by cylindrical air space between the liquid active core and the outer vessel, while the rest of the input geometry was like in the real reactor. Our results were obtained for twenty disk-shaped cells that were evenly distributed along the z-axis of the through channel of YAGUAR's moderator.

The modeled spectrum – the neutron fluence per lethargy unit – is shown in Fig. 2 in dependence of neutron energy. This spectrum has a Maxwellian part with the most probable thermal neutron energy of 26 meV, an epithermal part which follows a ~ *1/E* energy dependence (it is approximately constant in lethargy units of energy), and a fast neutron part due to neutrons at the beginning stage of the moderation process. The epithermal part of the spectrum is characterized by a spectral index *s*, which we define as the ratio of the flux integral over the epithermal region to the flux integral over the thermal region. For a 3-cm thick YAGUAR moderator the value of the spectral index is $s \cong 0.39$[1].

The modeled thermal neutron transient response of the YAGUAR moderator for the 500-μs rectangular burst of fast neutrons is shown in Fig. 3. It represents the flux integrated over the volume of the *nn*-cavity and over the thermal neutron velocities. Modeling confirmed the slowing-down time value of about 15 μs for the YAGUAR system. It includes the prompt fission neutron lifetime of ~ 10 μs and the time for the neutrons to reduce their energy below about 0.5 eV, and is averaged over all of the reactor space, including the moderator. After these 15μs neutrons enter the thermalization stage; they diffuse and exchange energy in collisions with the

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[1] In reactor physics the Westcott spectral index *r* is used and is defined as the epithermal flux per lethargy unit over the total thermal neutron flux. The value for our spectrum is $r \cong 0.08$.

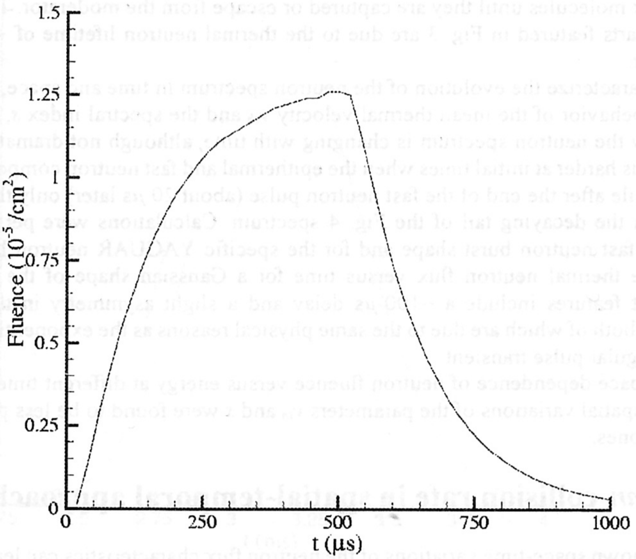

Figure 3: Modeled thermal neutron transient of the YAGUAR moderator for a rectangular fast neutron pulse of the 500-μs duration.

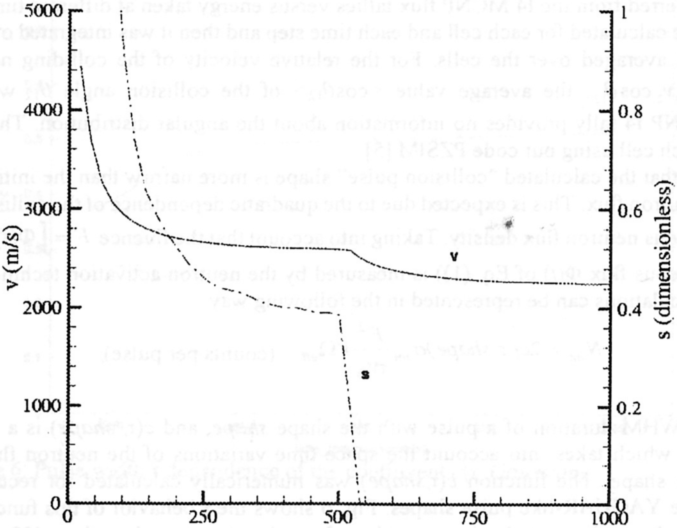

Figure 4: Time dependence of the average thermal neutron velocity v_{th} and the spectral index s for a rectangular fast neutron pulse of the 500-μs duration.

moderator molecules until they are captured or escape from the moderator. The exponential rise and fall parts featured in Fig. 3 are due to the thermal neutron lifetime of ~ 100 μs within the moderator.

To characterize the evolution of the neutron spectrum in time and space, we chose to follow the time behavior of the mean thermal velocity v_{th} and the spectral index s, as shown in Fig. 4. Obviously the neutron spectrum is changing with time, although not dramatically. The neutron spectrum is harder at initial times when the epithermal and fast neutron components dominate the shape, while after the end of the fast neutron pulse (about 20 μs later) only thermal neutrons are present in the decaying tail of the Fig. 4 spectrum. Calculations were performed also for the Gaussian fast neutron burst shape and for the specific YAGUAR neutron burst shapes. Fig. 5 shows the thermal neutron flux versus time for a Gaussian shape of the fast neutron burst. Prominent features include a ~100-μs delay and a slight asymmetry in the thermal neutron response, both of which are due to the same physical reasons as the exponential characteristics of the rectangular pulse transient.

The space dependence of neutron fluence versus energy at different times was also studied, however spatial variations of the parameters v_{th} and s were found to be less pronounced that the temporal ones.

3 The *nn*-collision rate in spatial-temporal approach

The shown space-time variations of the neutron flux characteristics can lead, in principle, to a non-linear detector response in dependence on the pulse duration. One can always calculate the collision rate at a given time step Δt in a local cell using Eq. (1), provided that the local spectral neutron density n_{loc} at time Δt is known. Subsequenty, *nn*-collision calculations were performed for twenty discrete axial cells with discrete time steps of $\Delta t = 20$ μs. Neutron densities versus velocity were inferred from the f4 MCNP flux tallies versus energy taken at different times. The collision rate was calculated for each cell and each time step and then it was integrated over time in each cell and averaged over the cells. For the relative velocity of the colliding neutrons, $v_{rel}^2 = v_1^2 + v_2^2 - 2v_1v_2\cos\theta_{12}$, the average value $\langle\cos\theta_{12}\rangle$ of the collision angle θ_{12} was used because the MCNP f4 tally provides no information about the angular distribution. They were calculated for each cell using our code PZSIM [5].

It was found that the calculated "collision pulse" shape is more narrow than the initial pulse of the thermal neutron flux. This is expected due to the quadratic dependence of the collision rate on the instantaneous neutron flux density. Taking into account that the fluence $F = \int \Phi(t)dt$ (and not the instantaneous flux $\Phi(t)$ of Eq. (1)) is measured by the neutron activation technique, the results of our calculations can be represented in the following way:

$$N_{nn} = 2c(\tau, shape)\sigma_{nn}\frac{F^2}{\tau v_{th}}V\Omega_{eff} \quad \text{(counts per pulse)}, \qquad (2)$$

where τ is the FWHM duration of a pulse with the shape *shape*, and $c(\tau, shape)$ is a weakly-varying function which takes into account the space-time variations of the neutron flux for a pulse of a given shape. The function $c(\tau, shape)$ was numerically calculated for rectangular, Gaussian, and the YAGUAR-like pulse shapes. Fig. 6 shows the τ behavior of this function for Gaussian pulses. A non-linear behavior is evident for pulse durations less than 400 μs. The asymptotic value here is $c(1000, Gaussian) = 0.52$. For *shape=Yaguar* the calculated value at $\tau = 1100$ μs is $c(1100, Yaguar) = 0.48$. Because of the quadratic dependence of the collision rate on the instantaneous neutron flux density, the pulse shape influences values of $c(\tau, shape)$ even

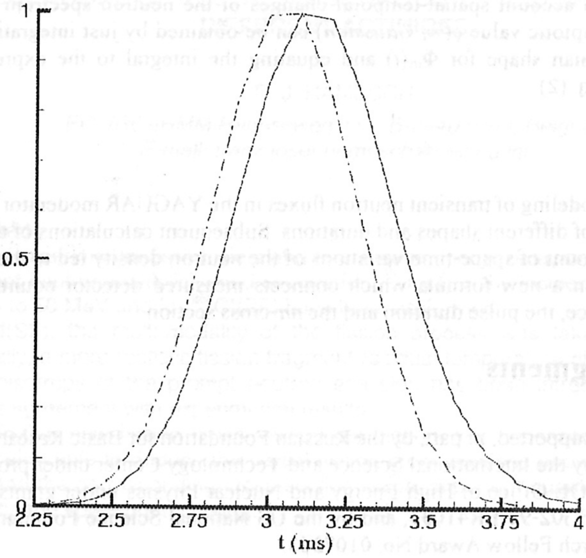

Figure 5: Modeled thermal neutron flux shape (full line) in response to a Gaussian fast neutron pulse (dot-line).

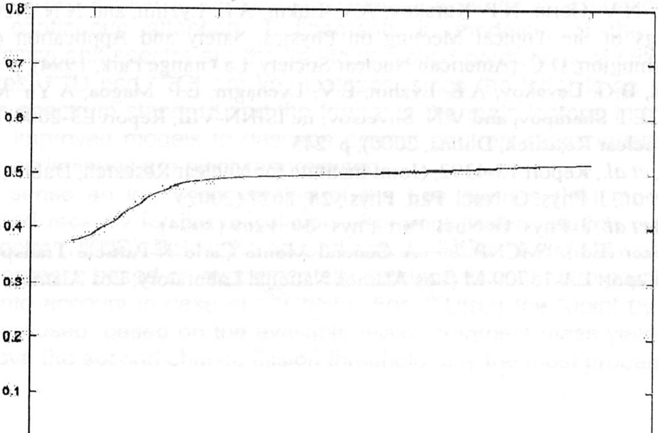

Figure 6: Pulse width τ dependence of the coefficient $c(\tau, \textit{Gaussian})$.

without taking into account spatial-temporal changes of the neutron spectrum parameters. In particular, the asymptotic value $c(\infty, \mathit{Gaussian})$ can be obtained by just integrating analytically Eq. (1) with Gaussian shape for $\Phi_{av}(t)$ and equating the integral to the expression for *Rnn* corresponding to Eq. (2).

4 Conclusion

Monte Carlo modeling of transient neutron fluxes in the YAGUAR moderator was performed for neutron pulses of different shapes and durations. Subsequent calculations of the *nn*-collision count rate with account of space-time variations of the neutron density led to the determination of the coefficient in a new formula which connects measured detector counts with thermal neutron pulse fluence, the pulse duration and the *nn*-cross section.

5 Acknowledgments

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