Eur. Phys. J. A **10**, 69–71 (2001)

THE EUROPEAN PHYSICAL JOURNAL A

Fission probabilities across the π-nucleon delta resonance

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Received: 15 August 2000 / Revised version: 22 January 2000
Communicated by M. Garçon

Abstract. Cross-sections for the π^+-induced fission of ^{209}Bi and ^{235}U have been measured in small steps across the 3-3 resonance to search for any mechanisms that might signal a change in the reaction mechanism across a region where strong coupling of available energy into nuclear excitation can be expected. The bismuth data are found to be in good agreement with a statistical calculation not including new mechanisms.

PACS. 25.80.Hp Pion-induced reactions – 24.60.Dr Statistical Compound-nucleus reactions

1 Introduction

For a broad range of pion beam energies near the 3-3 resonance (around 160 MeV), the probability of the pion being fully absorbed adds the pion rest mass to the kinetic energy for the initial energy available to the nucleus. Retention of such energy could then lead to high nuclear excitations that could induce unanticipated reaction mechanisms. The efficiency of this absorption process is higher near this energy than that for higher beam energies, where absorption is less likely [1]. The large cross-sections and strong interactions of a delta excitation reacting in nuclei are also effective at coupling reaction energy to overall nuclear excitation, leading us to search for even a small signal of new reaction mechanisms in resonant energy pion reactions.

The method we use to search for such an effect is the study of the beam energy dependence of the probability of pion-induced fission for ^{209}Bi. Fission is the slowest nuclear decay channel, and proceeds from whatever system may be left after faster processes. Near ^{209}Bi, the probability of fission changes very rapidly as a function of the fissility Z^2/A for many projectiles (protons [2], photons [3], and pions [4,5]), but has been observed not to change much with the beam energy of pions inducing that fission [4,5]. Only large steps in beam energy, and methods not necessarily consistent in detail, were used for these previous studies with pions. If unanticipated reaction mechanisms were to occur, the fissility and the fission probability of the products of these mechanisms might change with beam energy if mass changes are generated.

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Here we study this possibility in a dedicated experiment, sensitive to even a small probability of such mechanisms, by measurment of fission cross-sections induced in ^{209}Bi by π^+-mesons. Absorption of the positive charge increases the fissility of the system, and brings the system nearer an equality of protons and neutrons.

2 Method and results

The π^+ beams were obtained from the EPICS channel of the Los Alamos Meson Physics Facility. The magnetic channel and its absorber system provided a very pure π^+ beam, with a momentum known to 5%. The fission study was carried out in the air just outside a relative beam monitor. Absolute normalization of the beam was carried out by a system using the ^{11}C radioactivity induced in plastic scintillators the size of the fission targets, and is reliable to 7% [6]. The same three thin ^{209}Bi foils (0.4 to 0.6 mg/cm^2) were used for all measurements. Fission fragments were detected both downstream and upstream of the samples with Makrofol plastic track detectors, as used in our previous studies [5,7]. The low-intensity secondary beam and the thin samples require a very efficient detector system such as this. For a few cases we also measured fragments emerging perpendicular to the beam. These cross-sections were averaged for the overall yield. Angular distributions of fission fragments from ^{209}Bi have previously been observed to be nearly isotropic [8]. Target thicknesses were measured by weighing before the exposure, and again by destroying the Bi and weighing after the study. Cross-sections previously reported at 150 MeV

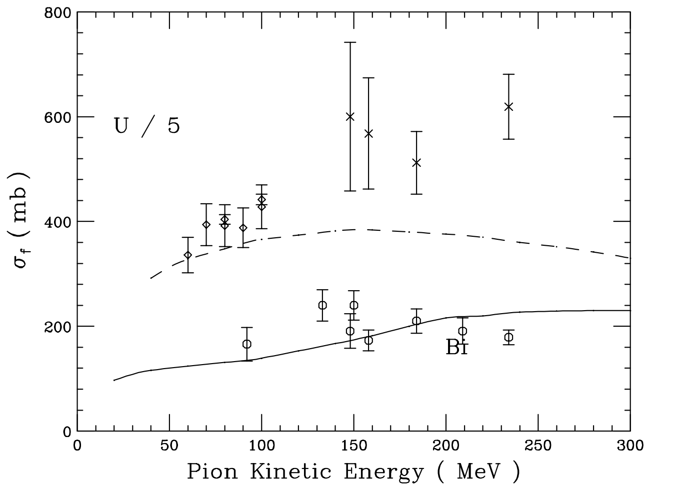

Fig. 1. Cross-sections measured for π^+ fission of Bi and U are shown. Crosses (^{235}U) and circles (Bi) are from the present work. Diamonds are for ^{238}U data from refs. [8] and [9], using different plastic track detectors and techniques. Solid and dashed curves for Bi and ^{238}U, respectively, show results of the statistical model calculations described in the text. Results for U are divided by 5 for clarity.

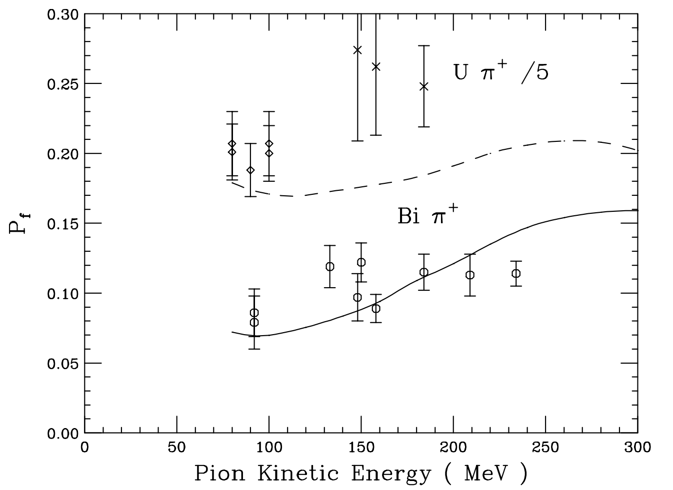

Fig. 2. Probabilities for π^+-induced fission of Bi and U are plotted, using computed cross-sections for the ratio. Data and curves are as in fig. 1.

[7] have been decreased by 13% to reflect the revised target thicknesses and are also included here.

The efficiency of the development and scanning process for the exposed Makrofol foils was determined by comparison to similar exposures to known strengths of spontaneous fission from ^{242}Pu. Analysis of track lengths in the Makrofol showed that the distributions for fragments from pions on our samples are very similar to that for fragments from ^{242}Pu [5]. Repeated counting of track densities by scanners gave a scatter in cross-sections of about 15%. These were averaged for the data shown.

Cross-sections for fission from ^{235}U were measured at the same time for some beam energies, so that the ^{209}Bi data may be compared to results for a system where the loss of significant mass due to new reactions before fission will not change the fission probabilities. The 20μg/cm^2 ^{235}U target was on a thick stainless-steel backing, and cross-sections were measured only downstream from the sample.

Cross-sections for fission induced by π^+-mesons from 92 to 234 MeV on ^{209}Bi and ^{235}U are shown in fig. 1. Data from earlier studies up to 100 MeV using a different detector foil are included, [8,9] but the track detector material and methods were not fully consistent with those used for the present study. Cross-sections reported for Bi at 138 MeV are now seen to be in error [10].

Fission probabilities are the ratios of these fission cross-sections to reaction cross-sections σ_R. Since such σ_R data are available at only a few beam energies for heavy targets [11], the denominators are here taken to be reaction cross-sections computed by a parameter-free optical model that has been successful in matching many pion-induced reaction observables across this energy range [12]. Distributions of neutrons and protons in ^{209}Bi and in U were taken to be the same in each nucleus, with parameters obtained by unfolding the nucleon size from measured charge distributions. The calculations have little sensitivity to these parameters. These impulse approximation calculations, which do not include the two-nucleon absorption channel, gave reaction cross-sections about 72% of those measured in ref. [11], where the data have uncertainties of about 20%. Other measurements of absorption cross-sections on heavy nuclei are about 84% of those from ref. [11], and thus nearer to the present calculations [13, 14].

Fission probabilities are plotted in fig. 2, where very flat energy dependences are seen for both Bi and U across this energy range including the 3-3 resonance.

3 Statistical model expectations

Cross-sections for π^+-induced fission of ^{209}Bi and ^{238}U were computed with the Cascade-Exciton Model (CEM), as recently improved and applied to a comprehensive study of fission of heavy nuclei by nucleons [15]. These calculations can provide a context which includes all relevant reaction processes except pion absorption and possible resulting unusual reaction mechanisms. Calculational parameters, save for one, were all the same as those found to give results in agreement with fission probabilities of ^{209}Bi and other nuclei for intermediate energy protons and neutrons [15]. Only the parameter B_s was changed, here using $B_s = 1.12$ for ^{209}Bi and 1.15 for ^{238}U. Proton-induced fission calculations for ^{209}Bi used $B_s = 1.18$, while $B_s = 1.12$ was required to match neutron fission of ^{209}Bi. This parameter is the ratio of the surface area of the fissioning nucleus to the surface area of an equivalent sphere, and enters the estimation of the level density parameters of fissioning nuclei at high excitation. The spherical ^{209}Bi ground state would have $B_s = 1.00$, while a saddle point would have $B_s > 1$.

Fission cross-sections computed with the CEM model are compared to the data in fig. 1. These closely match the magnitude and the energy dependence of the measured cross-sections for bismuth. Fission probabilities, using reaction cross-sections as above, also closely match the bismuth data. The comparison of calculations and data for ^{209}Bi cross-sections yields a $\chi^2/\mathrm{DOF} = 3.7$. CEM calculations for ^{238}U lie somewhat below the sparser data for ^{235}U. More detailed results of these calculations will be reported separately.

4 Conclusions

Pion absorption, delta formation and interactions peak at a pion beam energy near 160 MeV. If these couplings were to induce unexpected reaction mechanisms, we might expect fission cross-sections to show some new beam energy dependence. The present study was designed to test how much of the possible energy from the π^+ reaction is retained as by ^{209}Bi to create new mechanisms.

Absorption is the only reaction leading to fission for stopped π^-, where a fission probability of $8(1) \times 10^{-3}$ has been observed for Bi [16]. This datum lies far below the very flat trend for all energetic π^+ points seen in fig. 2.

We see no significant decrease in the energy dependence in the probability of π^+-induced fission of ^{209}Bi across the energy range where the coupling of the total pion energy to the nuclear system is strongest, indicating that no significant mechanism producing strong mass loss has occurred across this beam energy range. Such mass loss would result in smaller probabilities for fission. Rather, the data are in close agreement with calculations of a standard statistical model found also to be successful for fission induced by nucleon beams, where no absorption process is possible, with very similar parameters.

This work was supported in part by the US Department of Energy and the Brasilian CBPF. We thank A.J. Sierk for useful comments.

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