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EVALUATION OF FISSION NEUTRON MULTIPLICITY DATA FOR Th-232

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Abstract: This paper describes the evaluation of the energy dependent experimental data for the average number of prompt neutrons, $\bar{\nu}_p$, for the neutron induced fission of Th-232 in the energy range from 1 - 20 MeV. The evaluation takes in account not only the actual numerical data of $\bar{\nu}_p$ (E_n) but also certain physical concepts based on the energy balance in nuclear fission. The energy dependence of $\bar{\nu}_p$ is represented by two SPLINE fitted curves because of the anomalous behaviour near threshold and multiple chance fission which introduces a non-linear dependence on E_n. Data are renormalised wherever necessary to the latest recommended value of (3.757) for $\bar{\nu}_p$ for spontaneous fission of Cf-252. The present evaluation is compared with the existing ones. Recommended values of $\bar{\nu}_p$ (E_n are given over the energy range 1 - 20 MeV.

(Evaluation, Nubar, Th-232, Neutron Fission, E_n = 1 - 20 MeV, SPLINE fits).

Introduction

Energy dependence of fission neutron multiplicity ($\bar{\nu}_p$) data for Th-232 neutron induced fission are valuable for testing the nuclear models predicting the distribution of fission energy between the collective and internal motions. Since the neutron emission is one of the principal de-excitation mechanism for fission fragments, the E_K (average kinetic energy of the fission fragments) and $\bar{\nu}_p$ data should be correlated. In fact the measured data for E_K and $\bar{\nu}_p$ indicates that there is a redistribution of fission energy between the collective and internal motions and that this redistribution depends on the excitation energy of the fissioning nucleus. Moreover, the even-odd compound nucleus Th-233 is interesting to study because the Th-232 (n,f) cross-section exhibits large resonances in the threshold region and also the behaviour of $\bar{\nu}_p$ is different from that observed for all other fissioning nuclei. The energy dependent $\bar{\nu}_p$ data are important for fast breeder reactor analysis (i.e., reactivity and breeding ratio calculations). For reactor physics calculation evaluated data are more useful. This paper describe the evaluation of directly measured $\bar{\nu}_p$ data for Th-232 (n,f) reaction over the energy range from 1-20 MeV. The data derived from fission energy balance equations are not included for this evaluation.

Data Base

In all there are eleven (Refs.1-11) reported measurements for $\bar{\nu}_p$ for Th-232 (n,f) reaction. These data sets are scrutinised for the following points:

(a) Measurement technique and standard used
(b) Corrections applied and
(c) Errors reported.

The majority (Refs.3,6,8,9 and 10) of the measurements have been made relative to $\bar{\nu}_p$ for the spontaneous fission of Cf-252 and in some cases (Refs.2,4,7 and 11) relative to $\bar{\nu}_p$ for U-235. The general technique for these experiments is to use a fission chamber, which contain the Th-232 sample and standard Cf-252 or U-235 in different sections, to detect the fission event. This fission chamber is surrounded by neutron detector either liquid scintillator (Refs.3,5,6, 8,9 and 11) or BF_3 (Refs.2,4 and 7) or He-3 (Ref.10) counter to detect the fission neutrons. In the present evaluation, all the data used are renormalized to common standard Cf-252 ($\bar{\nu}_p$ = 3.757 ± 0.0048). The existing measured data below 6 MeV are plotted in fig.1 and above 5 MeV in fig.2 and total number of data points amount to 143 in all. From these figs.1 & 2, one find that within reported errors an overall good agreement is observed. The latest (Refs.9,10 and 11) three measurements cover large energy range (i.e., 1.3 to 14.74 MeV, 1.35 to 6.35 MeV and 1.084 to 22.80 MeV repectively) and are the major data sets for this evaluation. Rest of the data points are few in numbers, scattered and also old. Both BRC (Ref.9) and FEI (Ref.10) data sets are having very small errors of the order of ≈ ± 1%. The accuracy of the latest measurement (Ref.11) is quite poor due to low counting statistics but the data agree on the average with the BRC (Ref.9) measurements. FEI (Ref.10) data are higher by about 4% than the BRC data below 2.37 MeV incident neutron energy. At higher energies the differences is about 2%.

In general any $\bar{\nu}_p$ measurement involved two simultaneous steps, i.e., recording of fission event and subsequent detection of the prompt fission neutrons. In most of the experiments the detail about the recording of well defined fission events are not given; so it is not possible to discuss its contribution to the uncertainty in the $\bar{\nu}_p$ measurement. As mentioned earlier the fission neutrons are detected either by BF_3 or He-3 embeded in a polythylen block used as a neutron moderator or by large Gd or Cd loaded scintillator tank. Recent review paper (Ref.12) have discussed in detail the essential difference between these two techniques and only a brief mention would be given here. Liquid scintillator technique has a large neutron detection efficiency (ϵ_n ≈ 80 to 90%), is quite isotropic, require small corrections for the spectrum difference (since all neutrons are first moderated in the scintillator tank prior to capture in Gd or Cd) and angular anisotropy of the fission fragments in laboratory system. But, because of the higher sensitivity to gamma ray and long counting time (≈ 50 μsec during which the neutrons are moderated and captured), liquid scintillator technique have large delayed gamma rays and dead time corrections. Moreover, this delayed gamma rays correction is estimated from the published data on fission fragments having isomeric half-lives in the 0.15 to 80 μ-sec range and emit cascade gamma rays which exceed the threshold of the liquid scintillator in total energy. On the contrary BF_3 or He-3 counter detector technique has small neutron efficiency ($\epsilon_n \simeq 30\%$), less isotropic so require a large correction for the spectrum difference and angular anisotropy of the fission fragments, ϵ_n depends on the position of fission chamber along the neutron detector axis and this correction is quite large when long fission chamber is used. An incorrect estimation of the angular anisotropy correction could explain the large difference observed between the measured BRC and FEI data in the threshold region. In Th-232 (n,f) the fission fragments are emitted preferentially at large angles relative to the direction of incident neutron inducing fission. Since the angular distribution of the fission neutrons is correlated to the fragment direction, these neutrons are detected with a better efficiency than in the case of an isotropic emission. This correction is quite negligible in the case of the liquid scintillator, but not for the BF_3 or He-3 counter detector. Only advantage of this type of detector is its insensitivity to gamma rays and therefore the measured ratio does not have to be corrected for delayed gamma rays contribution.

As mentioned in (Ref.12), if the external random generator is used to trigger the neutron background measurements, it would underestimate the real background rate and subsequently, overestimate the $\overline{\nu}_p$. In fact, from figs.1&2 it is seen that the measured data of (Ref.11) which have used external random generator, are comparatively higher than BRC but have been retained for evaluation with less weightage in the SPLINE fitting because this measurement cover the largest energy range.

Thus the $\overline{\nu}_p$ data measured by these two different experimental techniques have systematic difference due to improper estimation of corrections applied and inherent limitations of the techniques involved.

Method of Data Evaluation

From fig.1 it is noticed that near the threshold the measured data show an increase ($\simeq 12\%$) in $\overline{\nu}_p$ with decreasing energy E_n, which though statistically not significant because of the large errors associated with each individual point, seems to be confirmed by the results of five different experiments. From these figs.1&2 it is also noticed that there is a strong increase in $\overline{\nu}_p$ near the onset of the (n,n'f) i.e., second chance fission. Because of this anomalous behaviour near threshold and the non-linearity introduced by the onset of (n,n'f) and (n,2n'f), i.e., multiple chance fission, a single linear least square fit cannot be used for fitting the experimental data. Therefore, to take into account these observed facts, the present evaluation is performed in two parts, one below (n,n'f) threshold and other above it, using two separate cubic SPLINE curves. Fitting in segments is also necessary because the value at different energy by their process origin are only partially correlated. Single SPLINE fitting produces unjustified structure in curve. Below the second chance fission threshold (~6 MeV) the fission neutrons are all evaporated from the fission fragments. Above this threshold, first some neutrons are scattered followed by the fission of residual nuclei. Although the neutrons emitted prior to fission have no direct connection with the fission process, whereas those emitted following fission do, both groups are nevertheless in coincidence with the fission event for any physical measurements.

As explained in previous section, these $\overline{\nu}_p$ data are derived from ratio measurements after subtracting the neutrons background and applying certain corrections. The background correction is statistical in nature while the other corrections are systematic, positive or negative depending on their contributions. The reported errors ($\pm\Delta\overline{\nu}_p$) on measured values are statistical only and for evaluation these measured data are least square fitted with weights $\omega_i = 1/(\Delta\overline{\nu}_{p_i})^2$

Result of Evaluation

In all 143 experimental data points from eleven different measurements are SPLINE fitted in two segments of energy i.e., from threshold to 5.14 MeV, 93 points and from 3 to 22.8 MeV, 78 points respectively. The smooth curves representing the present evaluation are shown in fig.1& 2 along with the data points. The evaluated data in tabulated form at energy interval suitable for linear interpolation are given in Table 1. In fig.3 the present evaluation is compared with ENDF/B-V (Revision 2), Davey's (Ref.13) and Russian (Ref.14) evaluations.

Table 1 Evaluated $\overline{\nu}_p$ for Th-232

*E_n	$\overline{\nu}_p$	E_n	$\overline{\nu}_p$	E_n	$\overline{\nu}_p$	E_n	$\overline{\nu}_p$
1.1	2.43	2.5	2.22	8.0	3.12	14.5	4.04
1.2	2.30	2.7	2.23	8.5	3.17	15.0	4.12
1.3	2.21	2.8	2.24	9.0	3.22	15.5	4.20
1.4	2.16	3.0	2.25	9.5	3.26	16.0	4.28
1.5	2.14	3.5	2.30	10.0	3.31	16.5	4.36
1.6	2.13	4.0	2.34	10.5	3.37	17.0	4.43
1.7	2.13	4.5	2.38	11.0	3.44	17.5	4.50
1.8	2.14	5.0	2.47	11.5	3.51	18.0	4.57
1.9	2.16	5.5	2.60	12.0	3.60	18.5	4.63
2.0	2.17	6.0	2.74	12.5	3.68	19.0	4.70
2.1	2.19	6.5	2.88	13.0	3.77	19.5	4.75
2.2	2.20	7.0	2.99	13.5	3.86	20.0	4.81
2.3	2.21	7.5	3.06	14.0	3.95		

* E_n is in MeV

Discussion and Conclusion

In Table 2, the evaluated data at twelve incident neutron energy E_n are compared with calculated $\overline{\nu}_p$ (Ref.15). The calculations have been performed in the framework of (TSM-GMNM) a semi-empirical scission point model with temperature-dependent shell effects. The calculated $\overline{\nu}_p$ do not show any increase in $\overline{\nu}_p$ with decreasing E_n near threshold and are little lower than the evaluated $\overline{\nu}_p$ but agree within calculation uncertainties $\pm$ 0.08. According to the conservation of total energy released in fission, the average total kinetic nergy, $\overline{E}_K$, and $\overline{\nu}_p$ are inversely related. Near threshold the evaluated $\overline{\nu}_p$ data shows a decrease as E_n increase from 1.2 to 1.7 MeV, whereas the measured $\overline{E}_K$ data of D'yachenko et al (Ref.16) show an increase. This behaviour of $\overline{\nu}_p$ and $\overline{E}_K$ indicate that the calculation method should be improved in the threshold energy region. In the present evaluation the errors estimated for fitted $\overline{\nu}_p$ values are $\simeq \pm 5\%$ in the energy range (1.0 to 3 MeV) and $\simeq \pm 3\%$ above 3 MeV.

Table 2 Evaluated and Calculated $\overline{\nu}_p$ for Th-232

E_n (MeV)	Evaluation	Theory
1.1	2.43	2.07
1.5	2.14	2.06
2.0	2.17	2.08
3.0	2.25	2.18
4.0	2.34	2.32
5.0	2.47	2.49
6.0	2.74	2.66
6.5	2.88	2.98
7.0	2.99	3.02
8.0	3.12	3.09
9.0	3.22	3.18
10.0	3.31	3.37

It can be seen from fig.3 that the present evaluated curve deviate appreciable from linearity and this deviation is larger than the required accuracy of ≃ 2%. The evaluation would be improved once the known systematic discrepency between two technique of measurements is reduced.

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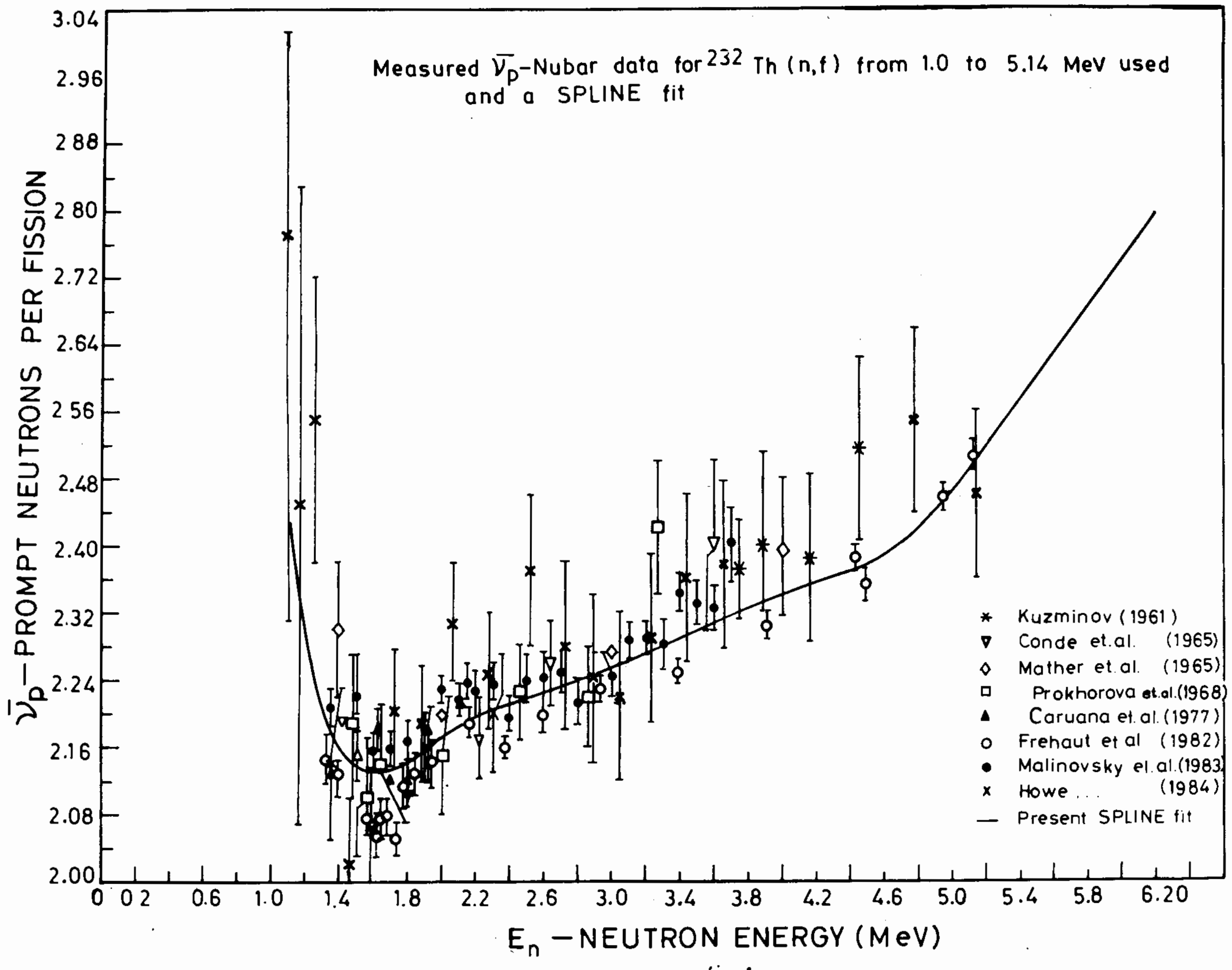

fig.1

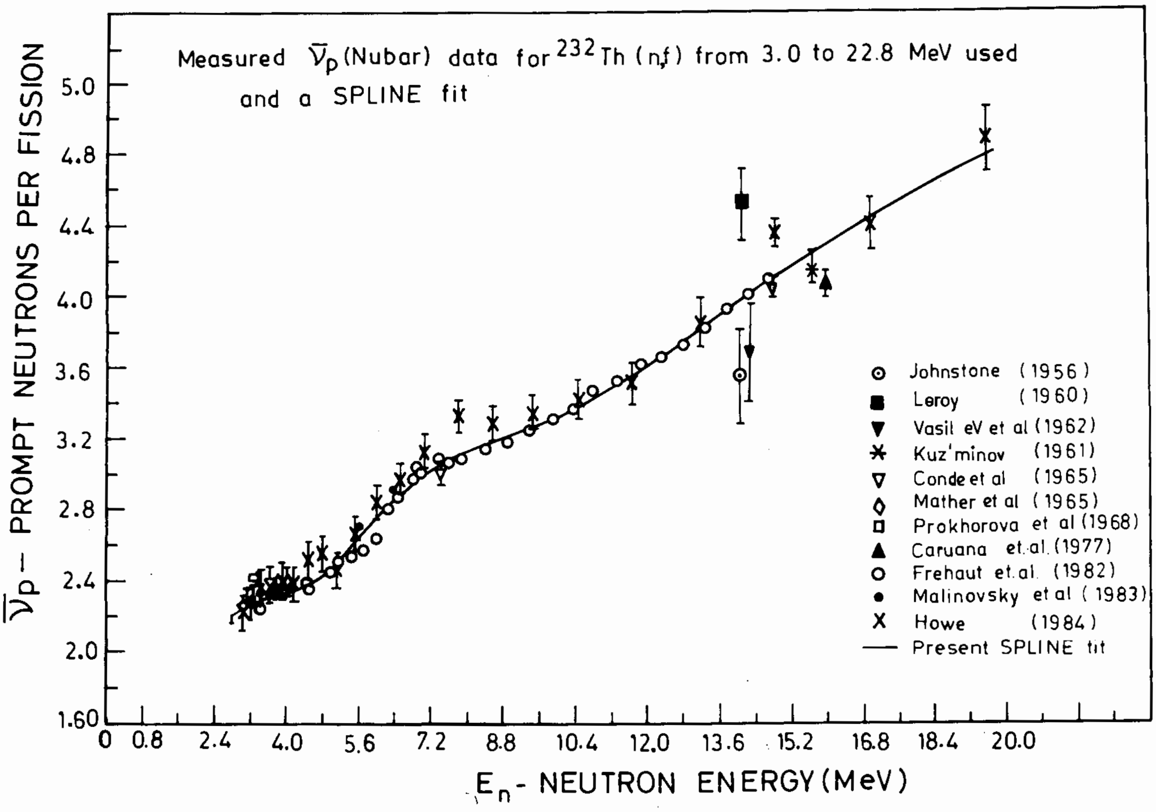
Measured $\bar{\nu}_p$(Nubar) data for ^{232}Th (n,f) from 3.0 to 22.8 MeV used
and a SPLINE fit
$\bar{\nu}_p$ – PROMPT NEUTRONS PER FISSION
5.0
4.8
4.4
4.0
3.6
3.2
2.8
2.4
2.0
1.60
0
0.8
2.4
4.0
5.6
7.2
8.8
10.4
12.0
13.6
15.2
16.8
18.4
20.0
E_n - NEUTRON ENERGY (MeV)
⊙ Johnstone (1956)
■ Leroy (1960)
▼ Vasil eV et al (1962)
✱ Kuz'minov (1961)
▽ Conde et al (1965)
◊ Mather et al (1965)
□ Prokhorova et al (1968)
▲ Caruana et.al. (1977)
○ Frehaut et.al. (1982)
● Malinovsky et al (1983)
X Howe (1984)
— Present SPLINE fit

fig. 2

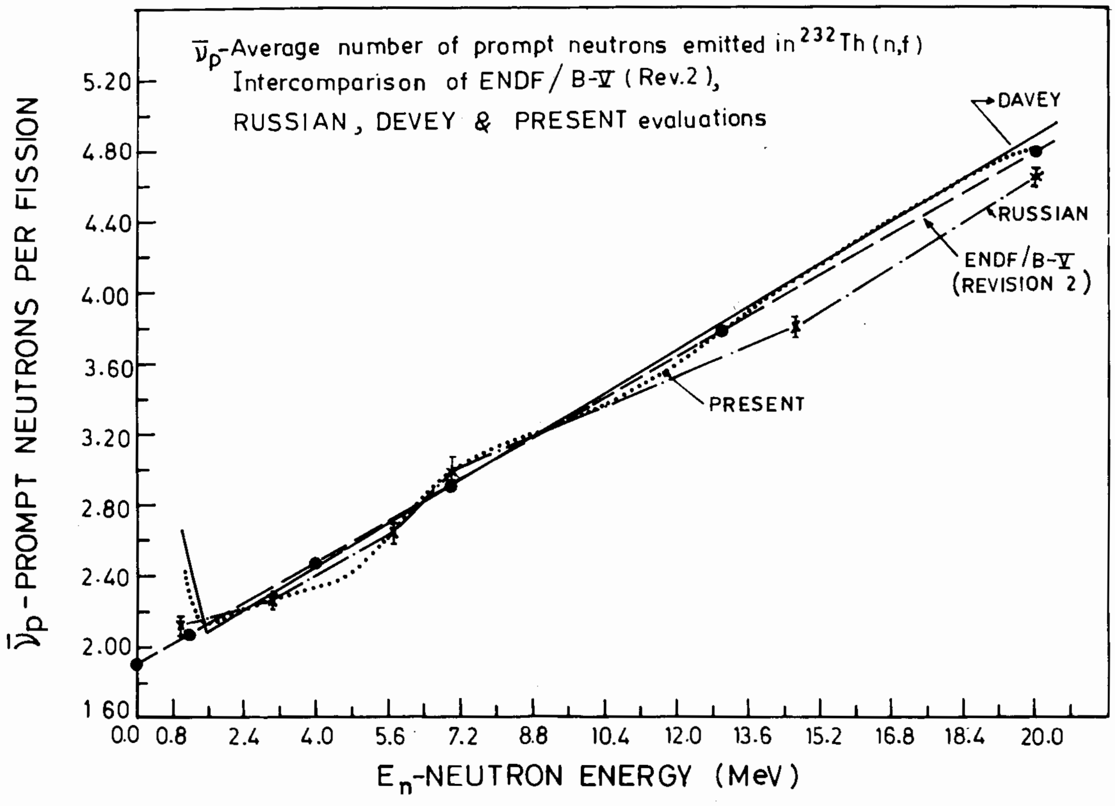
$\bar{\nu}_p$-Average number of prompt neutrons emitted in ^{232}Th (n,f)
Intercomparison of ENDF/B-V (Rev.2),
RUSSIAN, DEVEY & PRESENT evaluations
DAVEY
RUSSIAN
ENDF/B-V (REVISION 2)
PRESENT
$\bar{\nu}_p$-PROMPT NEUTRONS PER FISSION
5.20
4.80
4.40
4.00
3.60
3.20
2.80
2.40
2.00
1.60
0.0
0.8
2.4
4.0
5.6
7.2
8.8
10.4
12.0
13.6
15.2
16.8
18.4
20.0
E_n-NEUTRON ENERGY (MeV)

fig. 3