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1974 J. Phys. A: Math. Nucl. Gen. 7 L32

(http://iopscience.iop.org/0301-0015/7/3/002)

J. Phys. A: Math., Nucl. Gen., Vol. 7, No. 3, 1974. Printed in Great Britain. © 1974

LETTER TO THE EDITOR

Observation of neutron induced analogue resonances

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Received 8 January 1974

Abstract. Resonant structure has been observed in the zirconium total neutron cross section and in the $^{90}Zr(n, p)$ excitation function. It is interpreted as being due to states in ^{91}Zr which are isobaric analogues of the low-lying states in ^{91}Y.

The excitation of isobaric analogue states in the compound nucleus via the neutron channel is forbidden by the conservation of isospin. However, if the well known neutron decay of analogue states excited by protons (Robson *et al* 1965) is any indication, then it is quite possible that isospin mixing will allow analogue states to be excited by neutrons. To the present time there have been no experiments recorded in the literature which have observed this effect. This note discusses work which was undertaken with the specific aim of obtaining experimental evidence for or against the excitation of analogue states by neutrons.

A comprehensive survey of existing cross section data failed to reveal any conclusive evidence for the existence of neutron induced analogue resonances. The absence of any sign of analogue resonances in existing data of relatively high accuracy, for instance the measurements of Carlson and Barschall (1967), indicates that the resonant excursions must be expected to be very small. This point has a large bearing on the choice of a suitable target nucleus for the present investigation which concentrated on the twice forbidden total cross section and once forbidden (n, p) measurements. In making this choice the following criteria are important.

(i) Only those elements having a high natural abundance of one isotope are useful as targets.

(ii) The target nucleus should have zero spin in order to obtain large resonant excursions.

(iii) For this test case, it must be possible to predict with the minimum of error the neutron bombarding energies needed to excite the analogue states, since the identification of observed resonance anomalies as analogue states will depend largely on correlation with the predicted energies.

The target nucleus chosen was ^{90}Zr. The energies needed to excite the analogue resonances can be estimated to within ± 40 keV. This error does not include effects due to the negative energy shifts which are described in terms of the boundary matching problem in the *R*-matrix theory. It also does not account for variations in the Coulomb displacement energy, although in this case where the analogue states have an isobaric spin of $\frac{13}{2}$, these variations should be small. It is also important to note that the ^{91}Zr compound nucleus level density is quite high at the required excitation energies. This

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reduces the probability of statistical fluctuations masking the observation of analogue states.

A tritium gas target, bombarded by protons from the Melbourne University cyclotron produced mono-energetic neutrons of the required energies. The neutron energy spread was kept within the range 20 to 25 keV. Measurements of the interesting sections of the zirconium total neutron cross section were carried out using both $^{90}ZrO_2$† and natural zirconium‡ (^{90}Zr abundance 51·5%) transmission samples. The general techniques used in these measurements were very similar to those used at Wisconsin for many years (Davis and Noda 1969). However, the present approach does differ through the use of a 'twin detector' method. This 'twin detector' method has been used to achieve a high degree of relative stability in the counting equipment so that the accumulation of large numbers of counts, to obtain high statistical accuracy, becomes meaningful.

Each of the twin detectors consisted of a 2 in × 2 in NE213 liquid scintillator mounted on a 56AVP photomultiplier tube. To keep the relative efficiency of the detectors constant a common EHT supply was used, the detector gains were equalized and their output pulses fed into common electronics. Time of flight techniques were used to determine the detector from which a particular pulse had originated. The detectors were placed at equal small angles to the beam direction. At each energy a measurement was taken first with the transmission sample in front of one detector and then in front of the other. From these two measurements the square of the transmission was calculated rather than the transmission itself. In this way advantage could be taken of the symmetry of the geometry since any resonant effects, other than those due to the transmission sample, would in theory be cancelled.

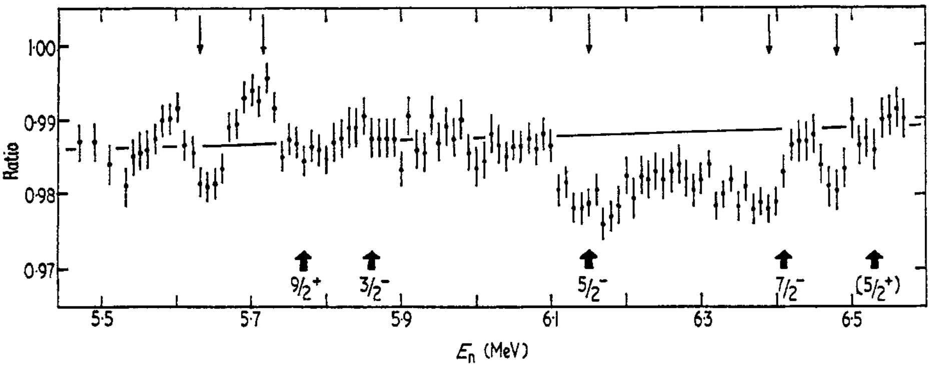

Figure 1. The ratio of the natural zirconium total cross section data obtained in the present experiment to the averaged data of Carlson and Barschall. The arrows along the top of the figure indicate the approximate energies of the observed resonances. The broad arrows indicate predicted energies of the analogues of the low-lying ^{91}Y states.

Figure 1 shows the composite results of the present measurements using the natural zirconium transmission sample relative to the zirconium total neutron cross section measured by Carlson and Barschall (1967) (see also Goldberg *et al* 1966) which has been smoothed with a 300 keV running average. The estimated relative error is ±0·3% or less where the plotted point is the average of more than one measurement. This

† Hired from Oak Ridge National Laboratories, Tennessee, USA.
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relative error is comprised of contributions, primarily due to counting statistics, but also arising from error of analysis and instabilities of the counting equipment. Displaying the results as a ratio reveals the approximate average trend of the data, as indicated by the straight line. This makes apparent the characteristic shapes of the resonances and establishes the approximate resonance energies. These energies are indicated by the arrows along the top of the figure. The structure, which was found to be repeatable, has been interpreted as five resonances. It is felt that the structure between 5·55 and 5·80 MeV is best interpreted as two separate resonances rather than a single interference shape. The predicted analogue resonance energies have been included for comparison and are indicated by the broad arrows along the bottom of the figure. It is worth noting that there is good agreement between the average trend of the total cross section, as measured here, and that measured by Carlson and Barschall (1967). The discrepancy in the absolute values is only slightly greater than 1 %.

The results of the measurements using the $^{90}ZrO_2$ transmission sample span the region from 5·08 to 5·91 MeV, which includes the predicted energy of 5·21 MeV for the analogue of the ^{91}Y ground state. No resonance was observed in this vicinity. However, the structure between 5·55 and 5·80 MeV was seen. The fact that this structure is common to the measurements using each of the transmission samples strongly supports the opinion that it is due to states in ^{91}Zr.

If the structure seen in the total cross section is indeed due to analogue states, then the (n, p) excitation function should show evidence of resonances similar to those which have been seen in (p, n) reactions via analogue states (Robson *et al* 1965). The $^{90}Zr(n, p)$ excitation function was measured using an ionization chamber in which one of the electrodes was a zirconium sheet. The charged particles produced in this electrode were primarily protons from the $^{90}Zr(n, p)$ reaction. A short section of the excitation function in the vicinity of 6·15 MeV was investigated. The two runs made in this region both showed evidence of a resonance. The combined data are plotted in figure 2, together with the total cross section data. There is a clear energy correlation

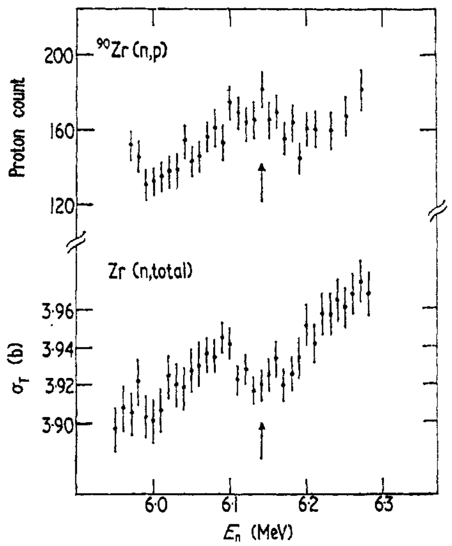

Figure 2. The combined data for the $^{90}Zr(n, p)$ excitation function near $E_n = 6·15$ MeV. The observed resonance correlates in energy with the resonance (dip) in the total cross section shown beneath it.

between the dip in the total cross section data and the resonance peak in the (n, p) excitation function.

The interpretation of the experiments can be summarized as follows. There are five resonances which can be reasonably associated with five of the analogues of the ^{91}Y states. The discrepancies in the energy correlation between the predicted and the observed positions of the resonance can be accounted for in terms of the negative energy shifts $\bar{\Delta}_\lambda$. Negative energy shifts of approximately 120 keV are needed to interpret the two resonances between 5·55 and 5·80 MeV as analogue resonances; negative energy shifts of this order of magnitude have been seen in previous analogue state studies (Lieb and Hausmann 1969). The fact that the ground state analogue resonance ($J = \frac{1}{2}$) has not been observed is not surprising as it has the smallest spin statistical factor of any of the resonances considered here. It is also important to note that the observed widths of the resonances are of the expected order of magnitude. Consequently, it is entirely plausible to interpret the resonant behaviour, seen in the present measurement of the zirconium total neutron cross section, as due to states in ^{91}Zr which are analogues of the low-lying states of ^{91}Y. This interpretation is given additional support from the results of the ^{90}Zr(n, p) measurement.

The resonant excursions seen in the present measurement are of the order of 1 % of the total cross section. Excursions of this magnitude imply that the neutron widths of the analogue states are an appreciable fraction of their total width. Preliminary theoretical studies within the framework of the Robson and Lane theory of analogue resonances (Robson and Lane 1967, Robson 1969) indicate that this is so and that the neutron width arises from external mixing. This is to some extent consistent with the conclusion reached by Richter *et al* (1972) for the ^{89}Y(α, n) ^{92}Nb reaction proceeding through analogue states. However, in that case it was considered that the mixing was more likely to occur in the α channel rather than in the neutron channel.

The theoretical aspects of the present investigations together with a more detailed description of the experiments will be presented in a later paper. It is hoped that this present letter will encourage the repetition of this type of experiment.

The authors wish to thank the Australian Atomic Energy Commission for their interest and support in the form of a research contract. One of us (GCH) also acknowledges the support of a Commonwealth Postgraduate Award.

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