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^{209}Bi(N,TOT.) CROSS-SECTIONS FOR INCIDENT NEUTRON ENERGIES 0.01-400 eV

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Abstract: The neutron induced total cross-sections of ^{209}Bi for the energies 0.01 - 400 eV were measured with the neutron time of flight (TOF) method at the pohang neutron facility (PNF), Korea. The PNF consists of a 100 MeV electron linear accelerator (LINAC), a water cooled Tantalum (Ta) target, 12.06 m TOF path length, four position automatic sample changer controlled remotely by the CAMAC data acquisitions systems, and a ^{6}LiZnS(Ag) inorganic scintillator as a neutron detector. The distance from the water cooled Ta target to the sample changer is 5.4 m. To reduce the gamma flash originated from the neutron target we have employed a neutron-gamma separation system based on their different pulse shape. The sample was highly pure. The size of the sample ^{209}Bi was 100 × 100 × 0.5 mm. In order to estimate the background and also to calibrate the energy we used notch filter of Cobalt (Co), Indium (In), and Cadmium (Cd) that has a large resonance peaks within our analyzed energy region. The area of the each samples of notch filter was 100 × 100 mm, and the thickness were 0.5 mm for Co and Cd; and 0.2 mm for the In. The transmission experiments were carried out on samples in and samples out method. The present measured values were compared with the others reported values and with the latest evaluated reaction data library ENDF/B-VII.0. The present measured neutron total cross-sections are generally in good agreement with the others experimental data and the evaluated data library.

Keywords: total cross-sections, transmission experiment, linear accelerator, neutron detector.

1. Introduction

Nuclear reaction cross-sections are needed for the safety analysis, evaluation of the neutron flux density, temperature coefficients, neutron reaction yields, etc. Neutron reaction data also provides reliable information on nuclear level densities. The total cross-section measures the probability that an interaction of any type will occur when neutrons strike a target. This is the only cross-section that can be measured absolutely as it is the only one not measured relatively to a standard cross-section.

Bismuth is a white, crystalline, brittle metal with pinkies tinge. It forms low melting alloys which are extremely used for safety devices in fire detection and extinguishing systems.

In 1997 at Leningrad Instituite of Nuclear Physics, Russia by using LINAC and TOF method Yu. A. Alexandrov et al. [1] measured the total ^{209}Bi cross-sections for the energies 1.02 to 94.94 eV. Koester et al. [2] determined Bi cross-sections from 1.3 to 5.2 eV at FRM research reactor (open pool, 4 MW thermal power) of the Technical University of Munich. At the Institute of Balseiro y Centro Atomico Bariloche, Bariloche, Argentina Mayer et al. [3] measured Bi cross-sections for the incident neutron energies from 0.12 to 582 eV. In 1984 at Joint Institute of Nuclear Research by using TOF method and fast pulse reactor A. B. Popov et al. [4] measured total cross-sections of ^{209}Bi for energies from 0.35 to 105 eV for the liquid metallic Bismuth in the stainless-steel container. At ORNL by using LINAC and TOF method J. A. Harvey et al. [5] measured the total cross-sections of ^{209}Bi for the energies from 1.86 eV to 0.25 MeV in 1972 for the sample of thickness 0.072 atoms/barn and at the same Laboratory previously in 1965. W. Waschkowski and L. Koester [6] measured Bi total cross-sections for 1.1 to 5.1 eV in 1976. In 1971 W. Dilg and H. Vonach [7] measured Bi cross section for 130 eV in Technische Universitaet Muenchen, Munich. L. A. Rayburn and E. O. Wollen [8] also measured the neutron total cross- sections of ^{209}Bi for energy at 1.44 eV. At Brookhaven National Laboratory K. K. Seth et al. [9] determined Bi cross-sections for 26.4 eV to 1.7 keV in 1958. In 1953 by using fast chopper at Argonne National Laboratory M. Bollinger et al. [10] measured Bi cross-sections from 1.5 eV to 9.9 keV. P.A. Egelstaff [11] measured Bi cross-sections for 0.14 eV to 286 keV. W. Kato [12] measured Bi cross-section for the energies between 53 and 754 eV at BNL. The Evaluated Nuclear Reaction data files [13] were prepared on the basis of [4,5].

Although the above measurements are available, however, all these data are very old and there are some discrepancies among the data of these measurements. Moreover, there is no experimental data for the very low energies. That’s why we have carried out new measurements to get the exact experimental cross-sections for a wide range (from 0.01 to 400 eV).

2. Experimental Details

The Pohang Neutron Facility (PNF) which is a pulsed neutron facility based on an electron linear accelerator utilized extra parts kept in the Pohang Accelerator Laboratory (PAL). The main object of the PNF is to measure the nuclear data in the neutron energy region from the thermal neutron to few hundred eV. In addition to neutron beams produced at the PNF, photon and electron beams are produced in this facility. Thus this facility also can utilize for other fields, such as test facility for the detectors, activation experiments, polarized neutron beam source, and so on. In addition to these, this facility could use for training students.

The PNF consists of a 100 MeV electron Linear Accelerator, a water-cooled Ta target, and 12.06 m Flight Path length. The electron LINAC consists of a theroionic RF gun, an alpha magnet, four quadrapole magnet, two SLAC type accelerating structure, a quadrupole triplet and a beam analyzing magnet. A 2 m long drift space is added between the first and second accelerating structures to insert an energy compensation magnet or a beam transport magnet in order to future research. The RF gun is a one cell cavity with tungsten dispenser cathode of the radius of 3 mm. The RF gun produce an electron beam with an average current of 300 mA, a pulse length of 6 μs and of energy approximately 1 MeV. The measured rms emittance for the beam energy of 1 MeV was 2.1. The alpha magnet is used to match the longitudinal acceptance from the RF gun to the first accelerating structure. Electrons move along an alpha-shaped trajectory in the alpha magnet and the bending angle is 278.6 degree.

As high energy electrons injected in the target produce gamma rays via bremsstrahlung and these gamma rays then generate neutrons via photo nuclear reactions. So for a photo neutron target it is necessary to use a heavy mass material because the emission of gamma rays is almost proportional to the atomic number Z of the target material and to the energy of the incident energy. We used Tantalum rather than fissile materials as the technology for the handling and characteristics of this target are well known. This neutron target system consists of water-cooled Ta target and moderator. The total length of the target is 74 mm and there is 1 mm gap between Ta plates to cool the target effectively.

Water is a good moderator but the hydrogens in the water molecule have a fairly high cross-section for neutron capture, removing neutrons from the fission process. But due to ability, less expenditure and other causes of good moderator viz less collisions needed for scattering, we used water as moderator.

Water moderator is contained in the cylindrical aluminium container with a thickness of 0.5 cm, a diameter of 30 cm and a height of 30 cm. The water moderator is mounted on an aluminium plate of thickness 2.5 cm and an iron table of thickness 2 cm. The water level in the moderator was 3 cm above the target surface according to the measurement of neutron flux. And the estimated flow rate of the cooling water is about 5 liters per minute in order to maintain temperature below 45 degree.

In the Pohang Neutron Facility neutron guide tubes are made of stainless steel with two different radii, 7.5 cm and 10 cm. These tubes are placed perpendicularly to the electron beam. The neutron collimation system is composed of white solid Boric acid H_3BO_3, Pb, and Fe collimates. These are symmetrically tapered from a 5 cm radius at the beginning to a 2.5 cm radius in the middle position where the sample changer is placed and 4 cm radius at the end of the guide tube where the neutron detector is placed. Between the target and detector room there is 1.8 m thick concrete. The total flight path length is exactly 12.06 m.

In this facility we used BC-702 ZnS(Ag) scintillator, which is ^{6}Li loaded scintillator**.** This silver activated zinc sulfide is the inorganic scintillator which has very high scintillation efficiency and found as a polycrystalline powder. BC-702 is a scintillation detector for thermal neutrons, with excellent gamma background discrimination characteristics. This detector consists of a disc of 6.35 mm in thickness, 20 mm in radius. The disk can be mounted directly to photo-multiplier tubes supplied by 800 V voltages. The detector incorporates a lithium compound (enriched to 95% ^{6}Li) matrix dispersed in a fine, ZnS(Ag) phosphor powder. The detection process employs the registration of products issued from ^{6}Li(n,α)^{3}H nuclear reaction in which the resulting particle and triton produce scintillations upon interacting with ZnS(Ag). The emitted light generates an electric pulse through photo multiplier tube (PMT) for further analyses.

3. Experimental Parameters and Data Taking

For this ^{209}Bi(n,Tot.) cross-sections we used Flight Path Length: 12.06 ± 0.02 m, Delay Time: τ = (7.50 ± 0.01) μs, Channel Width: 0.5 μs, Sample Thickness: 0.00847334 a/b (3.0 mm), Sample Weight: 74.8 g, Area: 5 cm × 5 cm, Data Taking Time: 58 hrs. If the beam intensities variation or its drifts was fast and/or large, then the partial measurements were excluded from the total statistics. Atomic weight of natural Bi, AW: 208.980 u, Density: 9.8 g/cm^3.

The samples were placed at the place of sample changers holes and were cycled into the neutron beam. The positions of the samples were chosen in the sequences, ^{209}Bi, Open, Notch Filter [The notch filter was consist of three elements in one sheet and for this notch measurements we placed this notch filter in one position of the sample changer], and Open. The exposure time for the each sample was 15 minutes and for each Open it was 7.5 minutes. The interleaving sequence of open positions in the sample changer was chosen to minimize the influence of slow and / or the small variations in the neutron intensity.

4. Energy Resolution

For the energy resolution in percentage we can use the equation [14]

$$\frac{\Delta E}{E} = \frac{2}{L}\sqrt{(\Delta L)^2 + (1.91313 \times E \times \Delta t^2)} \tag{1}$$

where the uncertainty (Δt) of the neutron TOF (t) is expressed in μs and is composed of uncertainties due to the flight path (ΔL = 0.02 m), the moderator thickness (0.03 m), the pulse width of the electron beam (1 μs), the channel width of the time encoder (0.5 μs), and the time jitter (negligibly small) from the neutron detector. The energy resolutions for the neutron energy of 0.01, 0.1, 1.0, 10, 100, 200, 300 and 1000 eV are 0.598%, 0.599%, 0.603%, 1.008%, 2.633%, 3.676%, 4.482%, and 8.132%, respectively.

5. Background Estimation

To estimate the background we have used the Notch Filter, which was consists of natural Cobalt, Indium, and Cadmium sheets. We choose these elements as these nuclide possess number of resonance's that were completely opaque to the neutron beam and the resonances are clearly visible. We have taken the opaque resonance's channel numbers against their number of neutron counts. And then we have fitted these values with the first order exponential decay fitting function

$$y = y_0 + Ae^{-x/t} \tag{2}$$

where y_0 is offset, A is amplitude, t is the decay constant, and x is the channel number of the time digitizer. The fitting functions curve and TOF spectra for the Notch Filter and for the open beam are shown in Fig. 1 and 2.

The above polynomial fit was applied to the bottoms of the opaque resonances on a run by run basis and subtracted from the TOF spectra of measured sample ^{209}Bi and open run. The ^{209}Bi and open events spectra along-with the normalized fitted background spectra are given in Fig. 2.

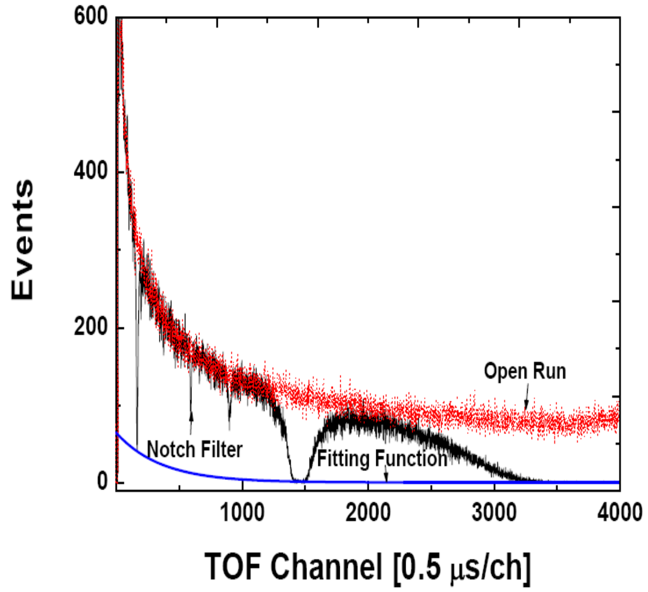

Fig. 1. The fitting function curve and TOF spectra for the Notch Filter and for the open beam.

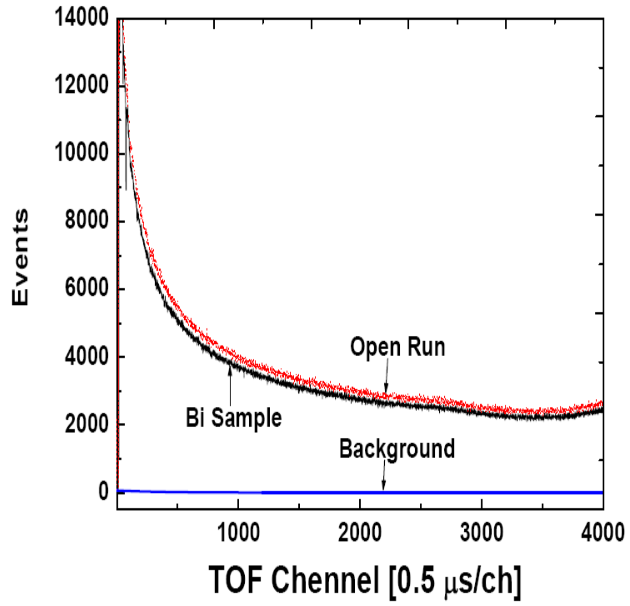

Fig. 2. The background fitted curve and TOF spectra for Bi and for the open beam.

6. Determination of cross-sections

The transmission rates can be used to determine the neutron total cross-sections. The transmissions coefficient is defined as the net ratio of the neutron counts for the sample and to the open beam. As the transmission and cross-sections are energy depended, so more accurately the transmissions coefficient (T) for the j-th group energy E_j can be defined as the fraction of incident neutrons passing through the sample compared to that in the open beam, and its mathematical expression is

$$T(E_j) = \frac{I(E_j) - BG(E_j)/M_I}{O(E_j) - BG(E_j)/M_o}, \tag{3}$$

where $I(E_j)$ and $O(E_j)$ are the foreground counts for the sample in and out; $BG(E_j)$ is the background counts for the sample in and sample out; M_I and M_o are the monitor counts for the sample in and open beam, respectively. In this measurement, we assumed the monitor counts to be equal. The above transmission coefficients can be used to measure the neutron total cross-sections and the expression is as follows:

$$\sigma_{Tot.}(E_j) = -\frac{1}{N_i} \ln T(E_J), \tag{4}$$

where N_i is the atomic density per square cm of the i-th isotope in the sample. The mean neutron total cross-sections of ^{209}Bi were calculated by the following equation:

$$\sigma_{Tot.Mean}(E_j) = \int \frac{\sigma_{Tot.}(E_j)}{\Delta E} dE. \tag{5}$$

The measured mean cross-sections from this experiment along with others experimental [1-12] and nuclear reaction data file ENDF/B-VII.0 [13] are shown in Figs. 3 and 4. The velocity weighted cross-sections are shown in Figs. 5 and 6.

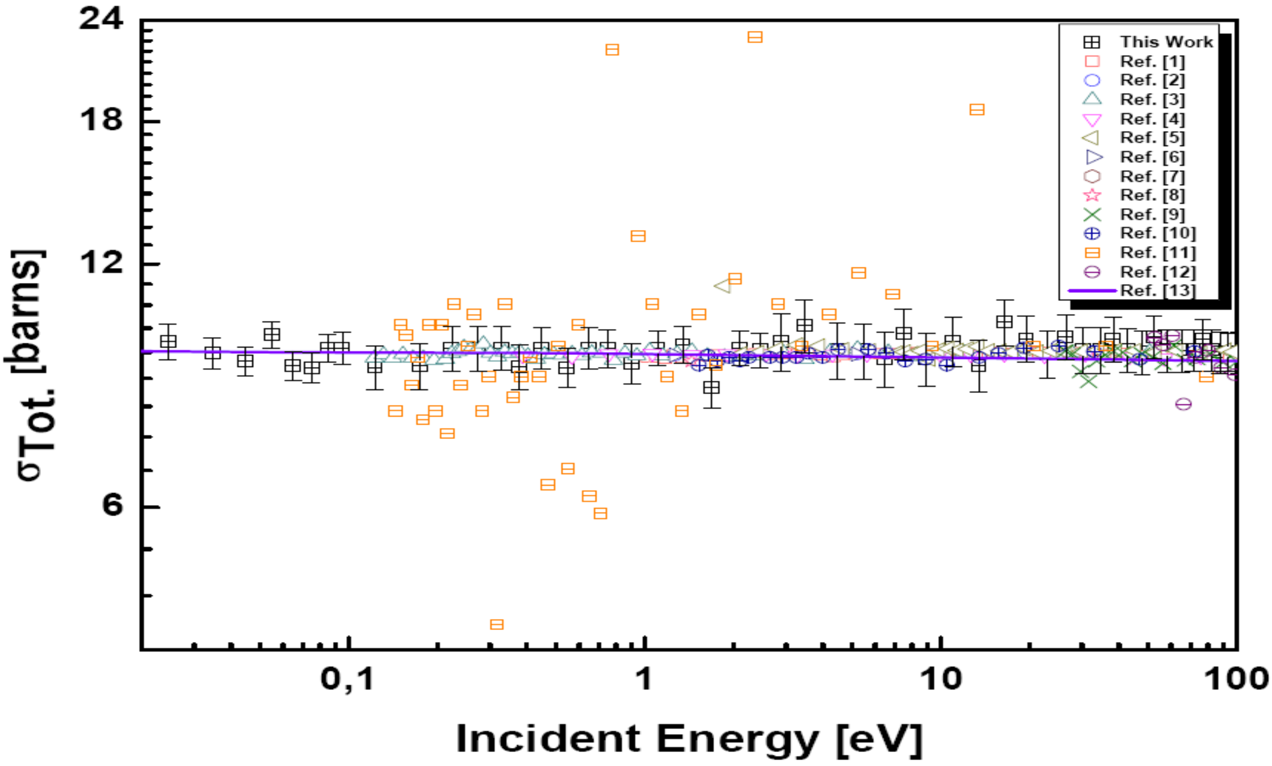

Fig. 3. ^{209}Bi(n,Tot.) cross-sections from 0.01 to 100 eV.

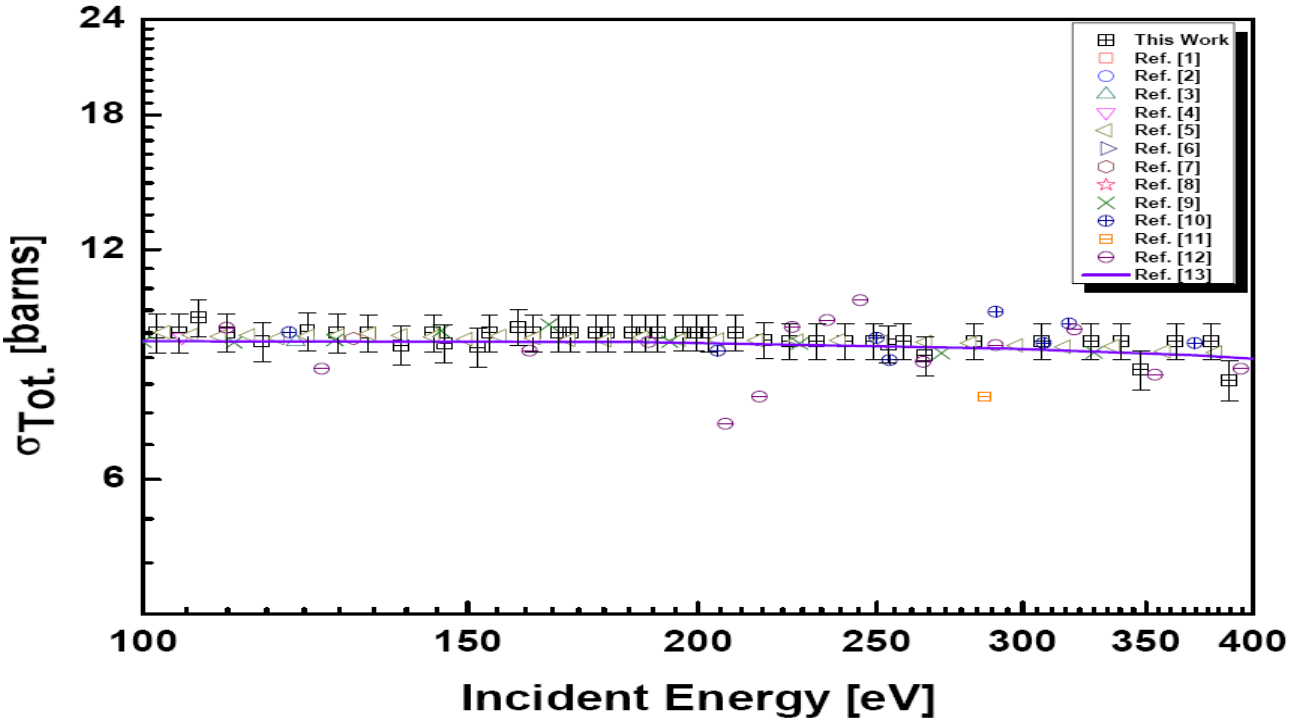

Fig. 4. ^{209}Bi(n,Tot.) cross-sections from 100 to 400 eV.

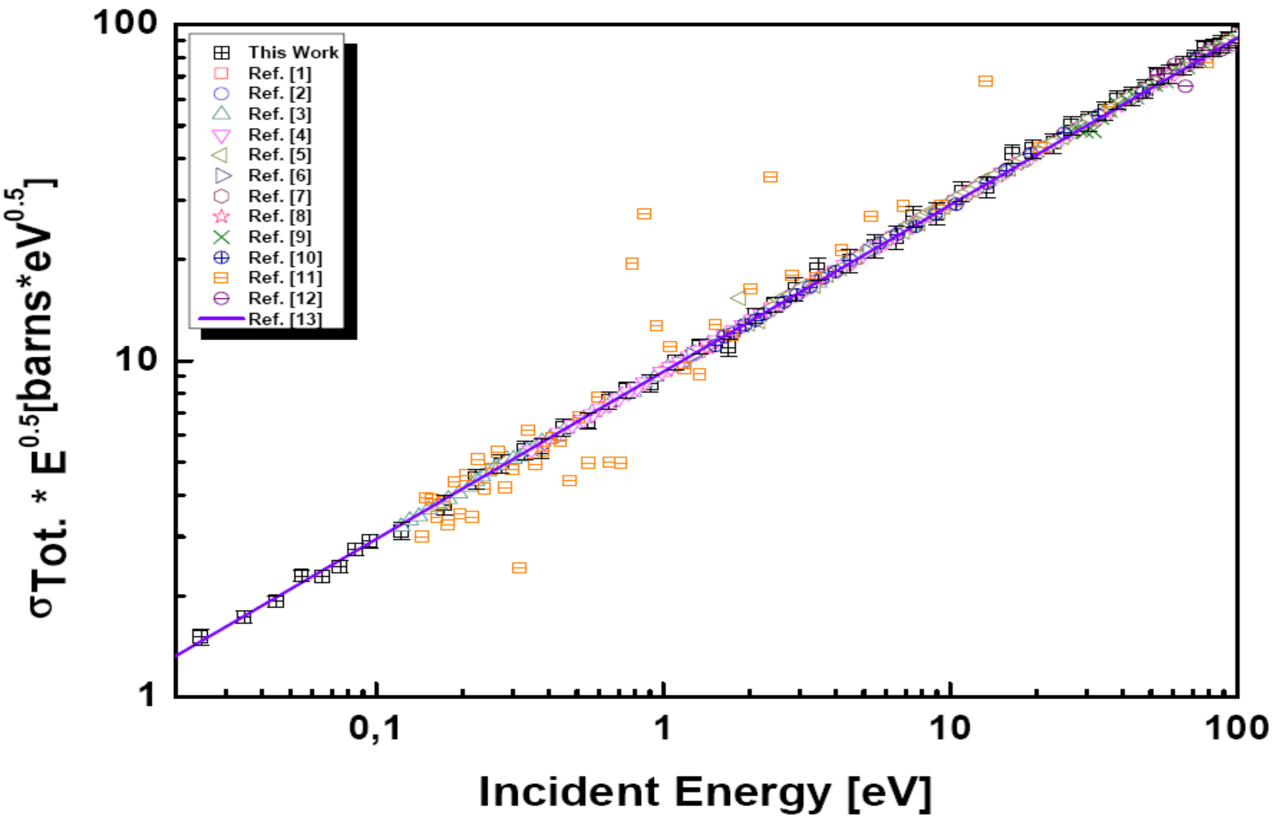

Fig. 5. Velocity weighted ^{209}Bi(n,Tot.) cross-sections from 0.01 to 100 eV.

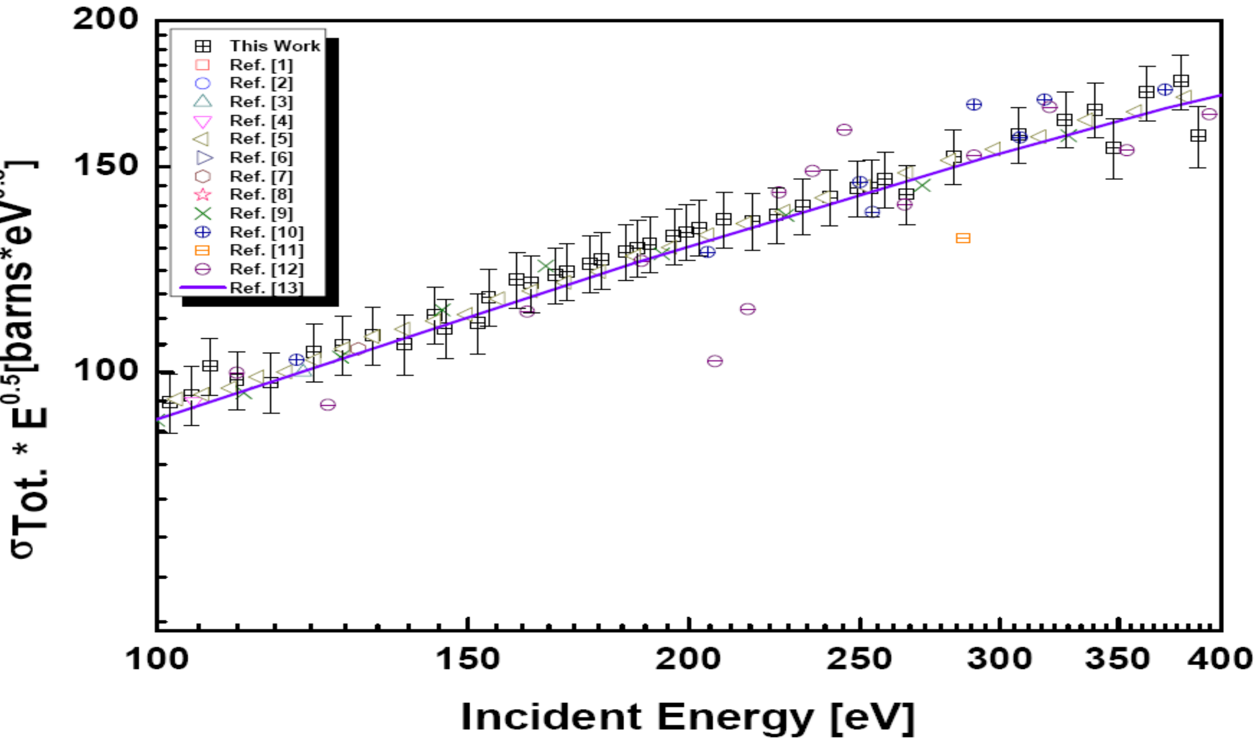

Fig. 6. Velocity weighted ^{209}Bi(n,Tot.) cross-sections from 100 to 400 eV.

7. Conclusions

The present works data for the neutron energies from 0.06 to 0.15 eV is slightly lower than ENDF/B-VII.0 and except this small region, the entire data are generally in well agreement with the all other existing data as well as data library ENDF/B-VII.0. The overall statistical uncertainties are less than 7%.

The elements which are single isotopes are particularly interesting since they may serve to confirm the theoretical predictions when the energy resolution is good [15]. The sample isotope ^{209}Bi contains 100% abundance. Therefore we selected ^{209}Bi and presented data are good agreement with calculated data library and EXFOR data. In a single reasonable resolutions facility we have measured ^{209}Bi(n,Tot.) cross-sections from very low (0.01 eV) to 400 eV so these new data may be used for different applications.

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