Bernard Peters and the composition of the cosmic radiation

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As a co-discoverer of the existence of extremely energetic heavy nuclei in the cosmic radiation Peters played a major role in measuring and understanding the significance of the chemical composition of the lighter nuclei in the radiation. The determination of the relative abundances of those elements between lithium and fluorine established our first estimates of the mean amount of matter traversed by the cosmic radiation in the interstellar medium. The modern continuation of this work has allowed us to estimate the mean density of the matter traversed and the mean lifetimes of the particles in the galaxy. Similarly his initial studies of the nuclear interactions produced by these nuclei with heavy target nuclei initiated a field of research that has become of major importance recently.

The discovery of the existence of heavy nuclei in the primary cosmic radiation was first reported in 1948 by Peters and colleagues[1] at the universities of Rochester and Minnesota. The presence of these nuclei in the cosmic radiation had not been generally anticipated, although there had been an early and, in hindsight, entirely reasonable prediction in 1939 by Alfven[2] that such nuclei should be present in the cosmic radiation. The detection of these nuclei came from the analysis of some of the first sensitive nuclear photographic emulsions to be flown on balloons to an altitude where a significant number of these nuclei, with their large nuclear cross-sections, could survive their passage through the residual atmosphere above the balloon. Some recollections of the excitement of this discovery can be found in the articles by Freier[3] and Ney[4] reported at a meeting held in Minneapolis in 1988 to commemorate the 40th anniversary of the initial observations. (Although Peters was unable to attend this meeting he did send a contribution discussing the relation of cosmic radiation to physics, astrophysics and cosmology[5].)

After the initial discovery of the heavy nuclei, Peters and Bradt[6-8], who were at the University of Rochester at this time, published a series of papers on the characteristics of these nuclei, as did the Minnesota group of Freier *et al.*[9] In their papers Bradt and Peters devised procedures to determine the charges of the individual particles which permitted them to estimate the elemental abundances, and initiated a discussion of the astrophysical significance of the relative abundances of these nuclei in the cosmic radiation that has continued to the present day. They also observed the first nuclear interactions of relativistic heavy nuclei with the nuclei of the nuclear emulsions, thus initiating a study of relativistic nucleus–nucleus interactions, a topic that, with the relatively recent advent of accelerators capable of producing beams of relativistic heavy ions, is currently one under active experimental study.

Relative abundances of elemental groups

The most important astrophysical question that was addressed by these early observations was provided by a study of the relative abundances of the various groups of elements present in the radiation. The interpretation of the abundances of the nuclides in the cosmic radiation depends on three main factors: firstly, the precision of the measured abundances themselves; secondly, the establishment of a well-determined comparison set of abundances appropriate to some astrophysical situation, such as the solar-system abundances; and finally, on an evaluation of the effects of acceleration and propagation of the nuclei from the source to the vicinity of the earth. Of these three factors none are completely satisfactorily defined as yet. However, steady progress has been made on all three fronts. A comparison of the measured cosmic-ray abundances with the abundances of matter in other astrophysical samples could be expected to provide a much deeper understanding of the nature of the cosmic radiation.

It was this question that led to the first major controversy in this field. Bradt and Peters[10-12] had reported that the abundance of the light elements, ^{3}Li, ^{4}Be and ^{5}B, the 'L-nuclei', was much less than that of

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the heavier elements, being consistent with a complete absence of L-nuclei in the primary cosmic radiation. The L-nuclei that they did detect in their emulsions were assumed to have been produced in the 10 to 15 $\mathrm{g\,cm^{-2}}$ of atmospheric matter overlying the emulsions when they were exposed on balloons. The conclusion that L-nuclei were rare in the primary cosmic rays was of considerable astrophysical interest, since these elements were already known to be very rare in the material out of which the solar system was formed and in the so-called cosmic abundances, e.g. Grevesse and Anders[13]. On the other hand, the Bristol group[14,15] reported from their analysis of emulsions exposed to the cosmic radiation, that these elements were just as abundant as the heavier ^{6}C, ^{7}N, ^{8}O and ^{9}F, the 'M-nuclei' elements, which are the most abundant elements in the solar system, apart from hydrogen and helium. In these analyses the production of L-nuclei in the overlying atmosphere was assumed to be less important, so that the majority of those observed were considered to be part of the primary beam. This result implied that the cosmic-ray nuclei either originate in sources with very different chemical abundances than those in the Sun and other main sequence stars, or indeed in any known source, or that there has been a great deal of fragmentation of the heavier nuclei by nuclear interactions occurring during the propagation of the cosmic rays through matter between the source and us. This latter assumption implies that the nuclei in the cosmic radiation must have traversed a significant amount of matter during propagation and that, consequently, they can have a galactic or extragalactic origin, rather than having been produced relatively locally.

The importance of obtaining a definitive result led to further measurements, both at Bristol[16,17] and Minnesota[18], which showed that indeed there was a finite but relatively small abundance of primary light nuclei, with the ratio of the L- to M-nuclei at the top of the atmosphere having a value between 0.35 and 0.20. These studies were actively followed in the sixties, with major contributions from many workers, including the Bombay group under the overall direction of Peters[19-21] and NRL[22]. Peters interest in this topic continued after he moved to Denmark, e.g. the study by Byrnak[23] acknowledges the interest shown by Peters.

Since those early measurements detectors have greatly improved. Electronic detectors capable of gathering greater statistics and with higher charge resolution have replaced the nuclear emulsions used by Peters and all the early workers. These detectors are now exposed either completely above the atmosphere, in satellites or space probes, or on very high-altitude balloons where the corrections for the 2 to 3 $\mathrm{g\,cm^{-2}}$ of residual atmosphere are relatively unimportant. Hence, our current knowledge of the abundances of the elements, and even of some of the individual isotopes, is now quite detailed and enables us to test various scenarios of source abundances and acceleration biases.

By the late sixties the L/M abundance ratio had been measured over a significant range of energies by the New Hampshire group[24], although, as is shown in Figure 1, there were still some unresolved systematic effects. In this figure a comparison of results from two measurements made a decade ago show that the earlier studies[24] still produced values for L/M that were significantly higher than those reported later[25]. Nevertheless, with the improved detectors attention was turning to measuring the abundances of the individual elements, since it was only from these that some of the more interesting questions about the cosmic radiation could be answered.

Individual elemental abundances

The assumption that the observed L-nuclei are all secondary in nature, having been produced by the fragmentation of the heavier nuclei during propagation, made it possible to derive a value of some 4 $\mathrm{g\,cm^{-2}}$ for the mean amount of matter that is traversed by the cosmic-ray nuclei, after they are accelerated to energies at which they can make nuclear interactions. This result could be compared with the values of about 2 $\mathrm{g\,cm^{-2}}$ derived from a similar analysis of the production of heavier secondary nuclei, such as those in the 'sub-iron' group, scandium to manganese, $21 \leqslant Z \leqslant 25$, produced

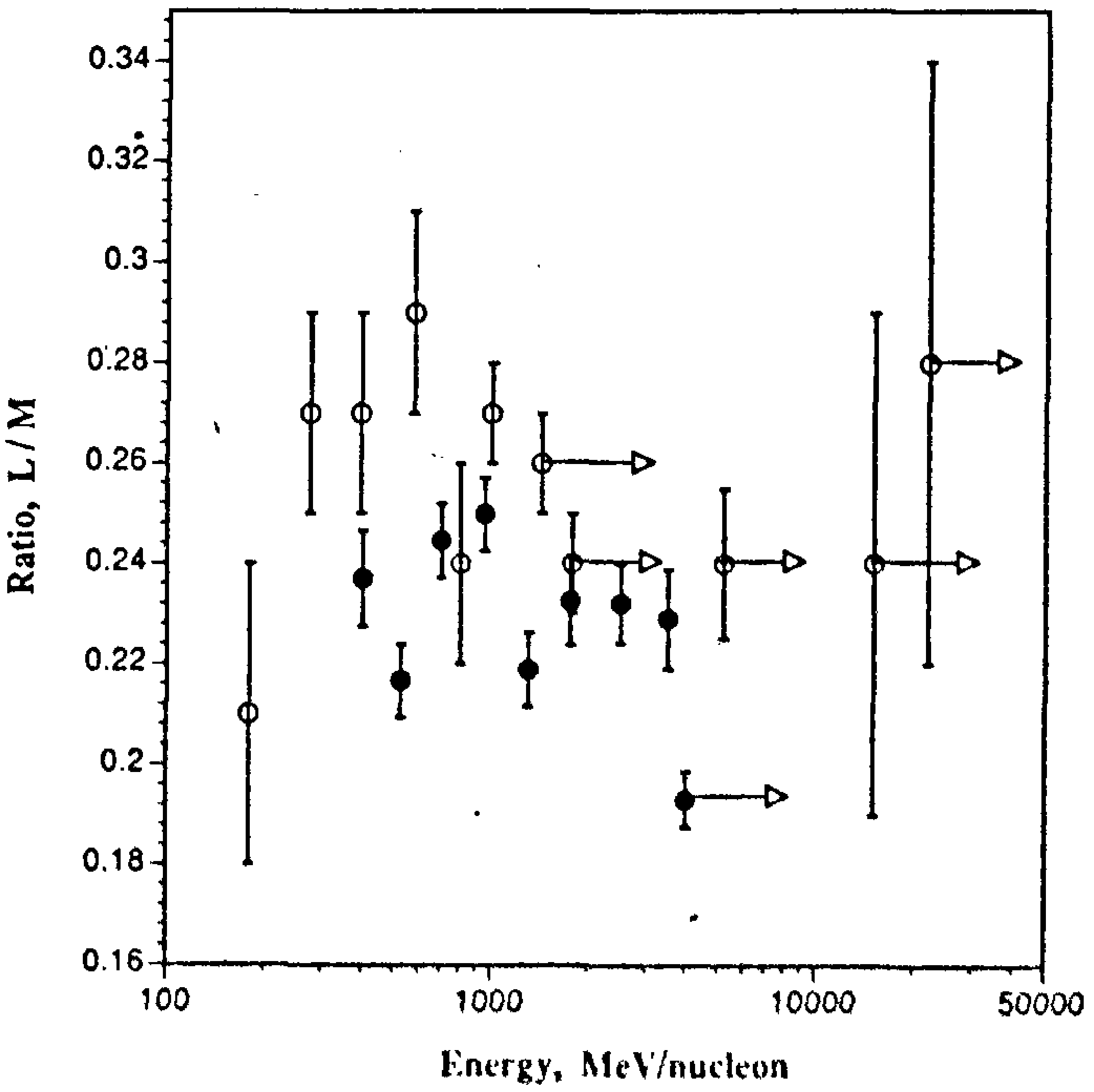

Figure 1. Abundance ratio of L- to M-nuclei measured as a function of energy by electronic detectors. Integral values are shown with right-pointing arrows. Open circles are results from ref. 24, closed circles from ref. 25.

by the fragmentation of iron and nickel primary nuclei, which have significantly larger interaction cross-sections than the L- or M-nuclei. The markedly different path lengths found for these two groups of secondary elements led to the development of the current model of propagation in which the path lengths show a distribution that is described by having a fundamentally exponential form[26], with a characteristic length of some 5 to 6 $\mathrm{g\,cm^{-2}}$. The questions of the density of the matter through which the nuclei propagate and how this matter is distributed are intertwined with the time for which the nuclei are assumed to have been travelling since they were accelerated. This quantity, the 'age' of the cosmic-ray nuclei, can only be addressed directly if some chronometer can be found that provides a measure of the flight time of the cosmic-ray nuclei. Fortunately, there are some radioactive isotopes that have the capability of acting as such chronometers.

In particular, among the L-nuclei the isotope ^{10}Be has a straightforward β-decay into ^{10}B with a half-life that is in the range of interest, 1.6×10^6 years. In principle, therefore, if one can calculate the relative production rates of Be and B from fragmentation of the heavier nuclei, one should observe an elemental ratio of Be to B that depends on the lifetime of the cosmic radiation. Furthermore, since the decay rate will be relativistically dilated, the observed ratio should be energy-dependent. In practice, the production calculations are strongly dependent on poorly known nuclear parameters, and since ^{10}Be has a relatively small, and energy-dependent, production cross-section, very sensitive to the assumed values of the cross-sections. In addition, the energy dependence of the Be/B ratio is further confused at low energies by the presence of ^{7}Be, which decays by electron capture, and hence has a decay rate which depends on the relative probabilities for electron pickup and stripping, which are strongly energy-dependent, being essentially stable in the cosmic rays at energies above about a hundred MeV per nucleon. More serious, since most of the measurements have been made at higher energies, was the fact that different measurements of the Be/B ratio were not in very good agreement, Figure 2, and certainly had a scatter that was too great to allow any reliable conclusions to be drawn as to whether most of the relatively small amount of the ^{10}Be produced during flight had decayed.

Isotopic abundances

It was, therefore, necessary to improve the detectors to a level at which they could resolve the individual isotopes, and, since ^{10}Be turns out to be relatively rare in the primary cosmic rays, to be able to resolve a small abundance peak of ^{10}Be from the much larger peak due to the ^{9}Be. The mass resolution of isotopes of nuclei moving with relativistic energies is not technically simple, and reliable measurements thus far have been restricted to relatively low-energy nuclei, those with energies less than about 500 MeV per nucleon, which can either be brought to rest in the detectors, or rather easily deflected in magnetic fields. The available measurements, all of which were made a decade or more ago, are shown in Figure 3, which is based on a recent survey by Mewaldt[27]. These observations can be interpreted if we adopt a 'standard' model in which the propagation occurs in a homogeneous medium after

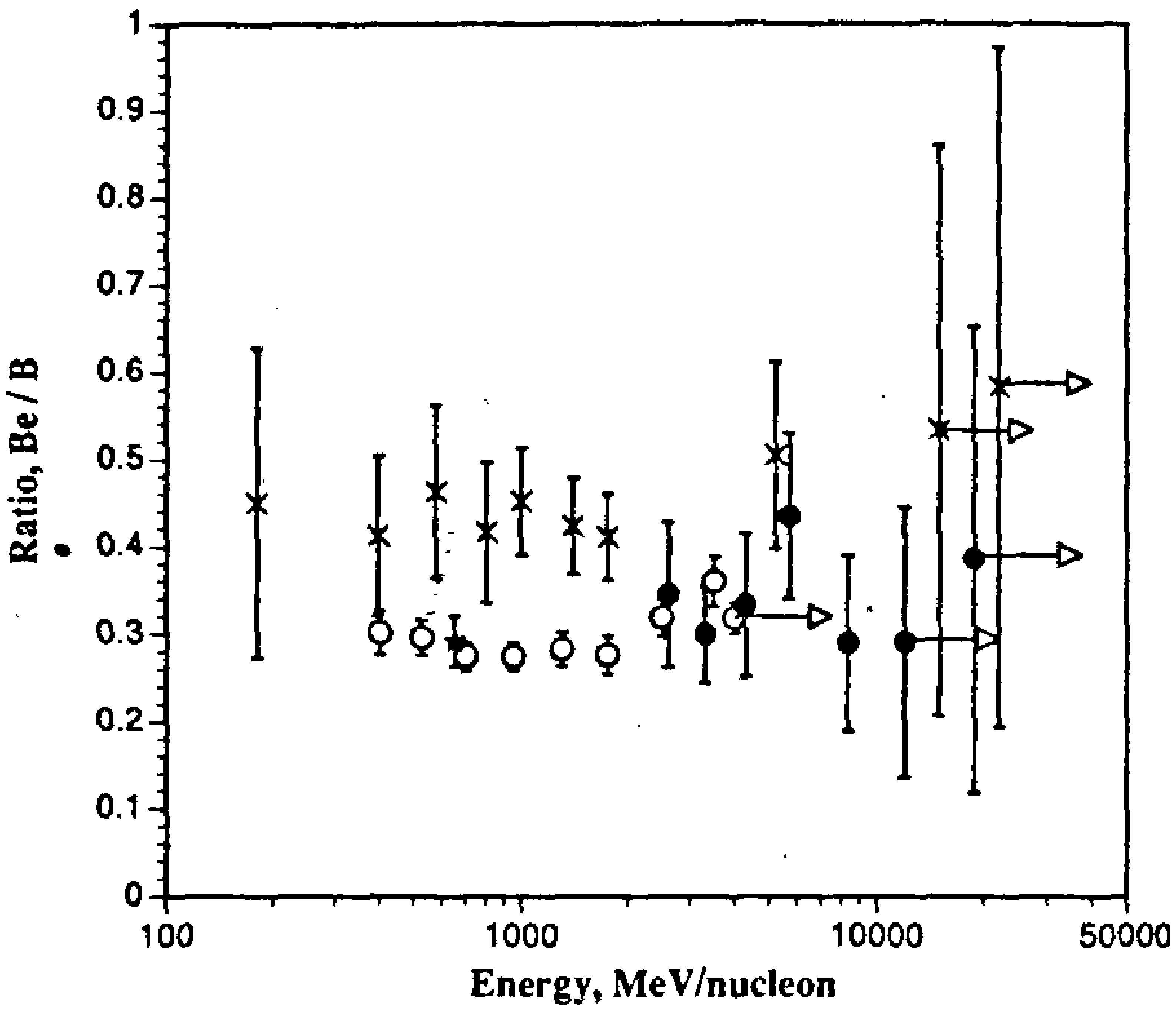

Figure 2. Abundance ratio of beryllium (Be) to boron (B) as a function of energy. Crosses from ref. 24, open circles from ref. 25, closed circles from ref. 31 and star from ref. 23.

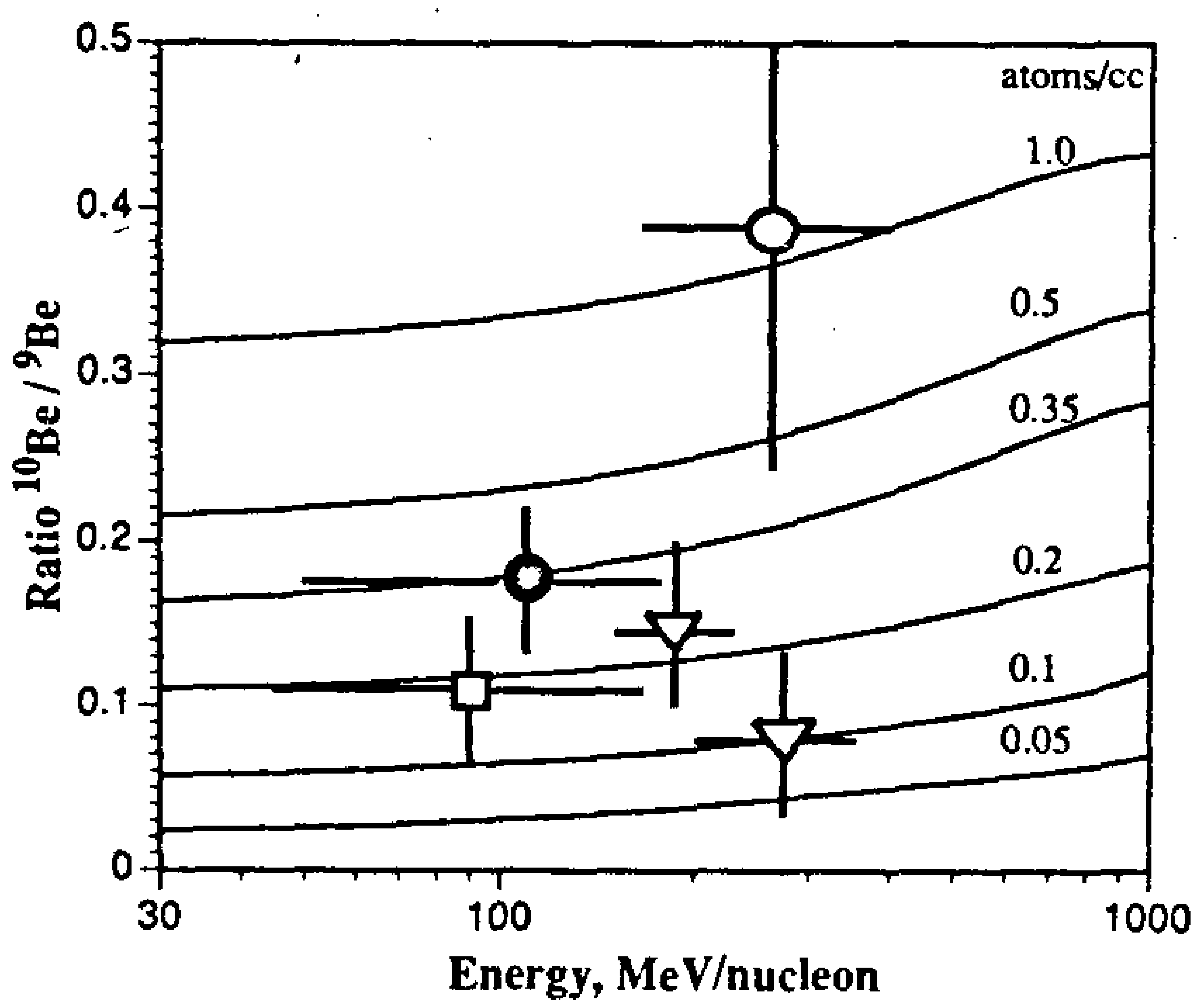

Figure 3. Abundance ratio of ^{10}Be to ^{9}Be as a function of energy. Curves from ref. 28, closed circle from ref. 30, open square from ref. 29, open triangles from ref. 32 and open circle from ref. 33.

acceleration and is characterized by an exponential distribution of potential path lengths. The curves shown in Figure 3 represent the energy sensitivity of the ^{10}Be/^{9}Be ratio for different assumptions on the mean density of the interstellar medium[28]. It can be seen that the observations are generally consistent with a mean density of ≈ 0.2 atoms cm^{-3}, considerably less than the normally assumed value for the matter in the galactic plane of ≈ 1.0 g cm^{-3}. Given that the mean path length for escape from the galaxy is estimated from the abundances of the secondary elements in the cosmic radiation to be ≈ 6 g cm^{-2}, this corresponds to a lifetime of 10–15 million years[27,29,30].

These conclusions are model-dependent and not as yet well defined observationally. Clearly it is important to improve the precision of the measurements and to extend them to higher energies. This will allow the models to be refined and the processes of propagation and storage in the galaxy to be better delineated. After a decade-long hiatus in this study due to a lack of new space opportunities there is now reason to expect that new results will be forthcoming in the near future. This field of research, co-founded by Peters more than forty years ago, is still active and still has questions that need to be answered. I feel sure that this is how Peters wants it to be.

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