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NEUTRON MULTIPLICITY–SPIN STATE CORRELATIONS FOR ^{239}Pu RESONANCES*

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Measurements were made of the fission-neutron multiplicity associated with eleven ^{239}Pu resonances in the energy range from 20 to 100 eV. It has been found that the multiplicity values are strongly correlated with the spins of the individual resonances and that the average multiplicity for the $J=0$ group is 2.6% higher than for the $J=1$ group.

It has been suggested[1] that the fission-neutron multiplicity ($\bar{\nu}$) might be a function of incident neutron energy in the resolvable resonance regions of the common fissile nuclides. We have measured the energy dependence of $\bar{\nu}$, for a ^{239}Pu sample, for incident neutrons in the range from 20 to 100 eV. The results show that the multiplicity values do vary from resonance to resonance, and fall into two distinct groups that appear to be correlated with the known spins of these levels.

For the experiment reported here the neutrons required for the time-of-flight measurements were produced by the Rensselaer 90-MeV electron linac, and the fission measurements carried out at the end of a 25-m flight path. Fission events were detected by the occurrence of a coincidence between the signals from a fission ionization chamber[2] located in the neutron beam and signals from a gadolinium-loaded liquid scintillation tank that surrounded the chamber. The fission neutrons were detected, after thermalization in the scintillant, by means of the gamma radiation emitted following neutron capture in the gadolinium. The detected neutron multiplicity for each of 256 time-of-flight channels were first stored in a buffer and then transferred to a 256×12 array in the memory of an on-line computer. Thus, if a fission event were recorded at time of flight i with ν neutrons detected, the event would have been stored in the ith time-of flight channel of the νth section of the computer memory.

Many of the techniques used in this experiment are standard and have been described in detail by Mather, Fieldhouse, and Moat,[3] Diven and Hopkins,[4] and others. The principal differences between this experiment and the others can be attributed to the necessity of working with reaction rates associated with a very broad spectrum of neutron energies rather than a monoenergetic beam. The methods used to correct our multiplicity data for time-dependent (a) background events, (b) accidental coincidences, and (c) scaler dead-time effects are briefly described below.

(a) In general, the background multiplicity per fission gate is correlated with the scattering, capture, and fission cross sections of the material present in the fission chamber. A comparison of the upper graph in Fig. 1 (background events per gate) with the lower (fission rate) indicates the character of the background correlations that we observed in this experiment. In order to determine the number of background events per gate, background sampling pulses from a free-running pulse generator were used to initiate simulated fission coincidences. The multiplicity data associated with the sampling pulses were stored in a temporary buffer. If no fission coincidence was detected during the 240-μsec interval centered on the opening of the gate, then the number of the time-of-flight channel and the value of the multiplicity were stored in an additional 256×12 array in the computer.

(b) The fission chamber and associated electronics were designed to minimize the likelihood of detecting alpha particle pile-up events. Nevertheless, there was a reasonable probability that

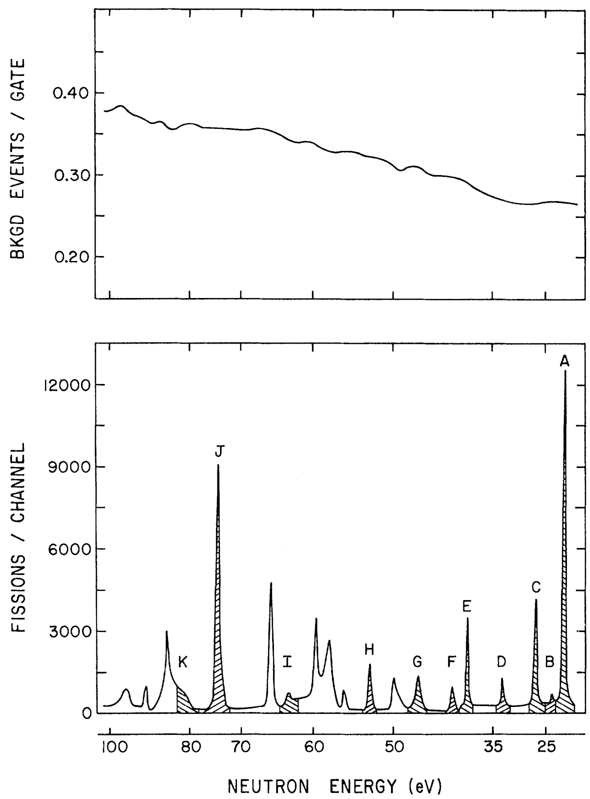

FIG. 1. Upper section: number of background events per background sampling gate. Lower section: total number of fission events per time-of-flight channel. The shaded areas, designated by the letters A through K, delineate the "resonances" that were chosen for analysis.

a few large-amplitude alpha pulses might be detected within the resolving time of the circuit. These pulses would have an amplitude that would fall within the range of true fission-fragment pulses and could, if their occurrence coincided with a signal from the scintillation tank, lead to the detection of a spurious event. The accidental coincidence rate is proportional to the product of the alpha pile-up rate, the coincidence resolving time, and the pulse rate from the scintillation-tank fission discriminator. The latter quantity was determined from a subsidiary experiment and showed significant resonance structure. The accidental coincidence corrections for the experiment reported here were in the range from 0.1 to 2.0% of the $\bar{\nu}$ values.

(c) Dead-time effects in the 7-MHz neutron multiplicity scaler were caused primarily by relatively large variations in background intensity rather than the few percent changes in $\bar{\nu}$. An iterative procedure was developed that corrected for scaler losses in each channel of data, while properly accounting for the time behavior of the events within the 32-μsec gate.

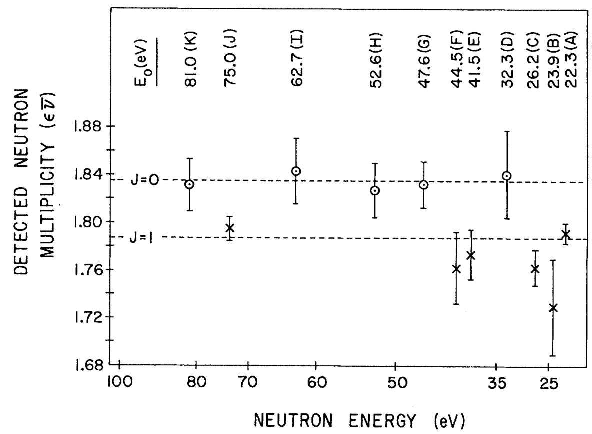

FIG. 2. Neutron multiplicity values ($\bar{\nu}$) for eleven time-of-flight regions. The regions are designated by the letters in parenthesis after the resonance energies. The circles correspond to resonances assigned to the $J=0$ state and the crosses to the $J=1$ state.

In addition to the time-dependent corrections there were also corrections for spontaneous fissions (probably due to ^{240}Pu and ^{244}Cm contaminants) and for the overall efficiency of the system for detecting fission neutrons. This efficiency, ϵ, is determined by comparison of the detected multiplicity for thermal neutron fission from this experiment with an accepted standard value of the ^{239}Pu thermal $\bar{\nu}$. The efficiency has not yet been determined for this experiment and the results are therefore presented in terms of $\epsilon\bar{\nu}$.

The multiplicity values reported here are based on data for eleven time-of-flight regions in the range of incident neutron energies from 20 to 100 eV. The regions, indicated on the lower graph in Fig. 1, were selected to correspond to isolated resonances or doublets with the same spin states, using as criteria the parameters from the multilevel analysis of the ^{239}Pu fission cross section reported by Farrell.[5] The values of $\epsilon\bar{\nu}$ that were obtained are shown in Fig. 2. It appears that the $\epsilon\bar{\nu}$ values fall rather cleanly into two groups, the higher of which we have assigned to fission through the $J=0$ state of the ^{240}Pu compound nucleus and the lower through the $J=1$ state. This assignment is based on the expectation that the $J=0$ state would be the lowest lying one at the saddle-point configuration and would therefore be associated with the highest excitation energy. The higher excitation energy may lead to the emission of more neutrons,

Table I. Assigned values of compound-nucleus spin (J) for selected ^{239}Pu resonances. Parentheses indicate uncertain assignments.

T.O.F. Region	Resonance Energy (eV)	Present Work	Sauter and Bowman	King and Block	Asghar	Cowan et al.	Melkonian and Mehta	Farrell
A	22.3	1	1		1	1	1	1
B	23.9	1						1
C	26.2	1			1	1	(1)	1
D	32.3	0	0			(0)	0	0
E	41.5	1	1	1	1	1	(0)	1
F	44.5	1	1	1	1	1	(1)	1
G	47.6	0	0		0	1	1	0
H	52.6	(0)	1	1	1	1	1	1
I	62.7	0						0
J	75.0	1	1	1	1	1	1	1
K	81.0	0				0		0

on the average, from the fission fragments.

The $\bar{\nu}$ spin assignments for these eleven resonances are listed in Table I along with assignments for the same levels determined by a variety of other techniques: Sauter and Bowman,[6] Asghar,[7] and King and Block[8] determined statistical g factors, Cowan[9] et al. measured the ratio of symmetric to asymmetric fission yields, Melkonian and Mehta[10] detected variations in fission fragment kinetic energies, and Farrell[5] performed a multilevel analysis of the ^{239}Pu fission cross section. In general the spin assignments based on the $\bar{\nu}$ grouping appear to be consistent with the other assignments. However, the statistical accuracies of some of the $\bar{\nu}$ values are poor and it is possible that one or more of the $\bar{\nu}$ spin assignments might be incorrect. This is probably the case with the 52.6-eV resonance which we would group with the $J=0$ levels but is assigned to $J=1$ in all of the other table entries. In addition to statistical considerations, the possibility also existed that systematic effects might have caused the appearance of a grouping where, in fact, none existed. Further experiments have shown that the measured values of $\bar{\nu}$ are unchanged for a factor-of-4 change in neutron intensity and are unaffected by a factor-of-3 change in the efficiency of the fission chamber. An analysis of our results in the light of recent α (capture-to-fission ratio) measurements[11] indicates that a factor-of-25 change in α has not produced more than a few tenths of a percent change in the detected $\bar{\nu}$ values.

We have computed the average values of $\bar{\nu}$ separately for the two spin groups and find that $\bar{\nu}(J=0)$ is 2.6% greater than $\bar{\nu}(J=1)$. This difference corresponds to the production of about 0.08 more neutrons for fission through the $J=0$ state. If we assume that the number of neutrons emitted per fission increases by 0.12/MeV of excitation energy,[4] then the observed change in $\bar{\nu}$ corresponds to about 0.7 MeV more excitation energy for the spin-0 state than the spin-1.

The same methods have been used to measure the energy dependence of the fission neutron multiplicity for ^{235}U and ^{233}U samples. A preliminary analysis of these data shows that the resonance-to-resonance variation in $\bar{\nu}$ for these two nuclides is smaller than the observed variations for ^{239}Pu and is apparently under 1%. The uranium $\bar{\nu}$ measurements will be continued with the hope of assigning J values to individual resonances.

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AN OBSERVABLE PECULIARITY OF THE BRANS-DICKE RADIATION ZONE

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It is pointed out that the Brans-Dicke theory predicts a transverse spin-0 component of the $O(r^{-1})$ radiative Riemann tensor. Unlike the conventional spin-2 radiative Riemann tensor, monopole oscillations may serve as a source. Under favorable conditions, neutron star formation within our galaxy will be detectable by Weber's gravitational-wave receiver.

We wish to point out that the Brans-Dicke scalar-tensor theory[1] predicts an $O(r^{-1})$ radiative Riemann tensor when scalar waves are emitted. Unlike other possible couplings of a scalar field to gravitation, such as a conventional Klein-Gordon coupling, this radiative Riemann tensor may exist in the absence of the usual spin-2 gravitational waves. Under favorable conditions, the amplitude for neutron star formation within our galaxy would be in the observational range of Weber's gravitational-radiation detector.[2-4]

As Dicke[5] has pointed out, there is a gauge in which the Brans-Dicke theory is mathematically equivalent to the conventional coupling of a massless Klein-Gordon field with an Einstein field. We denote the metric in this gauge by $\bar{g}_{\mu\nu}$, and the metric in the original Brans-Dicke gauge by $g_{\mu\nu}$. The connection is given by

$$g_{\mu\nu} = \lambda^{-1}\bar{g}_{\mu\nu},$$
$$\phi = \lambda\bar{\phi},$$
$$\bar{\phi}^{-1} = G_0, \tag{1}$$

where ϕ is the scalar field and G_0 is Newton's gravitational constant. In the $\bar{g}_{\mu\nu}$ gauge the coupled-field equations are

$$\bar{G}_{\mu\nu} = \frac{8\pi G_0}{c^4}\bar{T}_{\mu\nu} + \frac{2\omega+3}{2}\bar{\Omega}_{\mu\nu},$$
$$\bar{\Omega}_{\mu\nu} = \psi_{,\mu}\psi_{,\nu} - \tfrac{1}{2}\bar{g}_{\mu\nu}\bar{g}^{\alpha\beta}\psi_{,\alpha}\psi_{,\beta},$$
$$\bar{\Box}\psi = \frac{8\pi G_0}{(2\omega+3)c^4}\bar{T}, \tag{2}$$

where $\psi \equiv \ln\lambda$ is the effective Klein-Gordon field and $\bar{T}_{\mu\nu}$ is the matter energy-momentum tensor. The coupling constant ω characterizes the strength of the scalar field. Dicke's interpretation of the precession of the perihelion of mercury[1,6] gives $\omega \approx 6$. In this standard form, it is quite easy to set up the usual formalism for describing the asymptotic radiative behavior of a system whose matter sources are spatially bounded. Introducing a null polar coordinate system[7,8] with retarded time $x^0 = u$, liminosity distance $x^1 = r$, and ray labels $x^A = (\theta, \varphi)$ $(A = 2, 3)$, the metric takes the asymptotic Minkowski form

$$\bar{g}_{\mu\nu} \sim \eta^{\mu\nu} = 2l^{(\mu}n^{\nu)} - 2m^{(\mu}\bar{m}^{\nu)}$$

in terms of the null tetrad

$$l^{\mu} = (0, 1, 0, 0),$$
$$n^{\mu} = (1, \tfrac{1}{2}, 0, 0),$$
$$m^{\mu} = \frac{-1}{\sqrt{2}r}(0, 0, 1, i/\sin\theta).$$