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Resonances Suitable for the Calibration of a Time of Flight Neutron Spectrometer*

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Abstract

Neutron resonance energies have been obtained for a number of selected well isolated resonances in several elements and isotopes. The energy parameters were mainly obtained at Columbia University's 200 meter time of flight spectrometer with high precision. These energy calibration points are important for a number of experiments in neutron and reactor physics.

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Introduction

Reliable energy calibration points are necessary for many experiments in neutron and reactor physics. The best energy calibration points are prominent, sharp, reasonably well-isolated neutron resonances. In the energy region below 0.5 MeV the best method of determining the energy of a resonance is by using a neutron time-of-flight spectrometer. This paper gives a set of neutron resonances which can be used for calibration purposes. The factors affecting the determination of the energy of a neutron resonance are described so the user may know in detail the sources and magnitudes of the errors involved.

When neutron time-of-flight spectrometers are used to measure resonance spectra there are two principal origins for uncertainty in energy determinations of cross section maxima and other features of interest in the spectra. One can be broadly described as statistical in origin and it depends on the count rate, width of a timing channel, total counting time, and other similar sources. The other form of uncertainty can give an energy shift to all measured energies which may or may not be constant. Such a systematic uncertainty has been previously discussed[1] and it is much more difficult to detect and remove than that arising from statistical sources. In the next section details are given of sources of systematic uncertainty in a particular neutron velocity selector. If the zero point on the timing scale is not correctly determined, all calculated energies will be inaccurate by a quantity that varies monotonically with energy.

The best way to determine such systematic uncertainty is by comparison with others' results, preferably those obtained in a different laboratory employing different details of technique. In Table II is given a list of resonance energies which may be of use in determining zero point uncertainty.

Resonance Energy Uncertainties

For the case of the Columbia University Nevis Laboratory Synchrocyclotron neutron time-of-flight spectrometer the sources of systematic uncertainty are described. The details apply to this instrument alone. Yet the general principles are applicable to all neutron resonance energy determinations by time-of-flight methods.

The Nevis Synchrocyclotron has until recently operated by accelerating a bunch of protons to a maximum energy of about 350 MeV with a repetition rate of 70 Hz. A more detailed account of its operation for pulsed neutron production has been published elsewhere[2] but the pertinent facts are reviewed below. When the proton bunch is in orbit of radius 175 cm it has an approximate energy of 350 MeV and subtends an angle of about 1 radian at the orbit's center. The frequency of the applied RF is then 20 MHz. This circulating bunch of protons is deflected downwards to strike a lead block of size 8 by 20 cm and 3 cm high. The deflection voltage is about 100 KV and its rise time is much less than 50 nsec, the protons' orbital period. This voltage is applied to a parallel pair of plates between which the proton orbit passes. It is intended that within one orbit all protons strike the lead target and that none survive to strike the target 50 nsec later after completing one further orbit. Interactions between the fast protons and lead nuclei result in the emission of various particles, but mainly neutrons by spallations and evaporation processes. The energy spectra, angular distributions and numbers of such emitted particles have been calculated in detail, using Monte Carlo techniques which consider intranuclear cascades, by Bertini[3] and others[4]. In contact with the lead target and below it is a neutron moderator. At present the moderator is an aluminum box, 8 by 20 cm and 5 cm high, which contains water which is recirculated.

This design was found necessary to dissipate heat at a sufficiently fast rate. There is a finite time required to moderate the neutrons. This moderation time depends on the initial and final energy of the neutron and

also on the configuration of the moderator. Calculations of these moderation times have been made[5]. Allowance can be made for the moderation times and displacement of the zero time. These can simply be expressed as additions to the effective flight path lengths. These additions are an extra 2 cm approximately, which corresponds to a shift in the zero time plus a flight path length uncertainty of about 3 cm which corresponds to the time smearing, resulting from the moderation process.

Recent Monte-Carlo calculations[6] of the moderation times of fast neutrons created adjacent to moderators containing hydrogen compounds have shown that for neutron energies in the high keV region the time delay and time smearing cannot be expressed simply in terms of an uncertainty in flight path distance. This is because of considerations of variations of neutron mean free path with neutron energy in a given moderator.

Those moderated neutrons which emerge from the moderator moving in a direction along the flight path are those whose time of flight is recorded. The burst of neutrons which travels to the detectors at the end of the flight path has a creation width of about 20 nsec. This uncertainty contributes directly to energy determination as is shown below.

The energy of the neutron E_n is $(M_n/2)(L/t)^2$, where M_n is the neutron mass, L the flight path length and t the time of flight, if relativistic effects are negligible. The fractional uncertainties in E_n due to flight path length and timing measurement are $2(\Delta L/L)$ and $2(\Delta t/t)$ respectively. For a flight path length 200 m and various neutron energies, these energy uncertainties are tabulated in Table I, which is taken from reference 7.

An accurate determination of flight path length was made by a team of surveyors from the Brookhaven National Laboratory and the resulting flight path lengths in current use of 200 m and 40 m are believed known to better than 1 cm.

When the neutron arrives at the detector it strikes a block of ^{10}B of thickness 3 cm and if captured by a ^{10}B nucleus the resulting 480 keV gamma ray is detected in an adjacent scintillation detector. At the 200 m detector station, sodium iodide mosaic scintillation detectors are used. At the 40 m detector station plastic scintillators are used. In addition to the gamma rays detected from ^{10}B when used in a flat detector, an alternative mode of operation is to use self indication with the capturing sample in the neutron beam and between the scintillators. In this case capture gamma rays from the substance under investigation are directly detected. Contributions to timing uncertainties from the scintillation process is small. However, the neutron capture cross section of ^{10}B in the flat detector falls off rapidly with neutron energy. For slow neutrons their capture in the ^{10}B takes place at its front face, but as neutron energy increases the ^{10}B slab becomes less and less opaque and capture takes place throughout its thickness of 3 cm in the direction parallel to the flight path. Hence an energy dependent flight path length uncertainty results.

Times of flight are determined by the timing channel in which an event is detected. At present the time of flight analyzer[8] is based on a clock of frequency 100 MHz and the channels are of width 20 nsec. If an event occurs in a particular channel, there is no way of knowing at which moment in the 20 nsec period it happened. It is to be noted with all the uncertainties described so far that there is no point in using such narrow channel widths when detecting neutrons of all energies. Provision has therefore been made for variable channel widths of $(2^n \times 25)$ nsec where $n = 0,1,2,3.....$

Those contributions to energy uncertainty which stay constant in time can be examined and in general evaluated, but the condition of the proton beam pulse which strikes the lead target can vary as the state of the accelerating RF varies with time. When the proton beam strikes the lead target an intense burst of gamma rays is created. This burst is detected

in the well-shielded distant scintillation detectors at the detector stations and their time of arrival gives a well determined zero time. The velocity and distance traversed by the gamma rays is well known. The shape of the burst, continuously available for monitoring during operation, indicates if neutrons are being created during one or more orbits of the protons.

Criteria for Resonance Energy Selection

In order to be useful for checking energy determinations the resonances under consideration must be prominent, sharp and reasonably well isolated from neighboring structure. Also those isotopes which contain such resonances must be readily available in natural or isotopically enriched materials.

The resonance energies given below are mainly taken from the data of the Columbia University Neutron Velocity Selector Group. However, the data have been carefully compared with all other available resonance energies to reduce the chance of an energy shift being presented here.

Resonances given below are mainly in the energy region where neutron energy is less than 500 keV for it is believed this is the region where the present compilation is most needed. The criteria of separation and prominence of the resonances will depend on the properties of the spectrometer which is being used to examine them. Almost all the presently selected resonances should be of use for spectrometers with the highest resolution.

The results of other groups have been studied both in the tabulations of the BNL Sigma Center[9] and other results obtained since the publication of this Neutron Cross Section Compendium.

Some analyses of Neutron Cross Section data such as that analysis of Ti, Fe, and Ni by Garg et al.[10] may also at first sight seem to be sources of resonance energies that are useful for the present compilation. However, it must be noted that all results obtained from R matrix fits give

resonance energies for s-wave resonances which are not energies equivalent to peaks observed in total cross section determinations. Such experimentally observed peaks alone are useful in the present context. There is an interference between an s-wave resonance and the background. In an R matrix analysis allowance is made for this interference, so the energy of the resonance, E_0, does not correspond to the maximum observed total cross section. For p-wave resonances there is no such interference, hence an R matrix analysis resonance energy for a p-wave resonance corresponds to the maximum observed total cross section.

A comparison of our recommended results with other recently obtained resonance energy values in the eV and KeV region shows generally good agreement. In the KeV region, our recommended value of 298.5±1.0 KeV for the sharp s wave resonance in Na^{23} is within 0.05% of the value of 298.4 KeV in the Karlsruhe[16] set. At lower energies, our value of 820.9±0.5 eV in U^{238} compares well with 821.81±0.52 eV obtained at Geel[19]. The differences in our recommended values and other recent measurements are due mainly to systematic errors.

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TABLE CAPTIONS

Table 1. Energy uncertainties which arise from uncertainty in time (Δ t= 25 n sec) and uncertainty in flight path length (Δ L= 3.4cm) for a total flight length (L) of 200 m and neutron energy from 10 eV to 40KeV.

Table 2. The resonance energies of selected prominent sharp, isolated neutron resonances in readily available isotopes.

TABLE I

E_n (eV)	Time of Flight (μsec)	Energy Uncertainty due to flight path uncertainty of 3.4cm ΔE_L (eV)	Energy uncertainty due to timing uncertainty of 25 n sec ΔE_t (eV)
10	4560.0	0.0034	0.00011
100	1446.0	0.034	0.00346
1000	456.0	0.34	0.109
10000	144.6	3.4	3.46
40000	72.3	13.6	27.6

Table II

Isotope	E_n(KeV)	E_n(KeV)	Reference
Na^{23}	53.15	0.03	18
	298.5	1.0	18
Al^{27}	5.907	0.003	13
	119.8	0.3	13
	222.9	0.4	13
	255.7	0.5	13
	365.5	0.7	13
	435.5	1.0	13
	524.9	1.3	13
	646.9	1.7	13
S^{32}	202.2	2.4	13
	380.3	3.0	13
	591.7	8.0	13
Cl (unassigned)	14.81	0.02	13
	26.67	0.03	13
	113.8	0.2	13
Ca^{40}	20.47	0.02	13
	89.40	0.13	13
	133.8	0.3	17
	146.4	0.3	13
	170.9	0.4	17
	295.1	0.8	13
	640.9	1.0	16
	694.6	1.0	16
	758.0	1.0	16

Table II

Isotope	E_n(KeV)	$E_{n'}$(KeV)	Reference
Ti^{47}	3.074	0.004	12
	10.510	0.014	12
Ti (unassigned)	11.040	0.016	12
	11.460	0.017	12
Mn^{55}	17.80	0.02	13
	30.30	0.04	13
	41.09	0.05	13
	53.40	0.08	13
	81.59	0.08	13
Fe^{56}	27.91	0.02	13
	73.96	0.07	13
	83.63	0.09	13
	129.53	0.14	13
	168.96	0.26	13
	188.0	0.3	13
	318.1	0.6	13
	435.5	1.0	13
Co^{59}	8.049	0.005	13
	10.692	0.010	13
	13.268	0.010	13
	31.34	0.03	13
	41.49	0.06	13
	56.39	0.04	13
	66.28	0.06	13
	84.29	0.09	13
	142.3	0.1	13

Table II

Isotope	E_n (KeV)	ΔE_n (KeV)	Reference
	163.2	0.2	13
	186.6	0.3	13
Cu^{63}	2.6498	0.0013	13
	4.8621	0.0018	13

Isotope	E_n (eV)	ΔE_n (eV)	Reference
Mo^{97}	70.93	0.03	11
	2550.4	1.8	11
Ag^{107}	16.30	0.05	9
Ag^{109}	87.40	0.20	9
Cd^{111}	27.54	0.04	13
Te^{122}	72.79	0.03	11
Te^{123}	24.19	0.04	11
Ta^{181}	4.20	0.01	15
W^{183}	7.65	0.03	13
U^{238}	6.65	0.01	14
	20.90	0.10	14
	36.80	0.07	14
	66.10	0.15	14
	102.47	0.09	14
	116.82	0.11	14
	189.80	0.23	14
	208.49	0.25	14
	237.20	0.16	14

Table II

Isotope	E_n (eV)	ΔE_n (eV)	Reference
	273.56	0.20	14
	291.01	0.21	14
	347.74	0.28	14
	410.18	0.36	14
	518.27	0.25	14
	535.21	0.25	14
	594.84	0.31	14
	660.9	0.4	14
	820.9	0.5	14
	1139.9	0.5	14
	1244.9	0.5	14
	1522.3	0.4	14
	1782.1	0.5	14
	2186.0	0.6	14
	2671.3	0.9	14
	3456.3	1.3	14