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DELAYED NEUTRON EQUILIBRIUM SPECTRA FOR U-235, U-238 AND Pu-239

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Abstract: Equilibrium delayed neutron energy spectra have been measured which encompass up to 93% of the delayed neutrons emitted in the fission of U-235, U-238 and Pu-239. These measurements are compared with equilibrium spectra generated from six-group spectra derived from our separate aggregate measurements and also from compilations based on individual precursor data.

(fission delayed neutrons, ^{235}U, ^{238}U, ^{239}Pu, equil. energy spectra)

Introduction

The present study is part of a general program involving measurements of equilibrium and time-dependent composite delayed neutron (DN) energy spectra following fission. A DN equilibrium spectrum pertains to a reactor operating at a steady power level for a long period of time. This corresponds to the DN spectra from all Keepin groups/1/ being summed in a weighted fashion in a time integral from zero to infinity. This condition can be approximated in direct measurements of equilibrium spectra providing the lower limit on the time interval is significantly less than the halflife of Keepin group 6 (~0.26s) and the upper limit considerably larger than the halflife of group 1 (~56s). Using a modified version of our standard experimental arrangement, the widest time interval in the present measurements was 0.13 - 165s. DN equilibrium spectra were measured from the thermal fission of U-235 and Pu-239 and from fast fission of U-238.

Experimental Method

A neutron time-of-flight (TOF) spectrometer is employed which utilizes the beta decay of the DN precursors to establish time zero for TOF information. Two different sets of neutron detectors are used to span the neutron energy range 0.01 - 4 MeV. In our standard arrangement used for time-dependent DN studies/2,3/, fission products are transported from the irradiated fission chamber to two beta detectors by a two-stage system, which incorporates a helium jet to rapidly transfer the products through a capillary tube and deposit them onto a moving tape at a location below the detectors. With variable tape speeds, selectable delay-time intervals can then be provided at the beta detectors. To minimize the transfer time in the equilibrium spectra measurements, the tape and beta detector assembly were modified so as to exclude the tape transport delay.

The modified arrangement is shown in Fig. 1. The fission products are transferred by the helium jet directly onto a slowly moving, thin KAPTAN tape at a position immediately in front of a 5-cm long beta scintillator. The transfer time is now determined by the helium jet system alone and the tape speed can be adjusted to provide dwell times of up to 200s in front of the beta detector. BC501 liquid scintillator neutron detectors and a 4.6-m long capillary are used in TOF measurements for the neutron energy region 0.25 - 4 MeV. The mean transfer time for the fission products is about 0.13s and the time interval spanned by the measurements for this energy region encompasses up to 93% of all delayed neutrons emitted following fission. Li-6 glass scintillators are used for the neutron energy region below 0.25 MeV. In this case, the separation between the fission chamber and spectrometer is also increased to reduce the random coincidence background in the TOF spectra. The transfer time of the fission products over this distance is 0.65s, which results in about 75% of the total DN spectrum being measured below 0.25 MeV.

Whereas in our standard geometry the beta particles do not have to penetrate the tape to be detected, they do so in this modified geometry and KAPTAN was chosen to provide high transmission of the beta spectra. In a test study using the low-energy betas from a C-14 source, for example, 65% of its beta spectrum was detected after transmission through the tape, the effective beta cut-off energy being about 20 keV. Since most betas emitted from the fission products are much more energetic than this, the presence of the tape introduces negligible distortion to the equilibrium DN spectrum.

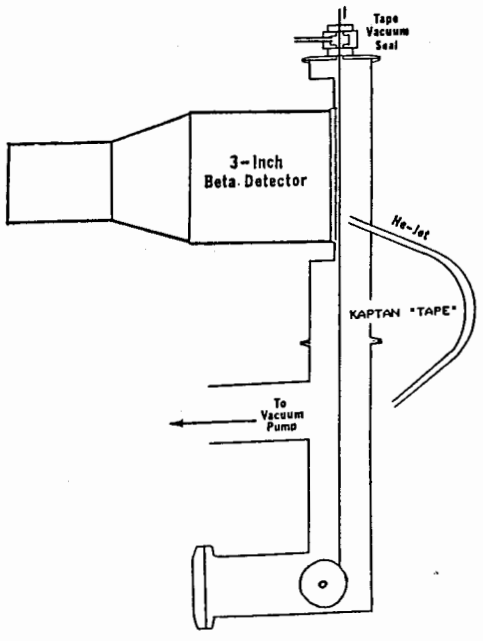

Fig. 1 Modified experimental arrangement for transferring fission products in DN equilibrium spectrum measurements.

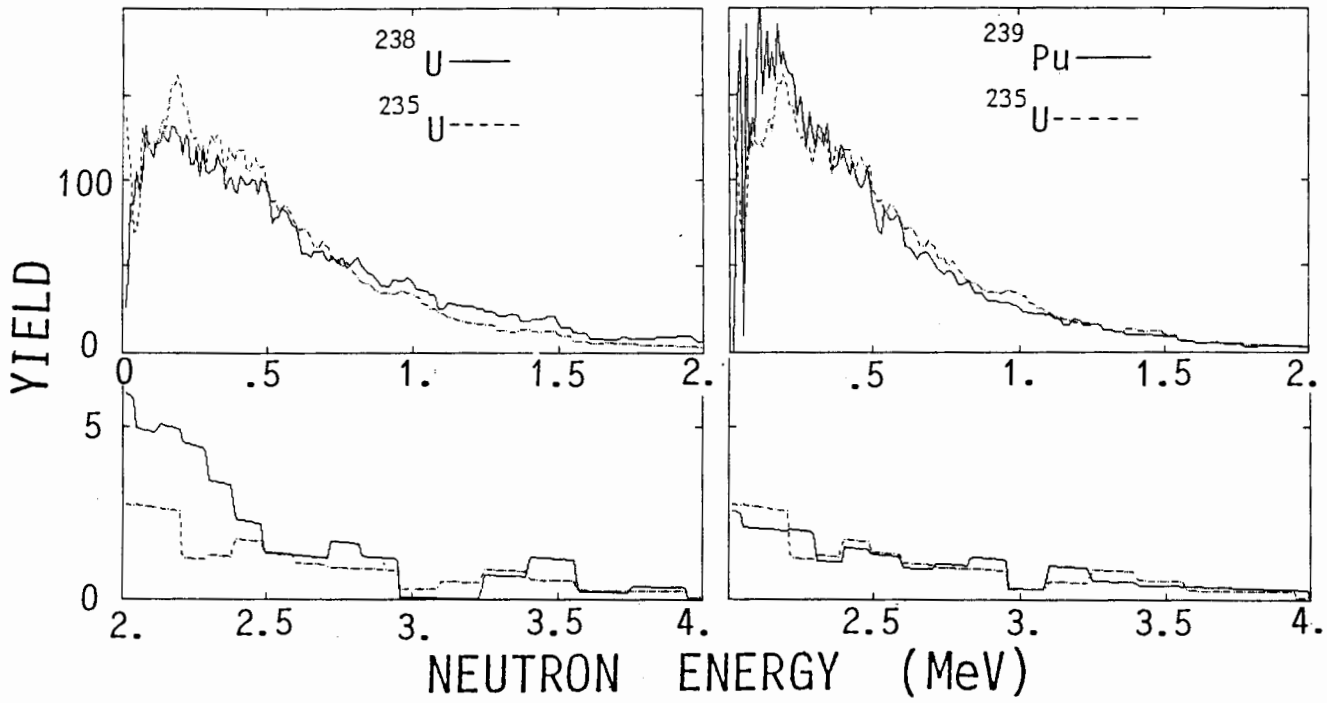

Fig. 2 Measured equilibrium delayed neutron energy spectra for U-235, U-238 and Pu-239. The spectra are all normalized to the same total yield.

DN Equilibrium Spectra

The measured DN equilibrium spectra resulting from U-235, U-238 and Pu-239 fission are shown for the energy range 0.01 - 4 MeV in Fig. 2. For comparison purposes the spectra are all normalized to the same (10^4) total yield. All three spectra display rather similar structures, although the U-238 spectrum is seen to be somewhat harder than that for either U-235 or Pu-239. The average energy for the measured U-238 spectrum is some 60 - 100 keV higher than for U-235 and Pu-239.

We have also calculated equilibrium spectra using the six-group spectra derived from our aggregate time-dependent delayed neutron measurements/2/. These results are shown plotted in Fig. 3 and are compared with the directly measured spectra over the energy range 0 - 2 MeV. The calculated spectra do not display to the same degree the sharper structure observed in the measurements since a smoothing function was applied in extracting the six-group spectra from the time-dependent measurements. The overall agreement between our directly measured equilibrium spectra and those deduced from our time-dependent studies is seen to be very satisfactory for all three cases.

We have additionally calculated equilibrium spectra for U-235 and Pu-239 using the six-group spectra recommended by England/4/, which are based on individual precursor measurements. These are shown compared with the present measurements in Fig. 4. In the case of U-235, except for the region near 0.2 MeV where the individual precursor data shows a sharp dip in the spectrum, the agreement is seen to be excellent. Somewhat less satisfactory agreement is had for Pu-239. The present measurements show neither the levelling off in the spectrum below about 0.25 MeV nor the same degree of structure at higher energies exhibited by the individual precursor data.

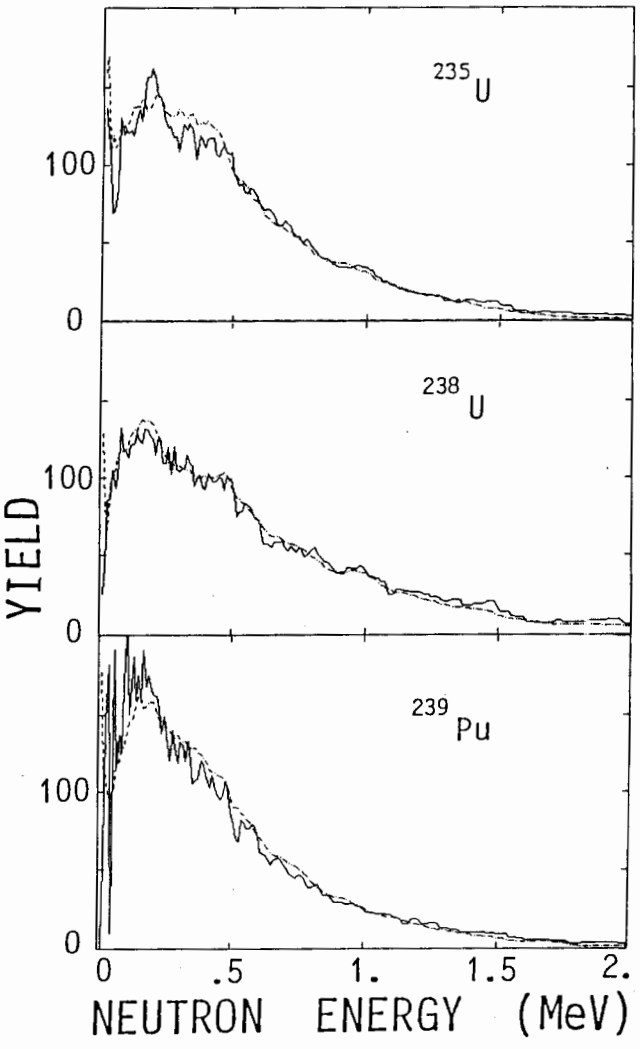

Fig. 3 Comparison of measured equilibrium spectra to 6-group generated spectra.

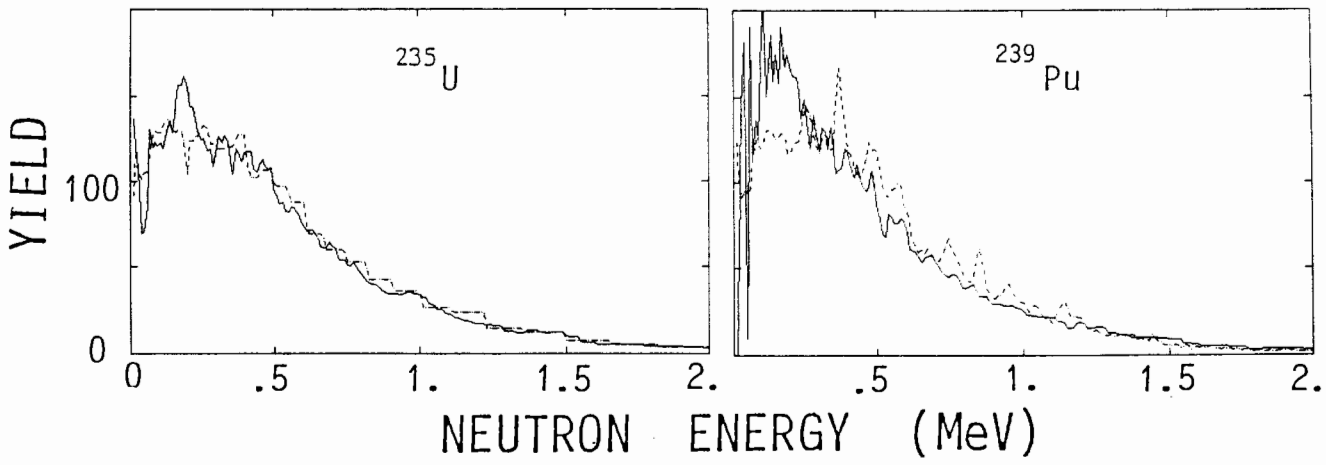

Fig. 4 Comparison of measured equilibrium spectra (solid curves) with spectra generated with the 6-groups proposed by England (broken curves), based on individual precursor data.

In conclusion, to emphasize the importance of the U-238 and Pu-239 delayed neutron studies, Table 1 is presented which shows these two isotopes contribute nearly 80% of the delayed neutrons in the prototype breeder reactor.

Table 1. Isotope contribution to fission and DN production in the core of a 1000 MWe heterogeneous fast reactor at the end of its cycle.

Isotope	% of Core Fissions	ν_d(DN/Fission)	% of DN
U-235	0.6	0.0167	0.86
U-238	10.6	0.0439	40.0
Pu-239	70.2	0.0063	38.0
Pu-240	5.4	0.0095	4.4
Pu-241	12.1	0.0152	15.8
Pu-242	0.5	0.0221	0.95

Acknowledgement

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