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ENERGY AND FLUX DETERMINATIONS OF HIGH-ENERGY NUCLEONS

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August 1969

Abstract

The fission track method is used to determine the energy and flux of neutrons and protons in the energy range above 50 to 100 MeV. Foils of U, Bi, Au, and Ta together with muscovite mica track detectors are exposed to nucleons of unknown high energy and flux. The effective energy of these nucleons is determined by comparing ratios of fission track densities of various targets (the ratios U/Au, U/Ta, and Bi/Au, for example) with calibration curves of energy versus track-density ratio. Knowing the effective energy, one can then select the appropriate cross section from experimentally determined cross-section curves, and can then determine an effective nucleon flux for the exposure conditions. This technique was tested using data from an experiment at the CERN P. S.; results were in good agreement with those from measurements of ^{11}C activity in plastic scintillators exposed under the same conditions.

Introduction

The fission track method offers a reliable and accurate way to measure the flux of neutron and proton fields at energies above 50 to 100 MeV as well as at low and intermediate energies. For monoenergetic particle fluxes, the procedure is quite straightforward. The flux integral can be obtained directly from the relationship

$$\rho = \phi \sigma n \epsilon$$

where ρ is the observed density of fission tracks per cm^2 in the detector material,

ϕ is the flux integral in particles/cm^2,

σ is the cross section for fission in the target foil at the specified particle energy in units of cm^2,

n is the number of target nuclei per cm^2 from among which a fission fragment can reach and register in the track-detector material (directly related to the range of fission fragments in the target material),

ϵ is the detector efficiency for registry of a fission track from this n-thick layer of the target (for our case, a value 0.5 for binary fission in foils that are infinitely thick with respect to fission fragment range.[1]

If, however, there is a distribution of particle energies, the relationship becomes

$$\rho = n\epsilon \int_{E\,min}^{E\,max} \phi(E)\,\sigma(E)\,dE,$$

and solution for $\phi(E)$ may be quite difficult, requiring a multiplicity of detectors characterized by different $\sigma(E)$'s and application of sophisticated mathematical techniques. (The reader is referred to an accompanying paper by J. Routti[2] for an extensive discussion of these matters.) Although we cannot obtain a complete description of such $\phi(E)$'s from one or two detectors, some quantities useful to health physicists can be derived from pairs of these detectors. In this report we discuss such application of the fission track technique, emphasizing a method that allows one to establish values for effective particle flux and effective particle energy of high-energy nucleon fields created by accelerator beam-target (or beam-loss) interactions.

Fission track detectors such as plastic, glass, or mica,[3] mounted on foils of materials which undergo fission, spallation, or fragmentation reactions, are exposed to high-energy nucleons, are then chemically etched to "materialize" the damage tracks, and are finally studied with an optical microscope. We prefer to use mica as a detector for two reasons: first, the diamond-shaped etch pits in mica are easier to distinguish than are the etch pits in plastic or glass; second, the etch pits in mica are caused only by fragments heavier than about mass 30, and are therefore more closely related to fission or other high-threshold energy interactions than are etch pits in plastic--where fragments of mass < 30 are registered.

Description of Method

Foils of U, Bi, Pb, Au, and Ta are good targets for high-energy nucleon detection. Their fission cross sections are high enough to furnish workable track densities from exposures of reasonable length and intensity. Cross section curves of U, Bi, Au, and Ta, as adapted for our use, are shown on Fig. 1. Some significant characteristics of the Fig. 1 curves include the following:

1. The Ta (fission) cross section increases substantially between 0.1 and at least 6 GeV;

2. The Au (fission) cross section increases appreciably between 0.1 and 0.7 GeV, then is reasonably constant at higher energies;

3. The Bi (fission) cross section increases between 0.1 and 0.7 GeV, then decreases at energies above about 1 GeV;

4. The U (fission) cross section curve is relatively flat at energies below 0.7 GeV, then has a negative slope at higher energies.

Therefore, because of these varying cross sections, one can determine an effective energy for incident particles by examining the ratios of track densities from combinations of detector pairs, for example U/Au, U/Ta, and Bi/Au. Curves of pair ratios versus incident particle energy can be constructed from calibration exposures in beams of known energy. Several sets of these curves are shown on Figs. 2, 3, and 4, based on the following sources of data:

1. Hudis and Katcoff (BNL),[4] who exposed sandwich arrays of mica coated with thin evaporated layers of U, Bi, Au, and Ag to proton beams of energies 0.6 to 29 GeV;

2. Kon'shin et al.,[5] who exposed glass detector-foil systems to proton beams of energies 280 to 660 MeV;

3. Wollenberg and Smith (LRL),[6] who exposed mica on foils of U, Bi, Au, and Ta to a beam of 5.5-Gev neutrons at the LRL Bevatron, and to beams of 230-MeV neutrons and 740-MeV protons at the LRL 184-inch cyclotron (we assume the fission response of these detectors to be the same for neutrons and protons at the energies considered here).

The LRL exposures included bare mica pieces to determine track densities on these "blank" faces as well as interior faces. This information provided a "background" value which was subtracted from track densities observed in the mica-target packages. Small adjustments (< 10%) were made in the LRL track density data to make it comparable with the data from the other sources noted above; these adjustments take into account the effect of fission fragment range and atomic mass number.

For the heavy elements, the fission component of the total reaction cross section predominates at energies below about 1 GeV, whereas at higher energies a substantial component is due to fragmentation* events. Hudis and Katcoff

*There is no general agreement regarding the distincition between the terms "spallation" and "fragmentation". As used here the terms carry the following

observed two populations of tracks: those associated with recognizable binary events (paired tracks registered in detectors on both sides of a thin target layer), and single tracks registered in only one detector. Because of the thickness of target foils, neither we nor Kon'shin et al. differentiated between paired and unpaired tracks.

The data used for the fission cross section curves in Fig. 1 are taken from Hudis and Katcoff's values for recognizable binary events and from undifferentiated track counts of Kon'shin et al. and the LRL authors. There is a good fit to the data points in the energy region below 1 GeV. The LRL-determined cross section value for Au at 5.5 GeV agrees closely with the line determined by Hudis and Katcoff points above 1 GeV energy. Our measured values for the Bi and U cross sections at 5.5 GeV (not shown on Fig. 1) lie somewhat below the appropriate curves in Fig. 1. This result is not well understood; one would expect an undifferentiated track count at this energy to contain an appreciable number of single (mainly fragmentation) as well as binary (fission) events, thus producing a high value for the cross section.

Plots of track density (or cross section) ratios versus incident particle energy are characteristics of exposure conditions. The plot of $\sigma U/\sigma$ Au vs E in Fig. 2 shows two distinct curves. The curve determined from binary events shows higher ratios for given energies than does the curve based on single and undifferentiated track densities. In the latter curve it is remarkable how closely points from widely different exposure conditions correspond to the drawn line. A similar situation exists on plots of σ Bi/σ Au vs E on Fig. 3. Again the curve for binary events indicates higher ratios for given energies than do the curves for undifferentiated and single events. Plots of cross section ratios versus energy of $\sigma U/\sigma$ Ta, σ Bi/σ Ta, and σ Au/σ Ta on Fig. 4 show well-defined curves based on Ta (fission) data of Kon'shin and our 5.5-GeV point.

The character of these curves is dependent upon a number of parameters, including those relating to the target-detector systems as well as those relating to the radiation field characteristics. It should be evident that if we are able to maintain constancy for the target-detector parameters, then curve characteristic variations must be due to radiation field parameters. Once sets of curves have been established from calibration exposures of standardized target-detector systems, the detectors can then be used to determine characteristics of unknown radiation fields.

For example, the effective energy of the incident particle flux can be determined from track density ratios of detector pairs, using Fig. 4. Then, appropriate cross sections for track production can be chosen, using the effective energy and Fig. 1. Finally, an effective flux can be calculated from these cross sections and the observed track densities. The effective flux determined here is defined simply to be: the flux of monoenergetic particles of the effective

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implications: Spallation generally occurs at the low end of the considered energy range; the reaction products consist of light nuclei that do not register in mica. Fragmentation occurs at the high-energy end of the considered range (above about 500 MeV); the reaction products consist partly of light nuclei that are massive enough to register in mica, but are not fission products in the usual sense of the term. Very simply, fragmentation can register in mica but spallation cannot; both can register in plastic.

energy that would produce the same track densities as were observed from the experimental conditions.

Although both effective flux and effective energy usually have fictitous values, these values are of considerable interest to the health physicist at high-energy accelerators. The angular distribution of secondary particles from a target (or beam-loss point) is an important parameter in many shielding problems, and the quantities derived here contribute significantly to the understanding of the true physical situation. The small size of detector-foil packages, their low sensitivity, and their complete freedom from irradiation rate dependence or postirradiation information loss, allow them to be used in large numbers close to high-intensity radiation sources.

We cite one application. Sets of Bi and Au detectors were used in the vicinity of an active target at the 28-GeV CERN proton synchrotron during the 1966 CERN-LRL-RHEL shielding experiment[7]. The detectors were located along a line above this target extending in a downstream (forward) direction over the next accelerator magnet. Detectors have an unobstructed view of the target ranged from 90 deg to 30 deg angular measure with respect to beam direction. Effective energies showed an increase from 240 to 700 MeV through this angular range, while effective flux integrals increased from 1.3×10^{10} to 3.3×10^{10} nucleons/cm^2 as the angle decreased. These flux integrals are to be compared with flux integrals obtained from plastic scintillators exposed simultaneously at the same locations; such detectors, which respond to nucleons of energies greater than 20 MeV via reactions of the type $^{12}C(n, 2n)^{11}C$, indicated values of 1.0×10^{10} to 3.3×10^{10} nucleons/cm^2 for the same angular range, showing the same sense of change in magnitude. The fission-track results are seen to be consistent with results from the well-established ^{11}C technique. Of course, the basic data from fission-track detectors can also be used in the threshold-detector scheme for neutron spectroscopy (see J. Routti[2,8]).

Low sensitivity can be a serious disadvantage for application of fission track detectors to many high-energy situations. Consider representative values for some of the important detector parameters. The fission fragment range in our heavy target elements is approximately 10 mg/cm^2, meaning that 2.5 to 3.0×10^{19} nuclei/cm^2 are available for fission from which fragments can reach the track-registry material. Given the track-registry efficiency of 0.5, and a fission cross section of 100 mb, it requires on the order of 10^6 particles/cm^2 to produce a track density of 1 track/cm^2. A manually operated optical microscope may employ viewing fields of areas ranging from 5×10^{-4} to 5×10^{-3} cm^2; it is clear that large areas cannot be scanned routinely by such a method, thereby imposing a severe restriction on low-flux determinations. Automatic scanning could relax this restriction considerably.

SUMMARY

The fission-track technique can be applied to measurement of the effective energy and the effective flux of a high-energy nucleon field. The method described is useful mainly in the high-intensity fields that typically exist near targets or beam-loss points at multi-hundred-MeV particle accelerators. Development of automatic scanning techniques is expected to extend utility of the method into lower-flux environments, although it is doubtful we will be able to apply the method in radiation fields of intensity as low as those defined to be safe for continuous occupancy. Finally, we note that U(fission), Th(fission),

and Bi(fission) all have thresholds below 100 MeV; thus the method is potentially useful at many medium-energy accelerators, that class of accelerator of major concern to this symposium.

ACKNOWLEDGMENTS

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This work was done under auspices of the U. S. Atomic Energy Commission.

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FIGURE CAPTIONS

Fig. 1. Fission cross sections versus energy of incident nucleon (neutron or proton) for targets of U, Bi, Au, and Ta.

Fig. 2. Track density (or cross section) ratios $\sigma U/\sigma Au$ versus energy of incident nucleon.

Fig. 3. Track density (or cross section) ratios $\sigma Bi/\sigma Au$ versus energy of incident nucleon.

Fig. 4. Track density (or cross section) ratios $\sigma U/\sigma Ta$, $\sigma Bi/\sigma Ta$, and $\sigma Au/\sigma Ta$ versus energy of incident nucleon.

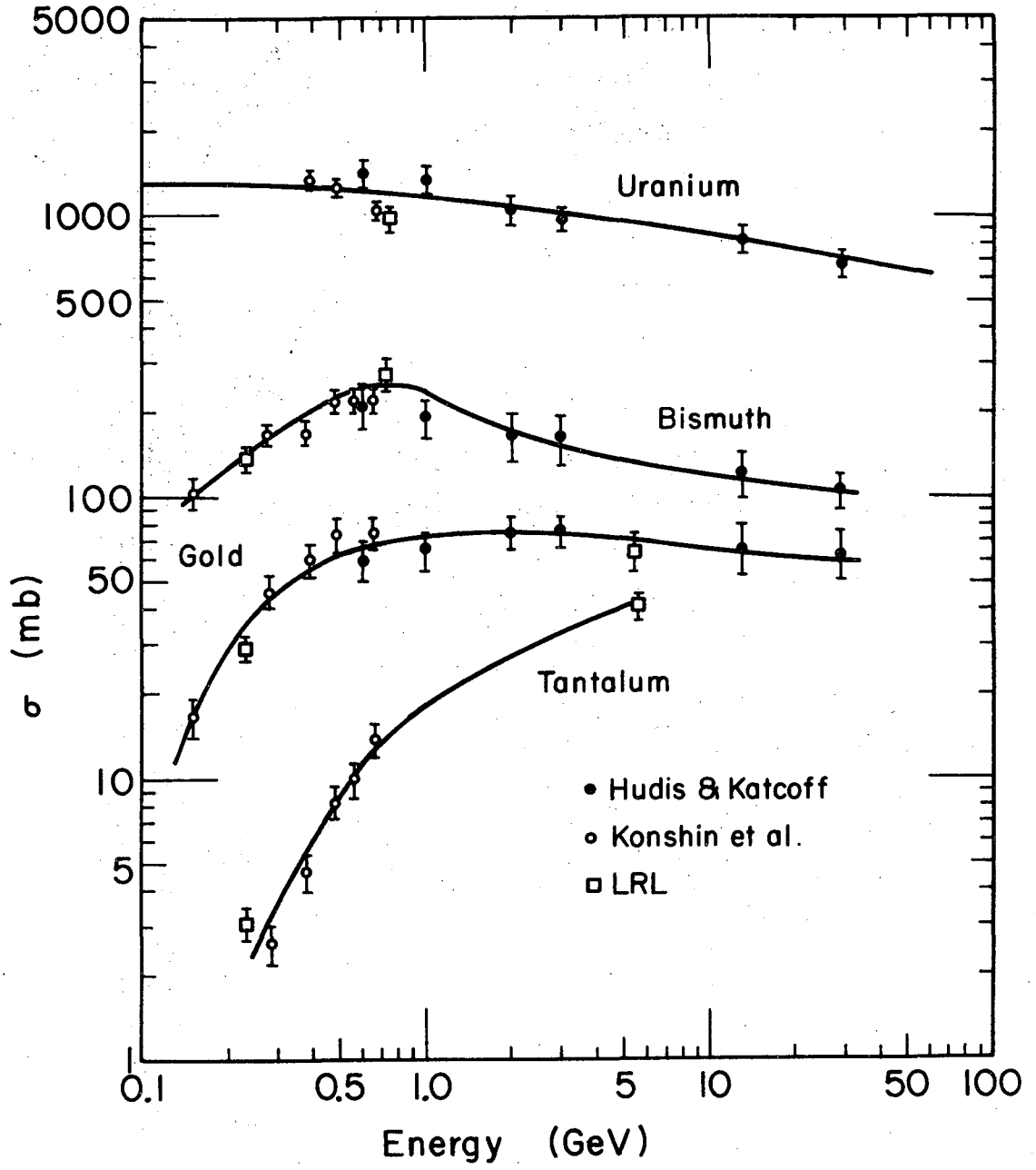

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Fig. 1

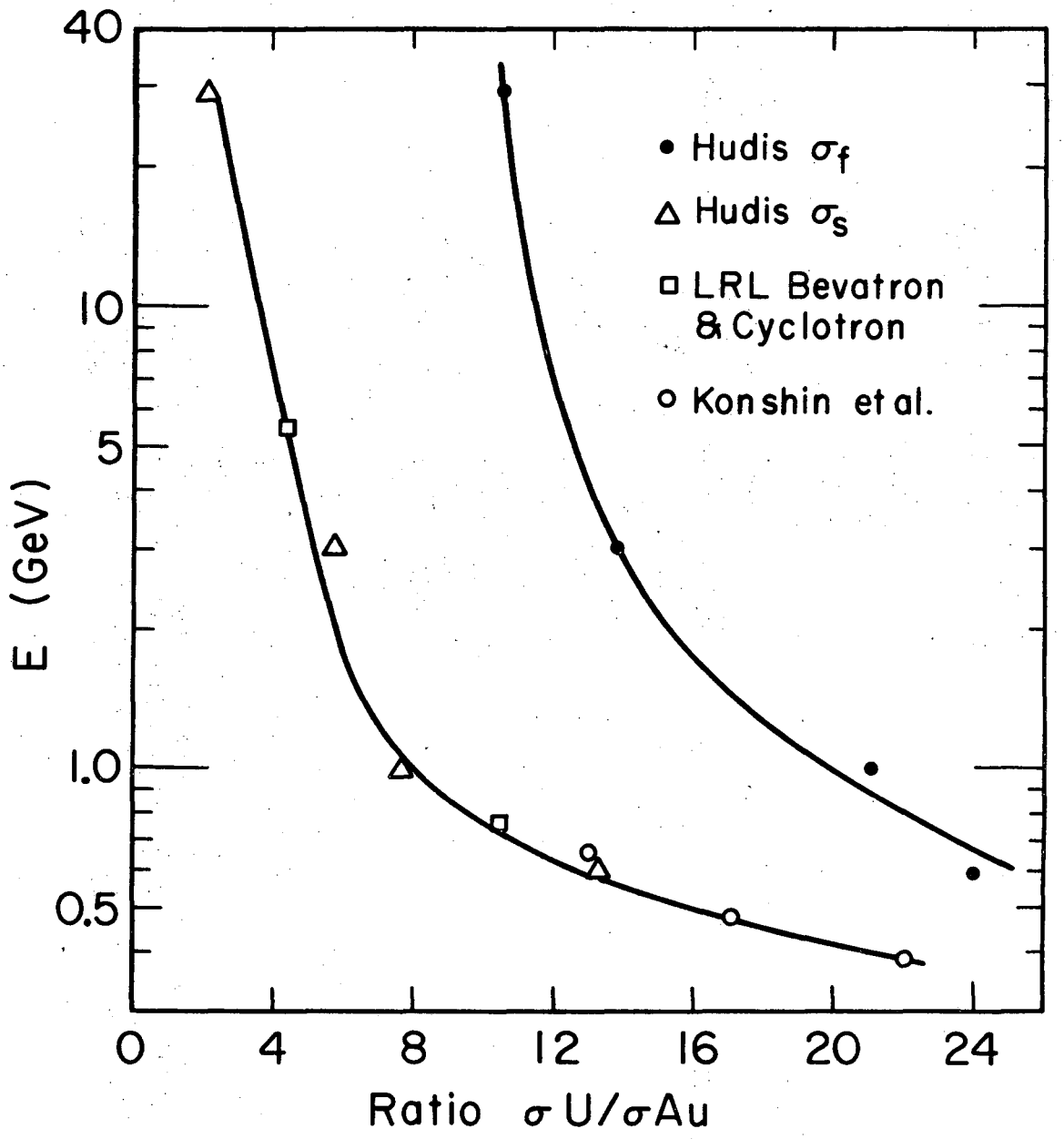

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Fig. 2

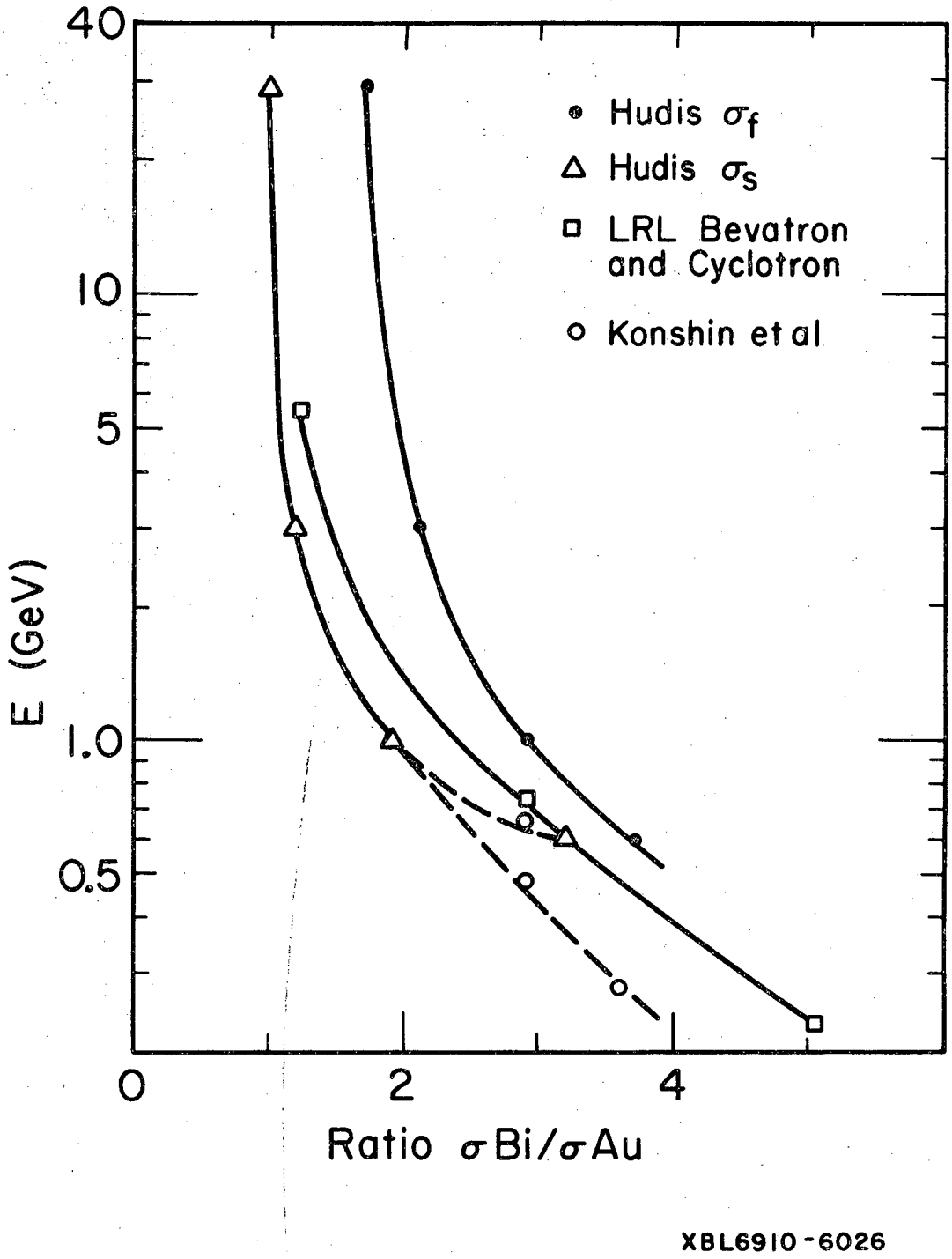
40
10
5
1.0
0.5
E (GeV)
0
2
4
Ratio σBi/σAu
Hudis σf
Hudis σs
LRL Bevatron and Cyclotron
Konshin et al
XBL6910-6026

Fig. 3

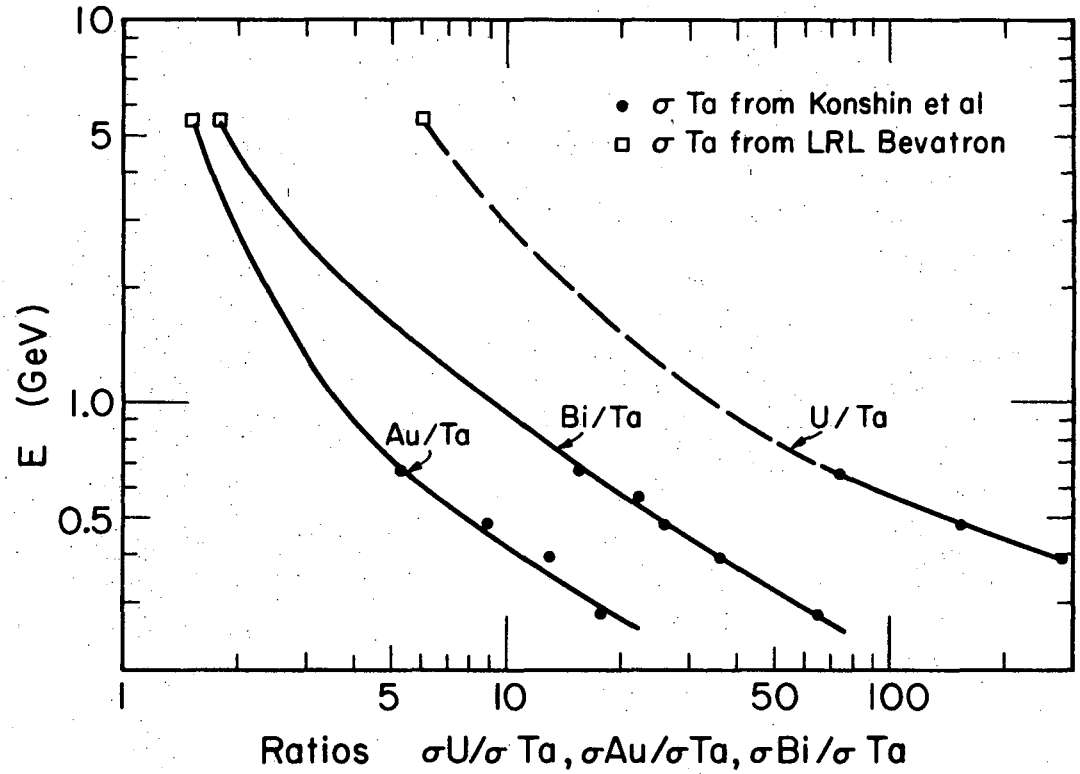

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Fig. 4

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