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Nuclear Reaction Data and Nuclear Reactors: Physics, Design and Safety

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Nuclear Data and Nuclear Models in 21st Century

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Workshop on Nuclear Reaction Data and Nuclear Reactors: *Physics, Design and Safety*

Nuclear Data and Nuclear Models in 21st Century

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> *A hundred years ago, some of the great physicist in England and Continental Europe predicted that physics was at an end. We know what actually happened...*
>
> *Looking at the predictions of 100 years ago, it would be foolish to make predictions for the next 100 years.*
>
> Hans A. Bethe
> 100 years of American Physical Society
> Rev. Mod. Phys, **71** (1999) 3

The following topics are considered in the lectures:
Current status of nuclear data;
Nuclear power: towards sustainable development;
Transmutation of nuclear waste;
Nuclear models for nuclear data evaluations;
Radioactive beams and exotic nuclei;
Medical applications;
Data for material analysis;
Nuclear data needs for nuclear astrophysics;
Appendix: Dark matter.

Current status of nuclear data

Modern nuclear installations and applications have reached a high degree of sophistication. The effective design and the safe and economical operation of these complex technologies require detailed and reliable design calculations. These calculations offer a valuable supplement to large-scale mock-up experiments by providing very detailed information about system behavior under both normal and off-normal conditions at a fraction of the cost of experiments. While simulation calculations are becoming more and more economical with the rapid advances in computer technology, the accuracy of these calculations is largely determined now, as in the past, by the accuracy of the nuclear and atomic input data.

Very detailed data are required to design a modern nuclear reactor for electricity production and to make decisions regarding the operation of the associated fuel cycle. These designs must conform with strict safety regulations and still remain cost effective. One can identify the following specializations that rely on the availability of accurate nuclear and atomic data:

fission reactor design,
nuclear fuel cycles ,
nuclear safety,
nuclear safeguards,
reactor monitoring and decommission,
waste disposal and transmutation.

There are also many nuclear applications outside the field of fission reactor technology that are of growing economic significance and that have substantial data requirements. These include:

nuclear astrophysics,
accelerator shield design,
radiation damage studies,
fusion device design and plasma processing technologies,
personnel dosimetry and radiation safety,
environmental monitoring and clean-up,
production of radioisotopes for medical and industrial
cancer radiotherapy,
chemical analysis by activation methods,
detection of concealed explosives and illegal drugs,
exploration for oil and other minerals applications.

Data Measurement: Traditionally, much of the nuclear and atomic data needed in applications has been obtained by direct measurement. These expensive and demanding measurements are performed using particle accelerators and sophisticated radiation detectors. Thus far, approximately 5 million nuclear data points have been measured and compiled into computerized form. Because of the large cost of these experiments and the large number of possible combinations of target, projectile, projectile energy, reaction product, and product energy and angle, it is not possible to measure and compile all data needed for all times. One is forced to concentrate on the data that are important for specific current applications. For this reason, the experimental database is much more complete for fission power applications than it is for fusion and for non-power applications.

Data Compilation: After measurement, it is necessary to compile the measured data into standardized computer databases, such as EXFOR and ALADDIN for further processing and application. The large task of data compilation is performed by the Nuclear Data Centers. There is a network of 13 Nuclear Reaction Data Centers, major of which are the US National Nuclear Data Center (BNL, Brookhaven), OECD NEA Data Bank (Paris), IAEA Nuclear Data Section (Vienna), Russian Nuclear Data Center (IPPE, Obninsk).,).

Numerical data related to nuclear structure are available in the ENSDF databases, and bibliographic information on nuclear structure is found in the NSR database. The NSDD Network includes 23 zNuclear Structure and Decay Data Groups and Centers, which are responsible for the evaluation of all the mass-chains on a continual basis. ENSDF contains evaluated experimental data summarizing the present knowledge on the structure and decay of nuclei. It contains information on nuclear level properties, radiations, radioactive decay, and reaction data for all known nuclides. For masses A>=45, this information is documented in the *Nuclear Data Sheets*; for A < 45 ENSDF is based on compilations published in the journal *Nuclear Physics*. If there are gaps in experimental data, they are not filled with theoretical or nuclear model calculations.

The new nwtwork for astrophysical nuclear data was developed intensively during the last years.

Data Evaluation: After measurement and compilation, it is necessary to evaluate the compiled data to arrive at tables of recommended values, which is the information mainly needed by data users. To be useful, evaluated data files must be complete (in the context of the intended use), so available experimental data often must be supplemented with theoretical predictions (fit to available experimental data where possible). In particular cases, gaps in the experimental data can be very extensive. For example, in comprehensive calculations of neutron activation for fusion applications, neutron cross sections are needed for more than 15 000 individual activation reactions. Cross-section data is available directly from experiment for only about 10% of the identified reactions.

Data Dissemination: Nuclear Data Centers provides data users in Member States with cost-free and convenient access to the numerical data needed in their applications. Most of the needed data can be retrieved online, via the Internet, directly by the interested user from the IAEA Nuclear Data Centre or the Atomic and Molecular Data Information System. With this method of data access, the user receives exactly the information needed when it is needed. In order to guarantee access to all data, regardless of the geographic location where they have been produced, the Agency has established international networks of nuclear and atomic data centres that integrate the activities of major data centres around the world. Wherever necessary, online access is supplemented by custom data retrievals performed by the data-center staff of the Nuclear Data Section, with the results distributed electronically or by post to the data requester.

In 1998 and 1999, the capability was developed to produce and distribute CD-ROM versions of all of the Agency's main nuclear-data databases. Through the use of this method of dissemination, even users not connected to the Internet can have fast desktop access to the very same data that were available from the nuclear data Web server at the time that the CD-ROM "master" was produced. In addition, the CD-ROM is the dissemination method preferred by scientists working with large data libraries having relatively static content, a good example being the very large FENDL-2 library. It occupies 270 Megabytes in compressed form but still fits easily on a single CD-ROM.

Nuclear Power: Towards Sustainable Development

During the next half-century, the energy needs of mankind are likely to grow substantially, all the more if one hopes to begin to bridge part of the gap between industrialized and developing countries. Where shall we find the energy, to sustain a long-term development? Today, this does not seem possible without a significant contribution from nuclear energy... but many stumbling blocks have appeared on the road of nuclear power.

Nuclear energy is not a goal per se, it is just a way, among others, to supply energy to mankind. Providing mankind with sufficient energy is a fundamental goal, because energy is a key ingredient to development and standard of living. Today, on Earth, six billion people consume annually the equivalent of nine billion tons of oil (toe) as "primary" energy, and the bulk of this energy comes from fossil resources: coal, oil and gas. During the next half-century, this energy consumption is expected to grow substantially, under the combined effect of two driving forces.

The first force is demography : barring catastrophic events of a planetary scale, the world population will increase (Fig. 1), and is likely to reach around 10 billions (even though longer term forecasts are close to impossible). Furthermore, most of the population increase will occur in those regions of the world which are today the least developed, and have a low energy use per capita. Let us recall that while a citizen of the United States needs 8 toe/cap every year, a Frenchman uses 4, a Japanese, 3, a Chinese 1 and many denizens of Africa, less than 0,5.

The second driving force will therefore "hopefully" be the development of vast populated regions of this world, the standard of living of which is today "alarmingly" low. I use the adverbs "hopefully" and "alarmingly" because the huge development gap which exists today between North and South is the biggest long term threat to peace on Earth.

Even taking into account significant conservation efforts by those countries which can afford it, it is to be expected that the world energy consumption will grow faster than the world population (Fig. 1).

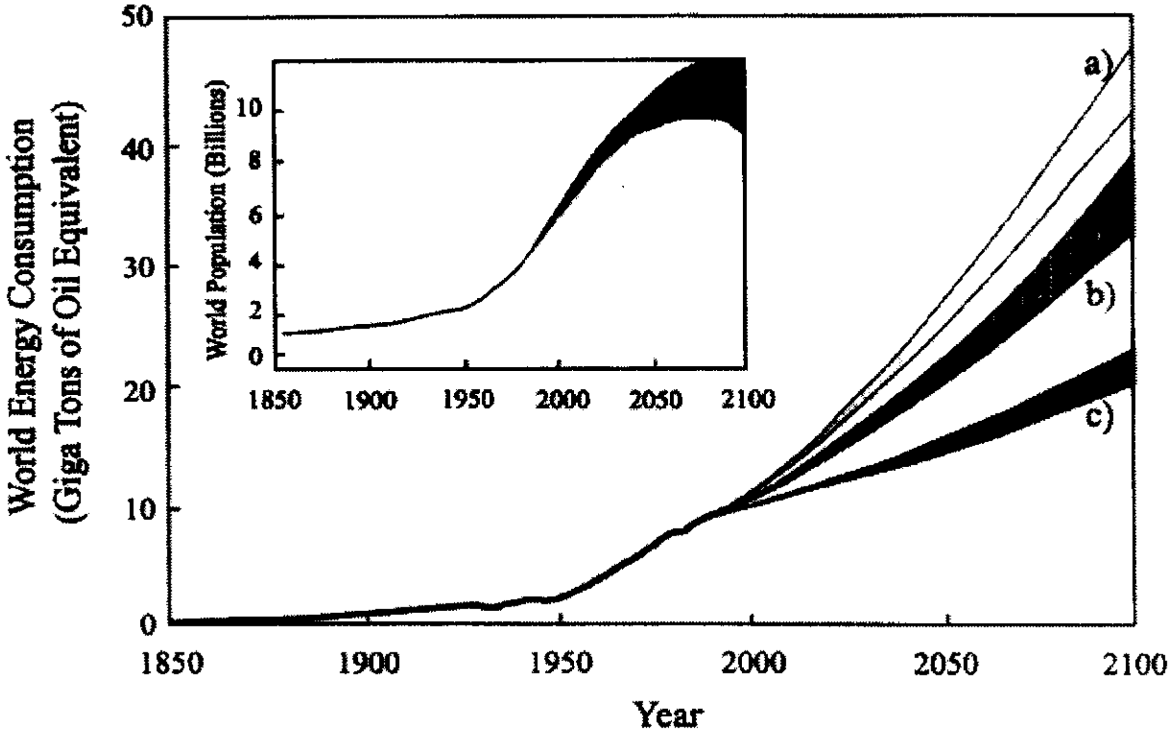

Fig. 1. Possible evolution of the world population (insert) and the world energy consumption

Nuclear power developed very intensively over a short period of time: Fission was discovered in 1938 ; the first man made fission chain reaction was triggered in December 1942, the first electricity was produced by nuclear power in 1951, but the first commercial reactor went critical in 1956 only. Four decades later, nuclear reactors throughout the world have generated 2400 billions kWh during 1997, 17 % of the world electricity, and more than the total world electricity generation in 1960!

To generate the same amount of electricity, one would need 550 million metric tons of oil, more than the yearly output of Saudi Arabia. Nuclear power accounts for more than 30 % of the electricity generation in the European Union, more than 75 % in France...

On the other hand, this is significantly smaller than the expectations of 1975, the year of the first oil shock. At that time, the official forecast for nuclear power in the year 2000 was in the range of 2000 GWe installed. The actual figure is today less than 400, a factor below 5.

A total of 436 nuclear power plants were operating around the world in 1999, based on data reported to the International Atomic Energy Agency (IAEA) Power Reactor Information System (PRIS). During 1999, four nuclear power plants representing 2700 MW(e) net electric capacity were connected to the grid, one in France, one in India, one in the Republic of Korea and one in the Slovak Republic.

Additionally, construction of seven new nuclear reactors started in 1999 — one in China (plus two in Taiwan, China), two in Japan and two in the Republic of Korea, bringing the total number of nuclear reactors reported as being under construction to 38.

The ten countries with the highest reliance on nuclear power in 1999 were: France, 75%; Lithuania, 73.1%; Belgium, 57,7%; Bulgaria, 47.1%; Slovak Republic, 47%; Sweden, 46.8%; Ukraine, 43.8%; Republic of Korea, 42.8%; Hungary, 38.3% and Armenia, 36.4%. In total, 17 countries and Taiwan, China relied upon nuclear power plants to supply at least a quarter of their total electricity needs.

Worldwide in 1999, total nuclear generated electricity increased to 2394.6 terawatt-hours. Cumulative worldwide operating experience from civil nuclear power reactors at the end of 1999 exceeded 9400 reactor-years (9414 reactor-years).

A table showing the electricity supplied by nuclear power reactors in 1999 and the respective percentage of electricity produced by nuclear energy is attached. Numbers with asterisks are estimates. Actual values should be available by the end of March. An updated table can then be found on the website http://www.iaea.or.at/worldatom.

One of the most distinctive characteristics of nuclear energy lies in the long time constants used. The total duration of a nuclear period - from design to the closure of the last plant (not including dismantling) - is over seventy years. The figures concerning the cycle are of the same oder of magnitude:

- The life of the present generation of nuclear power plants, which started around 1980, is expected to extend until 2040.
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- One "fuel cycle rotation" (fuel-in-core, cooling, retreatment new fuel) takes 15 to 20 years.
- Intermediate storage is designed for 50 to 200 years.

Therefore, if we are talking about innovation, there is no point in addressing the 2000-2020 period. We have to look at the 21st century as a whole.

Nuclear Power Reactors in operation and under construction during 1999

	in operation		under construction		electricity supplied in 1999		total oper. experience	
Country Name	No. of units	Total MW(e)	No. of units	Total MW(e)	TW(e).h	% of total	Years	1. Mons
Argentina	2	935	1	692	6.59	9.04	42	7
Armenia	1	376			2.08	36.36	32	3
Belgium	7	5712			46.6	57.74	163	7
Brazil	1	626	1	1229	3.98	1.32	17	9
Bulgaria	6	3538			14.53	47.12	107	2
Canada	14	9998			70.4*	12.7*	419	2
China	3	2167	7	5420	14.1	1.15	20	5
Czech Republic	4	1648	2	1824	13.36	20.77	54	8
Finland	4	2656			22.07	33.05	83	4
France	59	63103			375	75	1110	2
Germany	20	22282			160.4	31.21	590	7
Hungary	4	1729			14.1	38.3	58	2
India	11	1897	3	606	11.45	2.65	169	2
Iran			2	2111				
Japan	53	43691	4	4515	306.9*	36*	909	8
Korea Rep of	16	12990	4	3820	97.82	42.84	153	1
Lithuania	2	2370			9.86	73.11	28	6
Mexico	2	1308			9.56	4.98	15	11
Netherlands	1	449			3.4	4.02	55	0
Pakistan	1	125	1	300	0.69	1.2	28	6
Romania	1	650	1	650	4.81	10.69	3	6
Russia	29	19843	4	3375	110.91	14.41	642	6
South Africa	2	1842			13.47	7.41*	30	3
Slovak Republic	6	2408	2	776	13.12	47.02	79	0
Slovenia	1	632			4.49	36.23*	18	3
Spain	9	7470			56.47	30.99	183	2
Sweden	11	9432			70.1	46.8	267	2
Switzerland	5	3079			23.52	36.03	123	10
United Kingdom	35	12968			91.19	28.87	1203	4
Ukraine	16	13765	4	3800	67.35	43.77	238	1
USA	104	97145			719.4*	19.54*	2455	8
TOTAL*	**436**	**351718**	**38**	**31718**	**2394.63**		**9414**	**3**

There is no way to hide the fact that, when we talk about the 21st century, we open the door to a multitude of scenarios. We cannot restrict ourselves to "averaged" or "most likely" figures when dealing with population economy or energy around 2100. We must take care of the possible (very large) deviations.

For population scenarios, there is considerable difficulty in making a realistic estimate: the possible deviation is greater than a factor of two. For economic scenarios (with given population growth), the deviation is around a factor of two. For energy scenarios (when we specify economic figures), the deviation is between 1.5 and 2. Even if we allow for some overlap, the level of uncertainty concerning consumption in 2100 is between one and four. For this reason, it is impossible to define the future solely on the basis of "energy needs".

Clearly, quantities alone (energy needs) will not be sufficient to describe the future of energy. We must adopt a different approach, and study the "Transition to Sustainable Development" discussed in details in refs. [2-7]. We believe that this transition will take up the whole next century. It will be a long transition, dominated by cost: the cost of natural resources and the cost of external factors. The main question motivating research on nuclear energy will be how to deal with the transition period assuming that sustainability becomes feasible.

If we try to be more explicit: we must divide the 21st century into two periods of unequal length. "Before transition" will cover 2000-2030. The "Transition period" will cover the second portion of the century.

2.2. The road to the Transition period : 2000-2030

During that period, the mechanism defined by the Kyoto conference will be put in place. The way energy systems are operated or developed will change slowly. This will start a "ratchet mechanism": Coal → Gas → Nuclear or renewables.

Within the industrial world, the importance of energy will be decreasing, and the Kyoto "constraints" will play a dominant role. The impact of these constraints will be expressed by the cost of carbon emissions: 20 $/ton of carbon or 200 $/ton of carbon ? Anyway, this cost will grow regularly and play a prominent role.

In the ratchet mechanism, the use of coal is replaced by the use of gas (first transition) and then by the use of nuclear or renewable energies: no reverse transition is allowed. As a result, a new generation of PWR reactors, fairly similar to the existing generation, will be put in place and we shall therefore have set the course of nuclear industry for the next fifty years.

2.3. The transition to sustainability : 2030-2100

Somewhere after 2025, the features of the transition period will become clearer. Nuclear energy will have to take into account the very practical questions about sustainability which are so severe for fossil energies:

Economic development will be "dematerialized" in the developed world, "unequal" (with large differences between nations) in the developing world. Fossil energies will not disappear completely: their role will only be lower than now. All in all, it will be a "No urgency" situation, as far as energy problems are concerned.

- ^{235}U will be replaced by ^{238}U or Thorium around 2050-2075.
- End of gas will occur later than expected, due to CO_2 restrictions.
- Fuel cycle problems will have very little influence on industrial practice before 22nd
- Power plants may get much older than political bodies or organizations: as an example, we must remember that the last 1300 MW plant will stop around 2040.

Of course breakthroughs and disruptions remain possible:

- CO_2 constraint can be more easily tractable than we think.
- Disruptions (like Middle-East crisis or Tchernobyl accident) may happen.
- Demography changes may change value systems.

This being said, the problem of designing a sustainable nuclear energy remains. Its main challenge will be to take care of the depletion of ^{235}U reserves: we must remember that the energy content of these reserves is lower than what it is for oil or gas.

Preparing the future

"Preparing the future" means taking up a position with respect to the second period - the transition - and preparing the end of gas and ^{235}U. Clearly, the end will not be sudden, but it is necessary to think about choices beyond the first period. Can we do this today, taking into account the enormous uncertainties that we have already stressed ? Yes, we can, provided that we understand the main characteristics of the transition phase.

1. Innovation concerns the nuclear industry after the next plant generation only. The years 2000-2050 prepare for the second half of the 21stcentury i.e. 2050-2100. The central problem is the end of ^{235}U that translates on an increase in the price of ^{235}U.
2. Nuclear industry will remain entirely devoted to the 2000-2050 period and to industrial R&D. This means:

In the nuclear domain, when people think about innovation and development, they unconsciously refer to the "Golden Period" of the first development, when the "will to grow" swept away hesitations, and led to a fast selection of fuel and reactors systems. But we shall not live that period again.

Following the road to transition, we shall have to deal with uncertainties and industrial risks. The strongest safeguards will be provided by the international rules and agreements that will gradually define the meaning of sustainability in terms of energy. Energy scenarios will obey this new logic in which the cost of external factors will be one of the dominant factors.

Preparation for the future will not be granted by a growth scenario. On the contrary, it will become an objective in itself, an objective that will not be taken over by industry as it was in the first period. Whether we are talking about the design of fuel systems (^{238}U or Thorium) taking over from ^{235}U, or the processing of problems downstream of the cycle, R&D will obey its own logic, a logic of transition, far removed from the industrial constraints of the first period.

By respecting the principles above, and by consolidating its independence in terms of scheduling and financing, R&D can position itself with respect to the Transition towards Sustainable Development.

It is clear that radioactivity will not disappear, decay - heat will not be wished away. But, Nuclear Science has many things to offer! The field is almost unlimited, the final need is for tomorrow, but the opportunity to act is now.

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Transmutation of Nuclear Waste

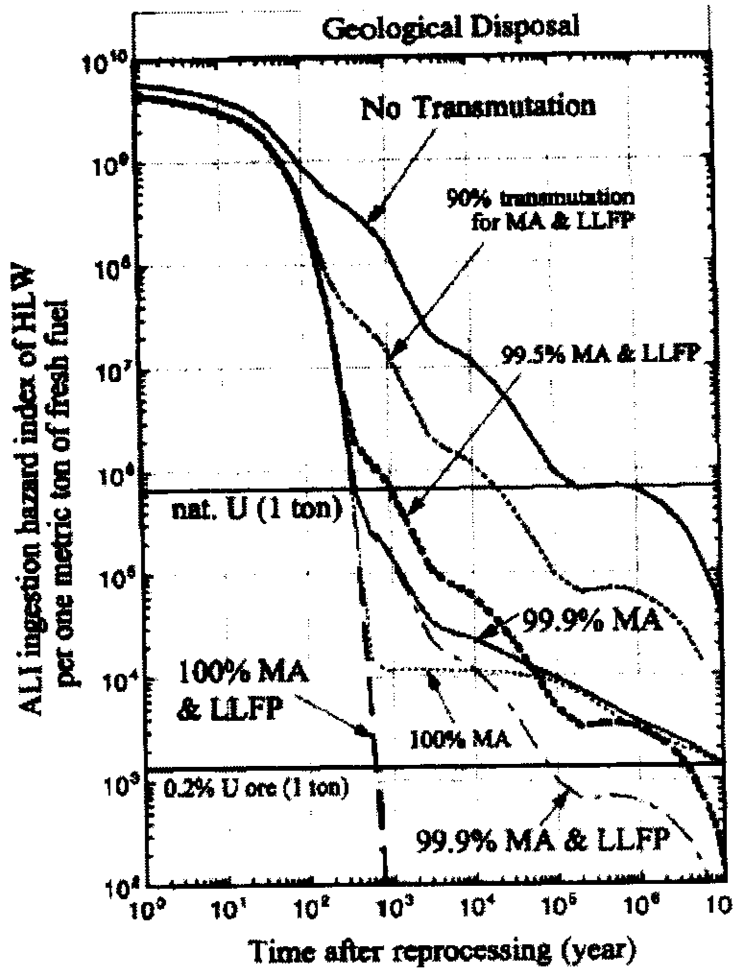
Every country which is using or is about to use nuclear energy has own policy according to its situation, and has own issues to be solved. On the other hand, there are global common important concerns in utilization of nuclear energy. The major three are to secure "Nuclear Safety", "Nuclear Non-proliferation", and "Radioactive Waste Management". As for nuclear safety, estimated risk of severe accident of reactor become presently very low, comparing with any risk in usual civilized life. This progress is obtained by major efforts for enhancing reactor safety technology and safe management. Nuclear non-proliferation should be secured not only by technical measures but also by all kinds of international political endeavors.

Any kind of waste including radioactive waste is raising a common serious problem in modern civilized society. In usual economic activities, such activity is highly evaluated that can produce any new value with lowest cost. But, waste management does not usually produce any new value. Even if waste is recycled, cost of recycle utilization is often higher than the value of the recycled product. Therefore, most of waste is disposed outside of usual economical activity by lowest expense. This situation will make the waste issue to be very difficult along big expansions of all kinds of economical activities. In order to resolve waste issue from a long term view point, any waste should be recycled as far as possible and the final disposed amount should be reduced decisively by using necessary cost and scientific and technical ability, because there is no outside area in the earth at present as well as in the future, due to expansion of human activities and population.

Although the amount of radioactive waste per unit electricity generation from nuclear power plants is rather small, the radiotoxicity of the radioactive waste should be reduced as far as possible prior to the ultimate disposal. Scientific data have shown that most of minor actinides and some long-life fission products can be transmuted to nuclides of which half-life are similar to ^{90}Sr and ^{137}Cs or less. Also element partitioning methods for this process have been successfully developed at least in laboratory scale. In this

The Objectives of partitioning and transmutation (P-T) are to reduce long-lived nuclides in HLW. Fig 2 shows that analyses show a possibility of reduction to 1/200 after about 1000 years from reprocessing for 99.5% transmutation f MA and LLFP in a double-strata fuel cycle. Partitioning is a necessary ingredient for transmutation process.

As mentioned before since the end of the 1980's research in transmutation, particularly Accelerator-Driven Transmutation of long-lived and radiotoxic nuclides has increased all over the world. In particular, interest in accelerator-driven systems for transmutation of nuclear waste (and possibly weapon-grade Pu) and, in somewhat lesser extent, energy production has increased over the past few years. Different reasons stimulate these research activities in many countries having very different fuel cycle policy from countries like France, Japan or Russia having "reprocessing" fuel cycle policy for Pu recirculation, through the countries which adopted once-through fuel cycle (like USA or Sweden) and ending on the countries without nuclear power at all (Italy, Poland). In France and Japan, where for a decade, active research programs on transmutation have been carried on, new problems concerning future of fast breeder reactors have stimulated greater interest in Accelerator-Driven Systems. ADS are considered as an viable option for minor actinides transmutation. In USA a road-mapping activity have just been started to formulate a DOE program on Accelerator-Driven Transmutation of Wastes and to define a place for this technology in a US waste management policy. In Russia, few hundreds former weapon researchers are currently involved in transmutation related projects, fi-



LLFP : FPs with $T_{1/2} \geq 30$ years

Fig. 2. Reduction of radiotoxixity by transmutation

nanced mainly by the USA, EU, Japan and Sweden through the International Science and Technology Center (ISTC). Countries like Italy and Spain has recently started well defined research programs ADS, while other countries have allocated additional funds to existing programs (Belgium, India, Sweden, South Korea, Czech Republic etc.) Part of

More detailed discussion of the transmutation projects proposed by different countries can be founded in Refs. [1-4].

Three different concepts for actinide transmutation are being considered in Russia, namely, accelerator-driven subcritical systems, molten salt reactor or accelerator-driven system and fast reactors cooled with liquid metal (Pb, Bi).

Development of Accelerator-Driven Transmutation Technologies has already become an exciting R&D topic of an interdisciplinary dimension, covering nuclear physics, nuclear technology including high intensity, medium energy accelerators, reactor physics, material sciences, chemistry and nuclear chemistry, radioactive waste treatment technologies etc. In many countries the synergy between neutron science, accelerator technology, nuclear physics and transmutation research has been recognized and common research and development programs have been formulated and launched.

In Russia, there is a unique experience (a total of about 70 operating years) of Lead-Bismuth as a coolant for reactors in submarines. Within the ISTC's project #559 which was financed and granted permission to start in 1996, a liquid Lead-Bismuth target will be designed in Obninsk to be irradiated in Los-Alamos at LANSCE. This may be an experiment which will be decisive for the development of a demonstration facility. IPPE (Obninsk), LANL; CEA/Cadarache and RIT are participating in the experiment. IPPE plays now an important role in transferring liquid Pb/Bi technology from military to civilian use.

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One of urgent topics independent from accepted transmutation concepts is improvement of evaluated data for main transmuted nuclides and creating nuclear data bases required for intermediate energies (above 20 MeV).

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Improved Evaluations for Minor Actinides

On the basis of new requirements on nuclear data for minor actinides the analysis of all available experimental and evaluated neutron data has been performed for neptunium, americium and curium isotopes. As a result the new versions of evaluated neutron data files for Np-237, Am-241,-243, Cm-242,-243,-244 have been created. These files were included to the BROND-3 library, which is under formation now in Russian Nuclear Data Center.

The complete analysis of all experimental data on the fission cross sections, radiative capture and inelastic neutron scattering was performed and used as the basis to prepare the updated neutron cross section evaluations for Np-237, Am-241 and Am-243 [1,2]. The evaluated fission cross section for Am-241 is shown in Fig.3 together with the renormalized experimental data and recent evaluations of other laboratories. The disagreement in absorption and fission cross sections influences directly to the (n,2n) and (n,3n) reaction cross section evaluations. Our recommended cross sections are shown in Fig. 4 in comparison with experimental data and other evaluations.

There are considerably less experimental data for curium isotopes. The neutron total and capture cross sections were measured at the resonance region only. On the other hand the fission cross sections were measured only for fast neutrons. That is why the all evaluations of neutron cross sections are based mainly on the analysis of fission cross section measurements and optical-statistical calculations for other cross sections. New experimental data on the fission cross sections for Cm-245 and Cm-246 obtained recently at the IPPE are in agreement with both earlier data and new evaluations of Minsk group. For Cm-243 the new measured fission cross sections differ from the new evaluation of Minsk group [3] considerably in the all energy region.

Our evaluations of the fission, inelastic neutron scattering and (n,2n) reaction cross sections for Cm-242 are shown in Fig. 5 together with the previous evaluations of these cross sections. The discrepancies between different evaluations are considerable and the problems of evaluations tests remains actual ones.

The available experimental data on the fission cross section for Cm-243 are shown in Fig. 6 together with various cross section evaluations. The same method of the statistical analysis of correlated data was used for the determination of fission cross sections that was used for neptunium and americium. The integral fission cross section was determined in the precise measurements on the fast critical assembly with the average neutron energy of 300 KeV to be equal to 2.651±0.090 barn [4], which is consistent with our evaluation and differs considerably from other evaluations. Thus our evaluation can be considered as being consistent with the benchmark experiment data.

The results of optical-statistical calculations of inelastic neutron scattering and the (n,2n) reaction cross sections for Cm-243, which is consistent with the evaluated fission cross section , are shown in Fig. 7. They differ considerably from the previous cross sections evaluations. For high-energy neutrons these differences are due to not discrepancies in the fission cross section evaluations only, but to the discrepancies in the neutron absorption cross sections. Both for curium and americium isotopes the Minsk group used the optical potential which results in lower values of the absorption cross section at the energies above 10 MeV than the observed fission cross sections for light curium isotopes at the energy of 14 MeV.

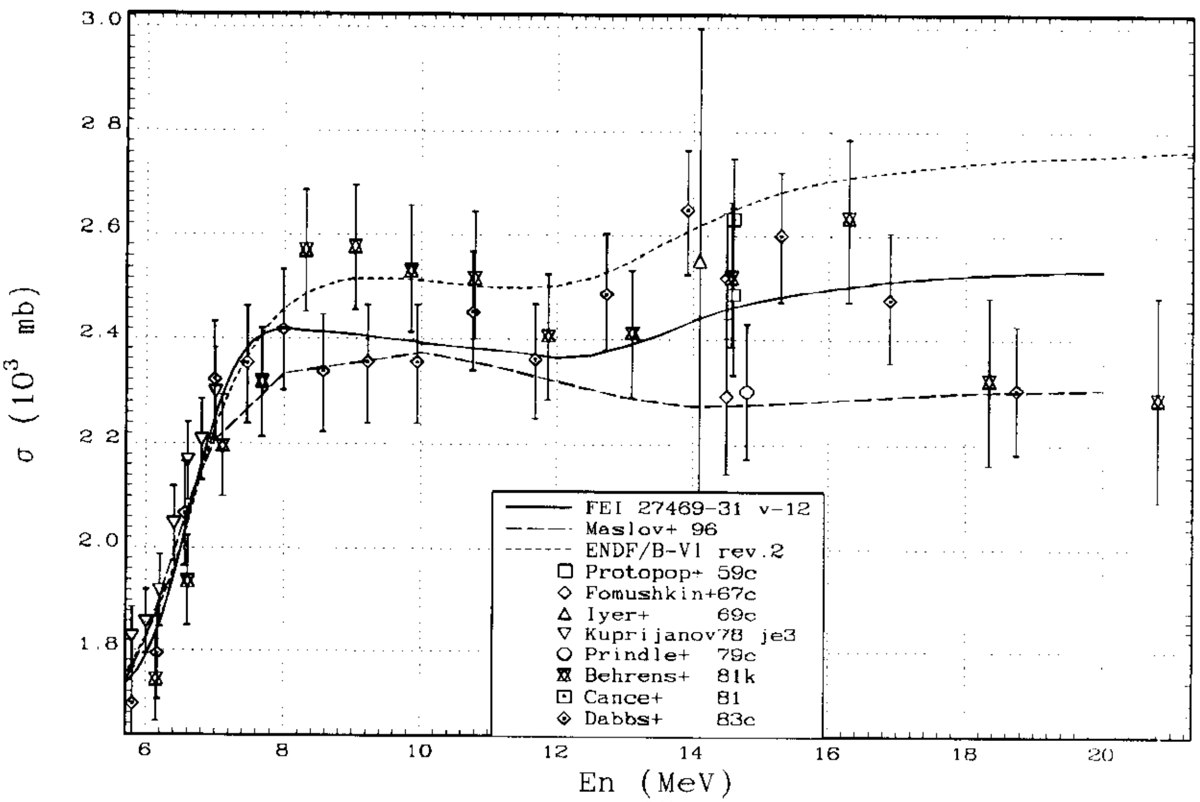

Fig. 3. Recommended fission cross section for ^{241}Am in comparison with the available evaluated and experimental data.

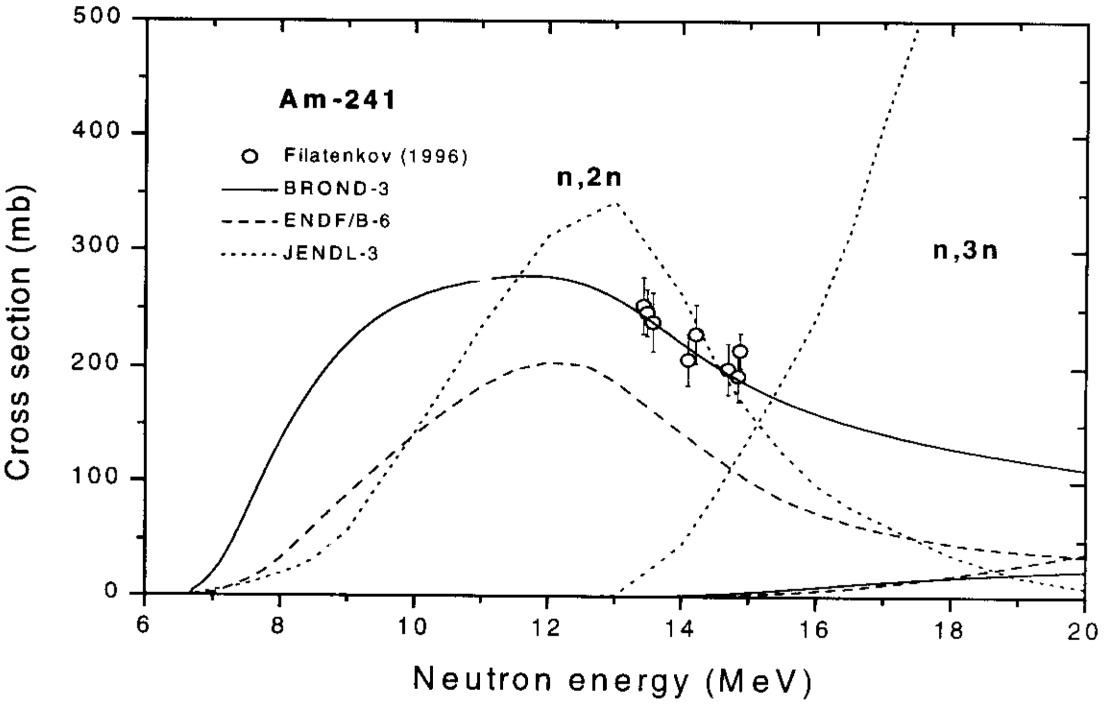

Fig. 4. Comparison of the evaluated (n,2n) and (n,3n) reaction cross sections for ^{241}Am with experimental data.

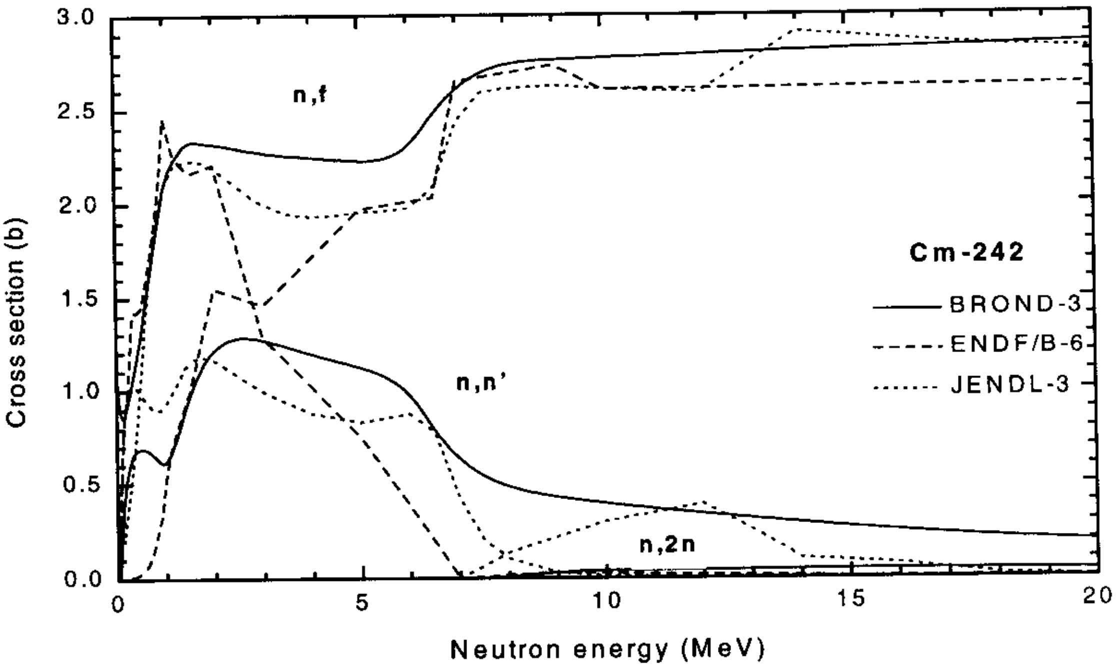

Fig. 5. Comparison of the evaluated fission, inelastic and (n,2n) reaction cross sections for ^{242}Cm.

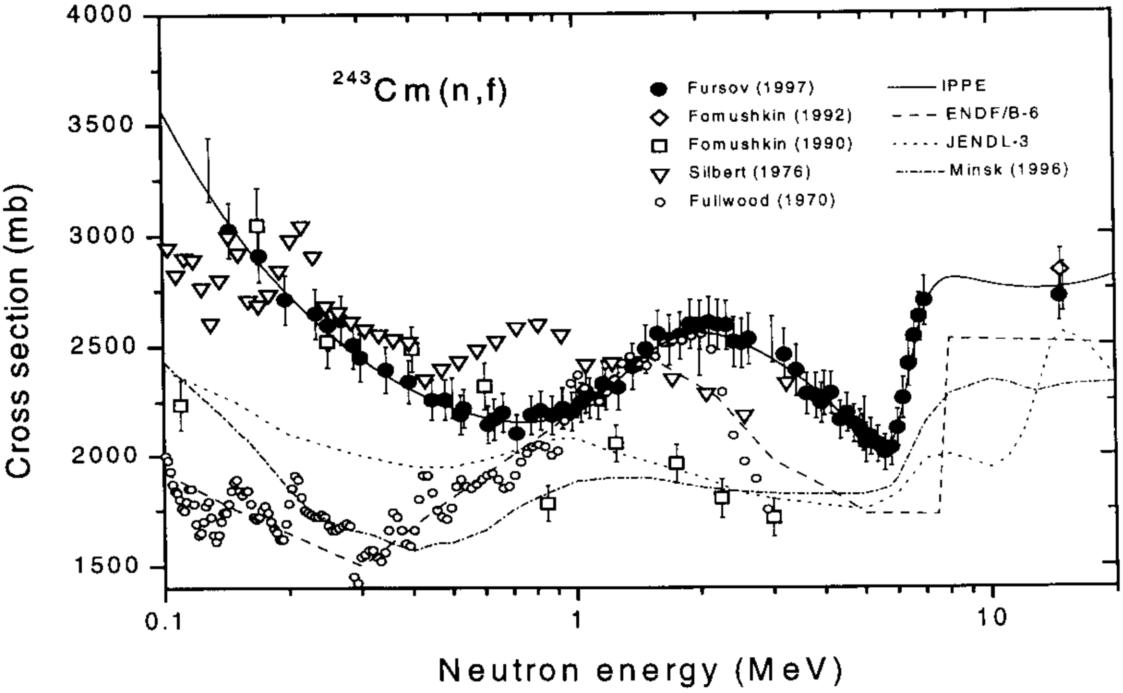

Fig. 6. Comparison of the evaluated fission cross sections for ^{243}Cm with experimental data.

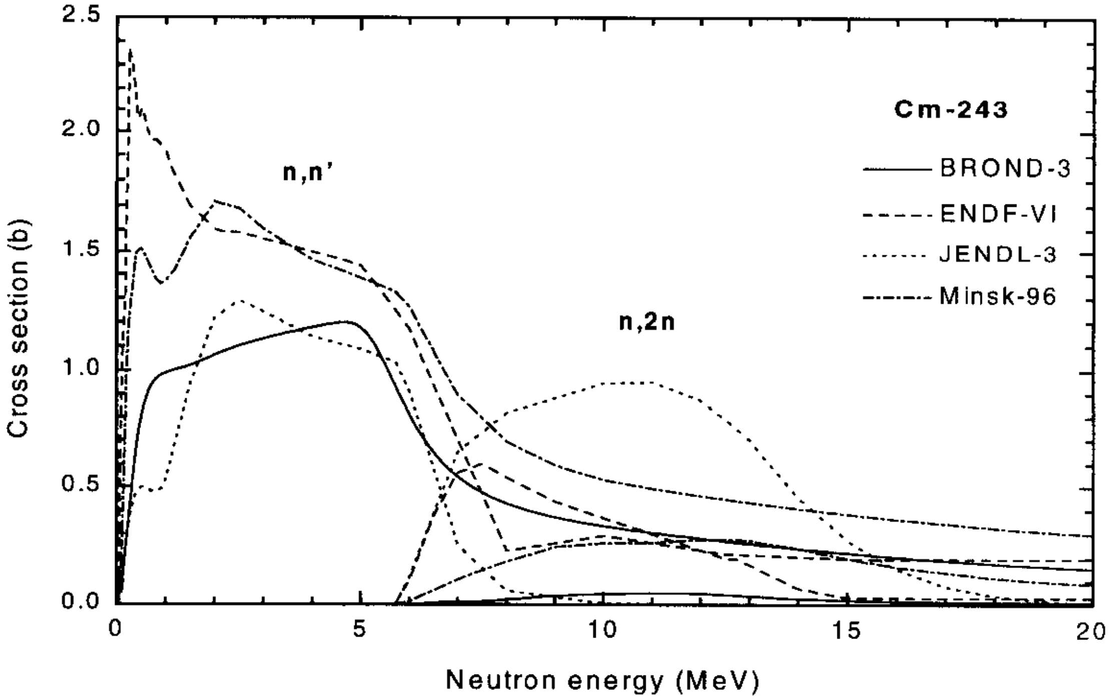

Fig. 7. Comparison of the evaluated inelastic and (n,2n) reaction cross sections for ^{243}Cm.

Nuclear Data Needs for Accelerator-Driven Systems

Practically all nuclear data used for the calculation of fast reactors are needed for the analysis of accelerator-driven power systems. In addition to this, however, a huge amount of nuclear data in the energy region from 20 MeV to 1.5 GeV is required too.

The available experimental data for energies above 20 MeV are not systematized, scarce and should be thoroughly analyzed and put to computer format EXFOR. Theoretical models and systematics developed for the description of nuclear processes in this energy region not always provide the accuracy required for the calculations and have to be improved.

It is worthwhile to support the activity on evaluations of most important nuclear data for the accelerator driven systems, which is developed now on the basis of international cooperation. It consists of the following directions of works:

The improvement of the accuracy of the existing nuclear data libraries for the most important nuclei in the region up to 20 MeV;

The creation of activation data libraries for neutron and proton induced reactions on nuclei in a wide region of mass numbers in the energy region from 20 to 150 MeV;

The creation of the transport cross section files for the most important nuclei in the energy region from 20 to 150 MeV;

The development and improvement of theoretical methods of cross section calculations for the neutron and proton induced reactions in the energy regions below and higher 150 MeV on the basis of selected benchmark data.

New Evaluations of for Lead and Bismuth

The development of accelerator-driven power systems with the heavy-metal liquid coolant requires a rather accurate data on the neutron and gamma-ray production cross sections for lead and bismuth. Discrepancies between the evaluated data of ENDF/B-VI, JENDL-3.2 and BROND-2 for these elements amount to 40-50% in many cases. To improve an accuracy of data new evaluations of the neutron induced reaction cross sections were performed recently at the IPPE.

The neutron total cross sections calculated into the frame of the coupled-channels model with the recommended parameters agree well enough with available experimental data. The resonance structure of neutron cross sections included into the ENDF/B-VI, JENDL-3.2 and BROND-2 is important up to energies of several MeV, but at higher energies there are no essential differences between the total cross sections recommended by the previous evaluations and new ones.

At the incident neutron energies below 7 MeV the inelastic scattering channels are dominant for all analyzed isotopes. As the discrete level schemes were taken into account in the present calculations up to excitation energy of 3.5-4.0 MeV, this energy region can serve for the checking of consistency of the chosen parameters of optical model and spectroscopic characteristics of low-lying levels of target-nuclei.

The calculated production cross sections for the most intense discrete gamma-transitions on separated lead isotopes and bismuth are shown in Fig. 8 together with the experimental data available. The careful analysis of experimental data was performed and the corrections to current standard and reference reaction cross sections were made for some data.

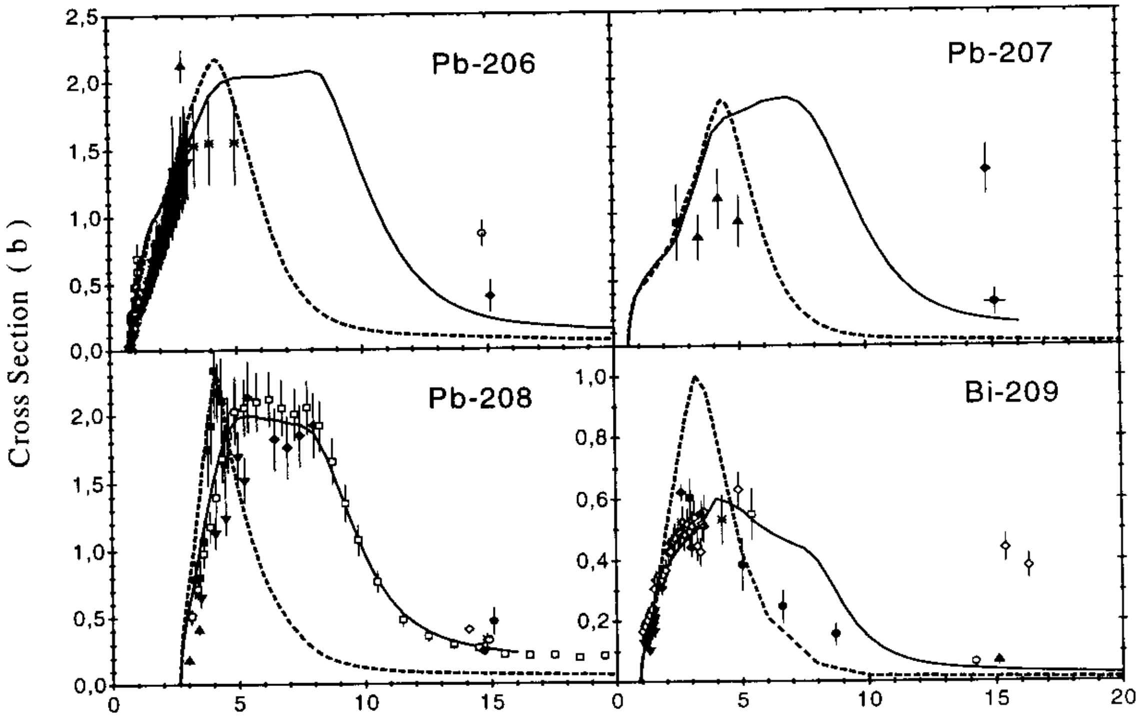

Fig. 8. Experimental data and recommended curves for the gamma-ray production cross sections corresponding to the transitions from the first excited levels to the ground states. The dashed curves are the ENDF/B-6 evaluations and the solid ones are the present calculations.

As it can be seen the available experimental data are generally well reproduced by the theoretical calculations. Similar results are also obtained for the production cross sections of some other intense gamma-lines corresponding to the gamma-transitions between low-lying levels of lead isotopes and bismuth. On the other hand the evaluated cross sections for the discrete gamma-transitions included into the ENDF/B-VI and JENDL-3.2 files differ strongly from both the experimental data and calculations. So a revision of previous evaluations seems very important and we prepare completely new evaluations of the discrete gamma-line yields based on the theoretical calculations considered.

Above the neutron energy of 7 MeV the (n, 2n) reaction channel opens. These reactions, as well as the (n,3n) reactions above its thresholds, contribute significantly to the total gamma-ray yield. Different evaluations of the $^{206\text{-}208}$Pb(n,2n) and ^{209}Bi(n2n) reaction excitation functions are compared with the available experimental data in Fig. 9. A good agreement of the calculations with experimental data was reached only for the models that include the shell changes of the level density parameters of near-magic nuclei.

Above 14 MeV the preequilibrium mechanisms of neutron emission become increasingly important for description of the high energy tails of the (n,2n) reaction cross sections, the competing (n,3n) reactions and the corresponding components of the neutron and gamma-ray spectra. In Fig. 10 the integral gamma-ray production cross sections are presented for all nuclei considered.

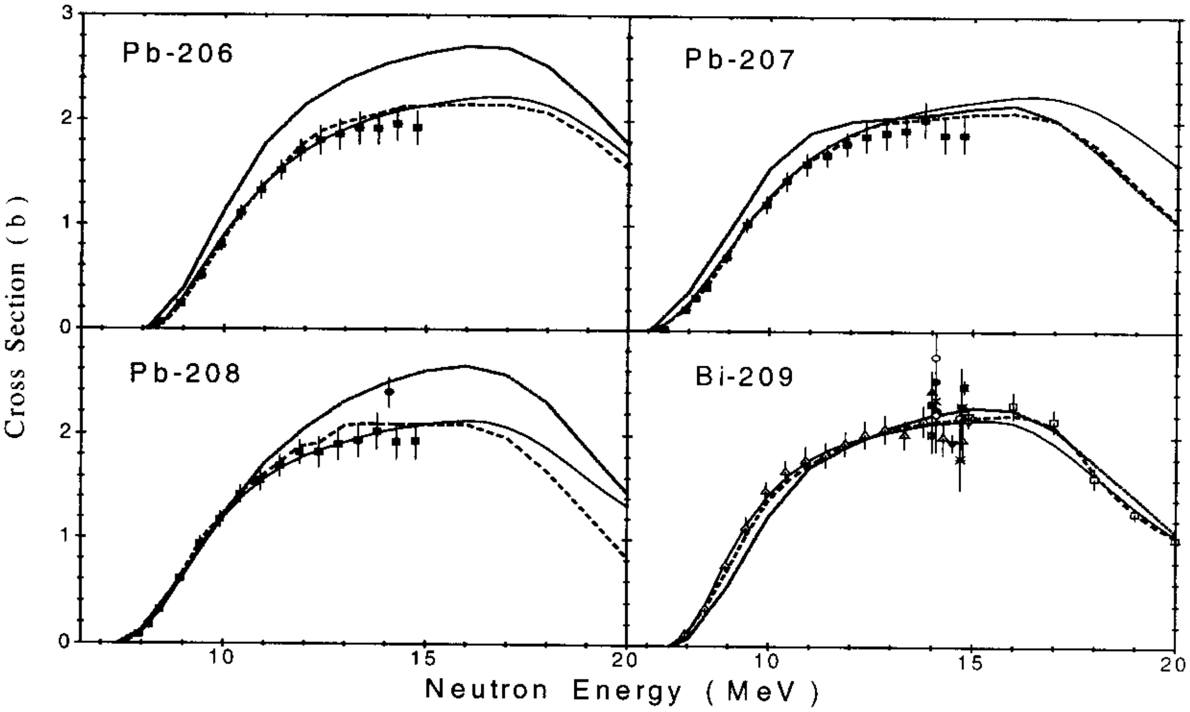

Fig. 9. Experimental data and recommended curves for the (n,2n) cross sections. The dashed curves are the ENDF/B-VI evaluations, the dotted ones are the JENDL-3.2, and the solid ones are the present evaluations.

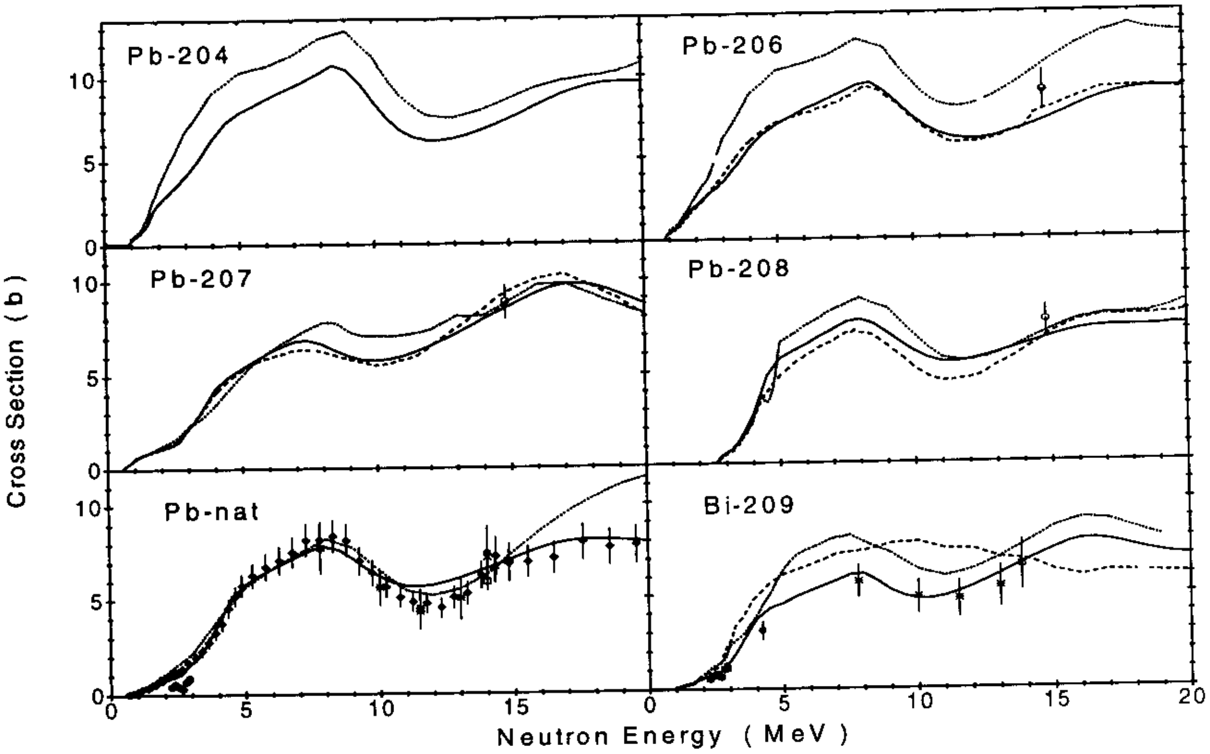

Fig. 10. Integral gamma-ray production cross sections as a function of the incident neutron energy. Curves are designed as in Fig. 9.

For the natural lead much more experimental data are available including the detail measurements of integral gamma-ray yields for the full range of incident neutron energies up to 20 MeV. All data agree well enough with the calculated gamma-ray production cross sections (Fig. 10). The similar agreement is obtained for bismuth too. All experimental data were corrected on the contributions of soft gamma-rays to integral production cross sections and such corrections are rather big for some data. Generally the calculated cross sections describe experimental data much better than the previous evaluations.

On the basis of the analysis performed we decided to accept the calculated gamma-ray spectra and integral production cross sections as the optimal versions of new evaluations recommended for the BROND-3 library.

Evaluations for Intermediate Energies

A lack of experimental data at intermediate energies of incident neutrons or protons has to be compensated by the development of reliable calculation methods. The codes based on the intranuclear cascade model combined with the evaporation model have been successfully applied for the energies above a few hundred MeV. At lower energies, however, nuclear structure effects are so prominent that their description requires more detailed consideration of competitive reaction mechanisms. Therefore, it was decided that the energy region from 20 to 150 MeV requires special consideration and the evaluated data files for this region should be prepared for most important structural and fissile materials in the same manner as for the energy region below 20 MeV. In accordance with that, the evaluated data files for about 30 of most important structural and shielding materials were extended in the ENDF/B-VI library up to 150 MeV by the Los Alamos group [7].

The list of first priority actinides that can be used in accelerator-driven subcritical systems, includes isotopes of thorium, uranium and plutonium. The majority of experimental data are available for ^{238}U. For this reason, ^{238}U is the best candidate for testing the models developed for nuclear data evaluations at intermediate energies.

The main results of experimental data analysis and calculations recommended for the intermediate energy neutron data file of ^{238}U were presented in Ref. [8]. The evaluations of the cross sections that can be compare with experimental data are shown in Figs. 11 and 12. In Figs. 13 and 14 the normalized spectra of emitted neutrons and protons are shown for different energies of incident neutrons. It can be seen that the preequilibrium processes give dominant contributions to the spectra at high incident energies. The complete files of recommended data for both the neutron and proton induced reactions are now under formation and testing in the IPPE.

Data for Thorium Fuel Cycle

Up to recent time the nuclear data for the thorium fuel cycle were not considered as the first priority ones. Thus, there are considerable discrepancies of the recommended evaluated data, and a lack of experimental information necessary to remove these discrepancies. The requirements to the accuracy of theses data are not so strong in comparison with the uranium-plutonium fuel cycle because at this stage the investigations of the feasibility of the problem only, but not its technical realization.

The main nuclei are Th-232, Pa-231, 232, 233, U-232, 233, 234. The required accuracy for the fission cross sections in the near threshold region is 3-5 %, for the capture cross sections is 5-10 %, for the inelastic neutron scattering is 20 %. For the intermediate energies data are required mainly on the transport cross sections for neutrons and protons for Th-232.

The works directed to improvement of neutron files for Th-232 in the energy range up to 20 MeV and development of the complete evaluated files in the energy range up to 150 MeV started in the IPPE on the basis of international cooperation.

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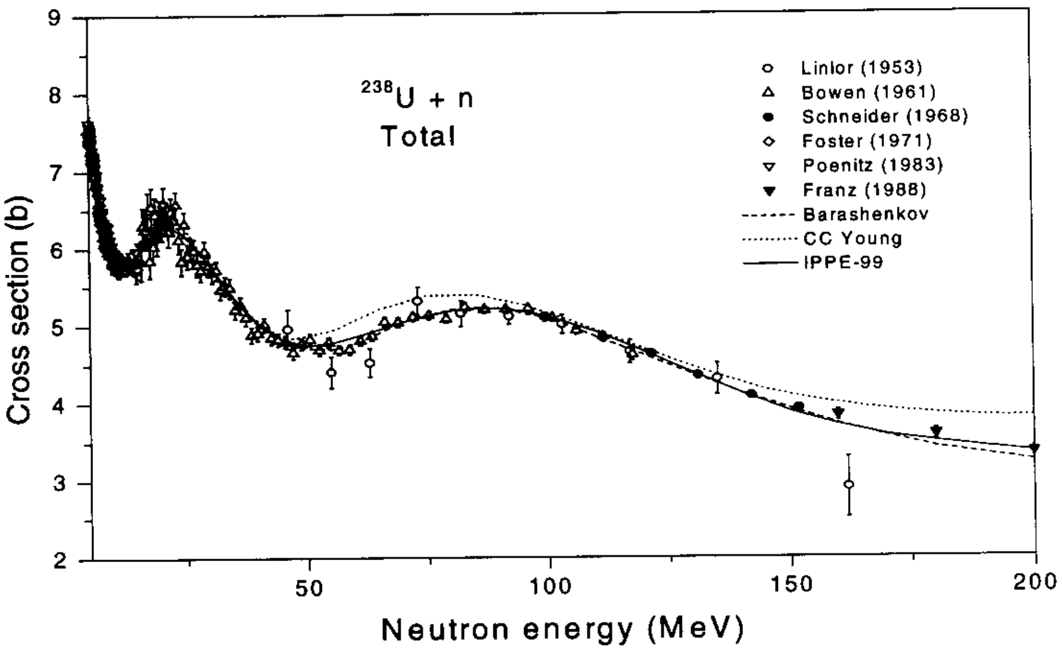

Fig. 11. Comparison of different calculations of the total neutron cross section with experimental data.

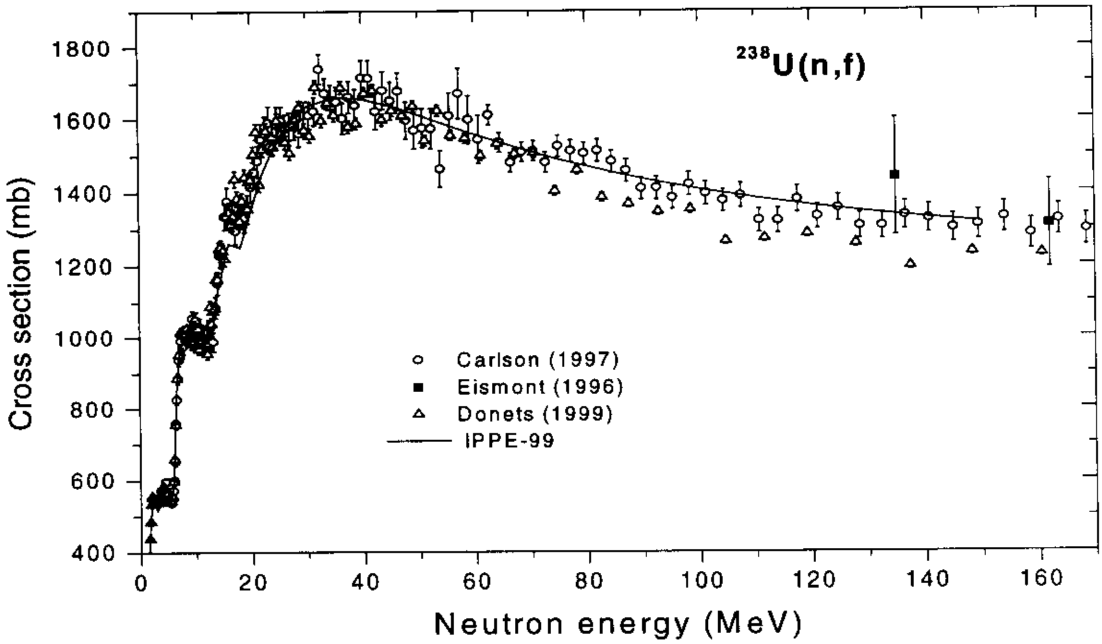

Fig. 12. Calculated fission cross section in comparison with experimental data.

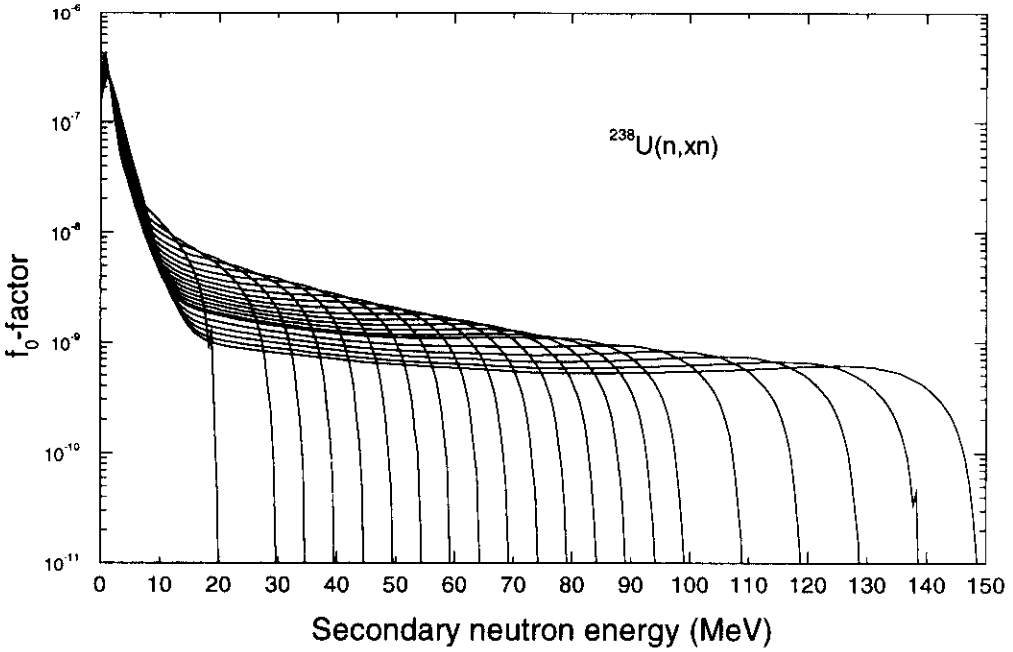

Fig. 13. Normalized secondary neutron spectra for the incident neutron energies from 20 to 150 MeV.

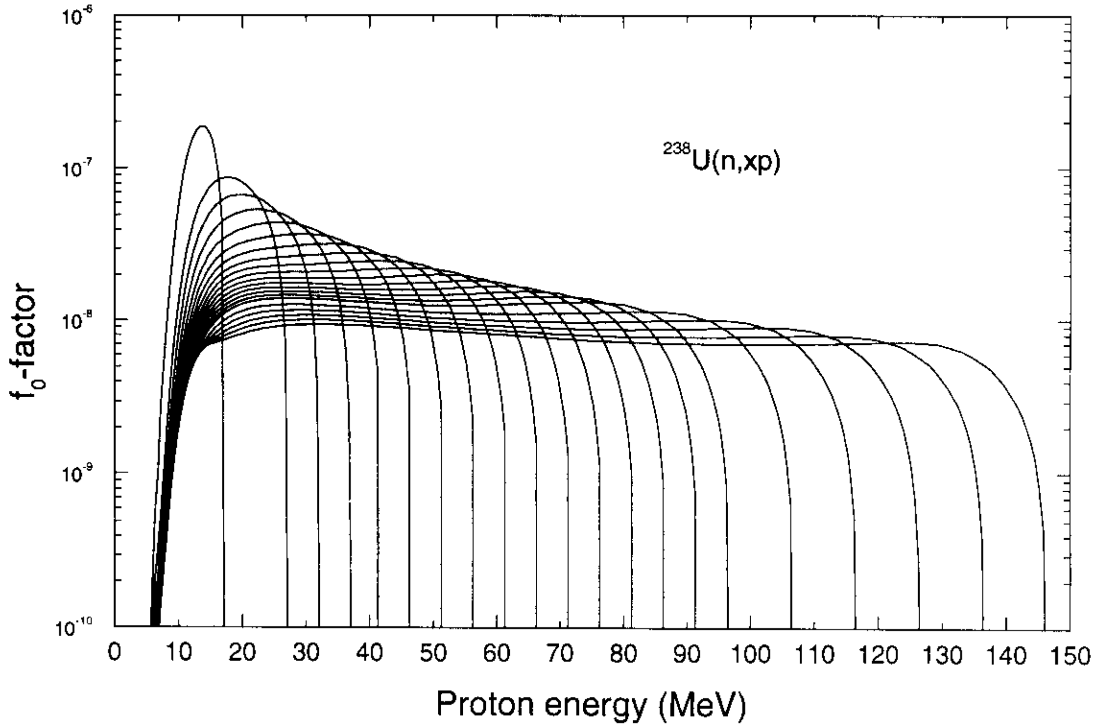

Fig. 14. Normalized secondary proton spectra for the incident neutron energies from 20 to 150 MeV.

Nuclear Models for Nuclear Data Evaluations

A long--standing problem, how to meet nuclear data needs of the future with limited experimental resources, puts a considerable weight on nuclear model computation capabilities. Originally almost all nuclear data was provided by measurement programs. Over time, theoretical understanding of nuclear phenomena has reached a considerable degree of reliability, and nuclear modeling has become an important source of evaluated nuclear data. The nuclear measurement program could never supply all of the needed data, so results of theoretical programs have been assimilated in order to supplement the measurement results (under the understanding that the importance of measurements remains critical for data testing and benchmarking). Due to the widespread use of nuclear models in generating evaluated nuclear data there is a substantial demand for input data needed to perform such calculations.

Considering low-energy nuclear reactions induced with light particles, such as neutrons, photons, protons, deuterons and alphas, one addresses a broad range of applications, from nuclear power reactors and shielding design through cyclotron production of medical radioisotopes and radiotherapy to transmutation of nuclear waste. In all these and many other applications one needs a detailed knowledge of cross sections, spectra of emitted particles and their angular distributions. Particularly for low and medium incident energies the nuclear theory mastered a set of well established nuclear reaction models that cover almost all aspects of physics involved and thus also all data of practical interest. Three rather wide groups of nuclear reaction models are used usually:

i) formal theories of resonance reactions that describe very accurately the resonance structure of neutron and proton induced reactions measured with a good resolution;

ii) generalized statistical models including fission, preequilibrium and direct processes and combined with the optical model;

iii) intranuclear cascade models developed initially for high energies, but modified latter at intermediate energies of incident particles.

An example of the cross section evaluations on the basis of the resonance and statistical model is shown in Fig. 15. The evaluation results depend very strongly on input parameters of models related to both nuclear structure and nuclear reaction data.

In Fig. 16 the experimental data on mass yields of fission and spalation reaction products are compared with calculations for different versions of the intranuclear cascade model. Again the calculated yield strongly depend on both model parameters and approximations used in description of fission and particles evaporation.

Practical use of nuclear model codes requires a considerable numerical input that describes various properties of nuclei involved such as nuclear masses, discrete levels, neutron resonances, optical model parameters, nuclear level densities and gamma-ray strength functions. Leading nuclear data laboratories, groups and experts were using a variety of different input sets, often developed over years in their own laboratories. Many of these partial input databases were poorly documented or not documented at all and not available for other users. With the trend of reducing funds for nuclear data evaluations, a threat become real that the accumulated immense knowledge on input parameters and the related state-of-the-art may be reduced or even lost for the future applications.

In this situation it was extremely important to launch a coordinated research project aimed to develop an internationally recognized input parameter library with contributions from all major players around the world. The idea was discussed in the nuclear data community in the beginning of 90-ties and was supported by the International Nuclear Data Committee as a top priority nuclear data project for the IAEA.

An ultimate objective of any international effort along these lines is to develop a library of evaluated input model parameters. Considering that such a task indeed is immense, it was decided to proceed in two major steps. First to develop a single starter file of input model parameters that summarized present knowledge on input parameters. This database will be of immediate practical value for a number of users and it should represent a firm basis for any future improvements and developments. The second step should focus on testing and validation of the Starter File, its improvements and extensions, and on development of input modules (interfaces) for selected nuclear reaction codes, including retrieval capabilities.

With these objective in mind the IAEA initiated the Coordinated Research Project (CRP) under the title "Development of Reference Input Parameter Library for Nuclear Model Calculations of Nuclear Data (Phase I: Starter File)".

The project, abbreviated as RIPL (Reference Input Parameter Library), was coordinated by the Agency in 1994-1997. The output of the CRP is twofold. First, the complete electronic RIPL Starter File has been produced and made available to users cost-free all around the world. Second, the present Handbook was prepared, containing detailed description of the RIPL library. The second stage of RIPL is under development now.

It seems necessary to organize in the future similar projects for the intranuclear cascade models and the nuclear structure models selected for practical applications. Of course the upgraded versions of models should be involved into these projects and their input parameters will reflect a father growth of our knowledge on properties of nuclei.

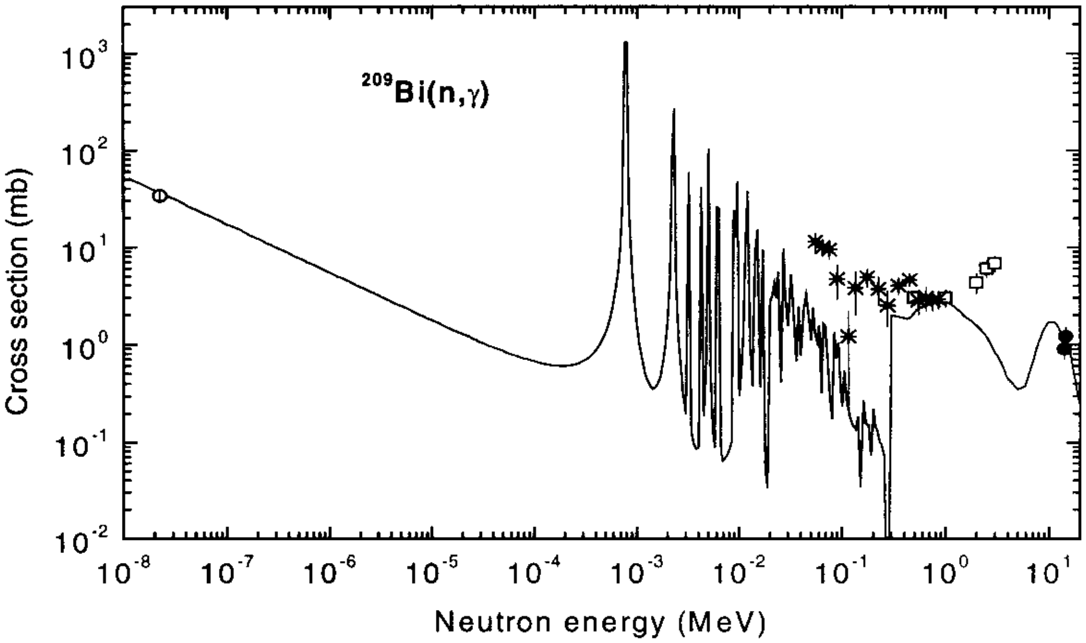

Fig. 15. Evaluated neutron radiative capture cross section for ^{209}Bi in comparison with experimental data.

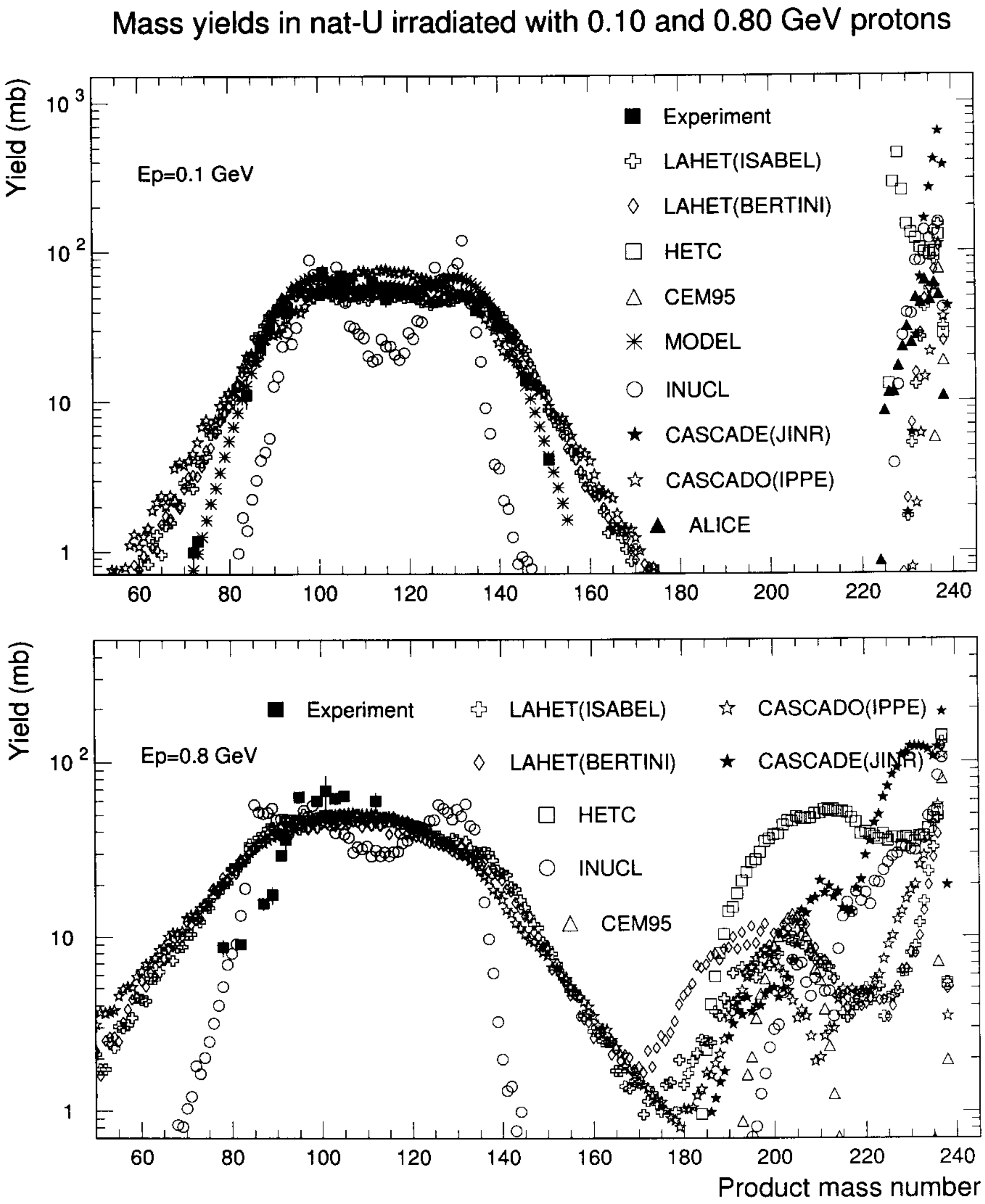

Figure 16. Product mass distributions of U(p,x) reaction under 0.1 and 0.8 GeV protons irradiation.

Radioactive Beams and Exotic Nuclei

Radioactive beam facilities developing intensively now in several leading laboratories of Europe, America and Asia open wide perspectives for studies of nuclei far from the beta-stability valley including nuclei close to the proton and neutron drip-line and new elements. Nuclear mass measurements could serve one of examples of the corresponding research.

The binding energy of the atomic nucleus is one of the most fundamental properties of such a many-body system. Accurate mass data serve as testing grounds for nuclear models and stimulate their further improvement. Furthermore, systematic investigation of the binding energy as a function of proton and neutron numbers allows the direct observation of nuclear properties like pairing, shell and sub-shell closure, as well as deformation effects, and lead to a deeper understanding of nuclear structure.

The mass evaluation of 1995 (Audi and Wapstra) shows 2650 different isotopes. Only for 1825 of them mass values are measured unambiguously. The rest has not been measured at all, although about 400 of them exhibit a relatively long nuclear lifetime above 1s. On the other hand, mass predictions from various nuclear models differ up to several MeV for these unstable isotopes. Therefore, accurate experimental mass values are urgently needed. The systematic mapping of the mass surface from the valley of stability to the drip line could lead to essential improvements of nuclear models.

Large efforts are presently devoted to the application of classical as well as new mass spectrometric techniques, such as time-of-flight, Smith-RF or Schottky mass spectrometry, for the accurate mass determination of short-lived isotopes far from the valley of beta stability.

ISOL-TRAP (CERN) has very successfully continued its mass measurement program during last five years [96B]. More than 70 mass values of rare earth elements and neutron-deficient isotopes with Z=80-85 have been determined with an accuracy typically better than 20 keV.

First systematic Schottky mass measurements of neutron deficient nuclides in the Ho to Po region were performed at the ESR (GSI, Darmstadt) during 1994 and 1995. (96S). Using ^{197}Au and ^{209}Bi primary beams, the masses of about 290 different nuclides produced in the target of the fragment separator have been measured (Fig. 17). For about 1/3 of these isotopes this was the first determination of their mass. Accuracies in the order of 100 keV/c(2) and below for these heavy nuclides could be achieved, corresponding to relative accuracies of 5 times 10(-7). Due to the very good mass resolution of Schottky mass spectrometry in the order of 3 times 10(-6), the ground and isomeric state of several nuclei could be clearly resolved.

The Schottky mass spectrometry is now beeing optimized towards the determination of the half-life of shorter-lived nuclei (99B). Furthermore the resolution and the sensitivity will be improved. The TOF-method will be widely used ready to measure masses of very short-lived nuclei.

The striking progress made during the last decade in development of radioactive beams opens great perspectives for future experiments with exotic nuclei.

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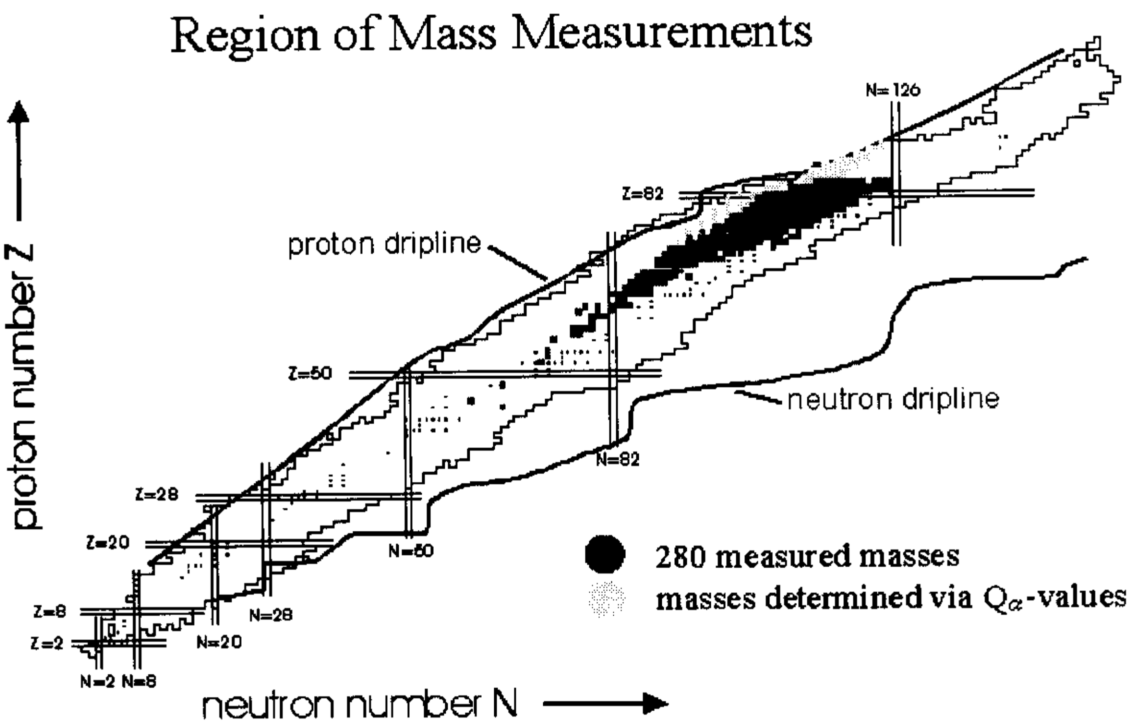


Fig. 17. Region of nuclear masses measured during the last years in GSI.

Medical applications

Electrons along with bremsstrahlung gamma-rays, also neutrons, proton and recently heavy ions are widely used in cancer radiation therapy. Data libraries, including nuclear ana atomic interactions, form a basis for Monte Carlo transport calculations that provide accurate estimation of doses required for tumor control and normal tissue tolerance.

An example of the quality of modern data is shown in Fig. 18 , that compare absorbed doses of ^{12}C ions in water, constituting 65% (mass) of human body. In order to optimize dose delivery to the tumour precise knowledge of energy deposition in tissue-like material is essential. This includes not only the energy loss of the primary particle but also the contributions of the projectile fragments [www-aix.gsi.de/~bio/therapy.html].

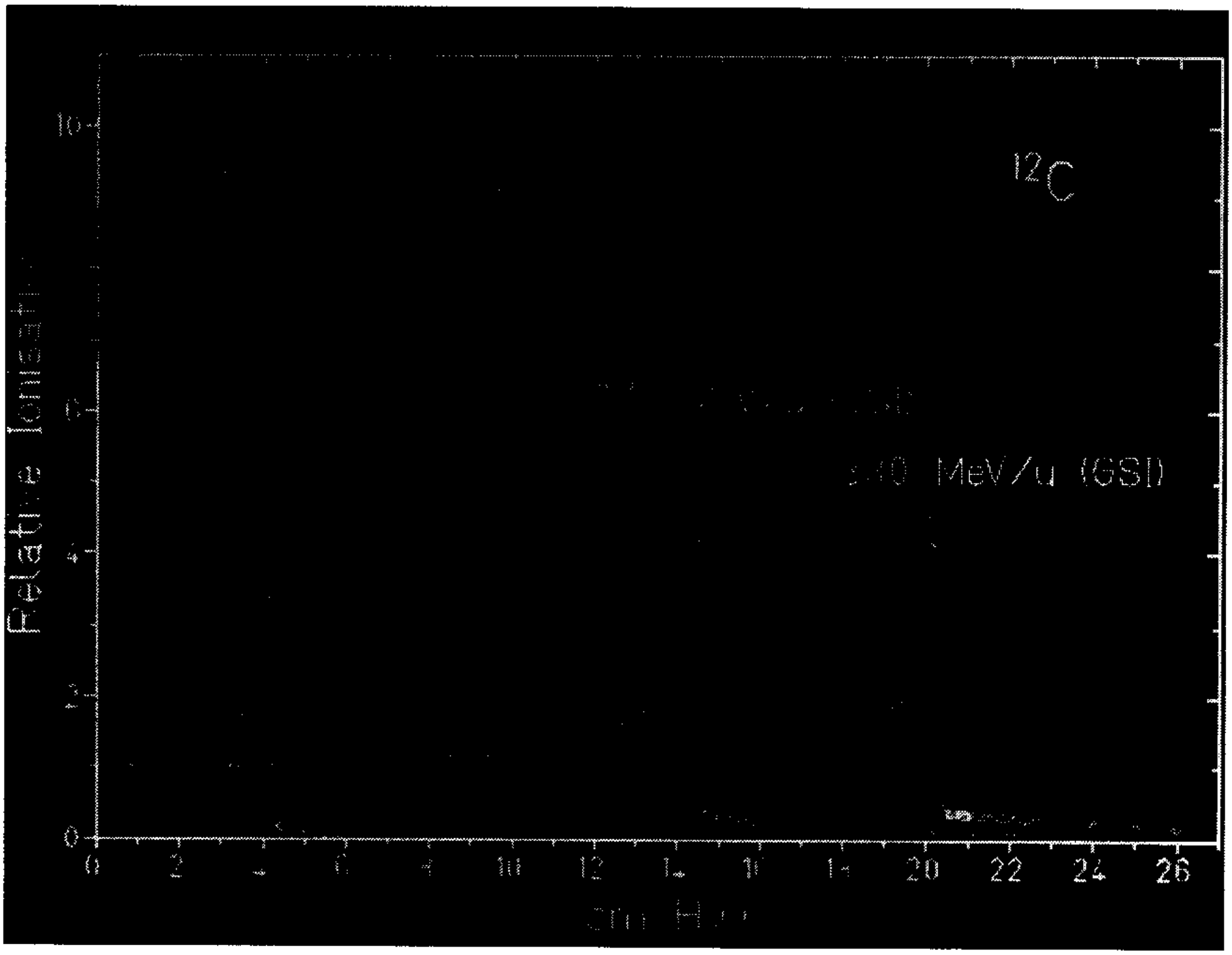


Fig. 18. Measured Bragg curves in water (points) together with model calculations.

Beams of ions like carbon represent the most advanced tool or radiotherapy of deep seated tumors. They combine an excellent physical depth-dose profile (Bragg curve) with an creased relative biological efficiency (RBE) in the target volume (Fig. 19).

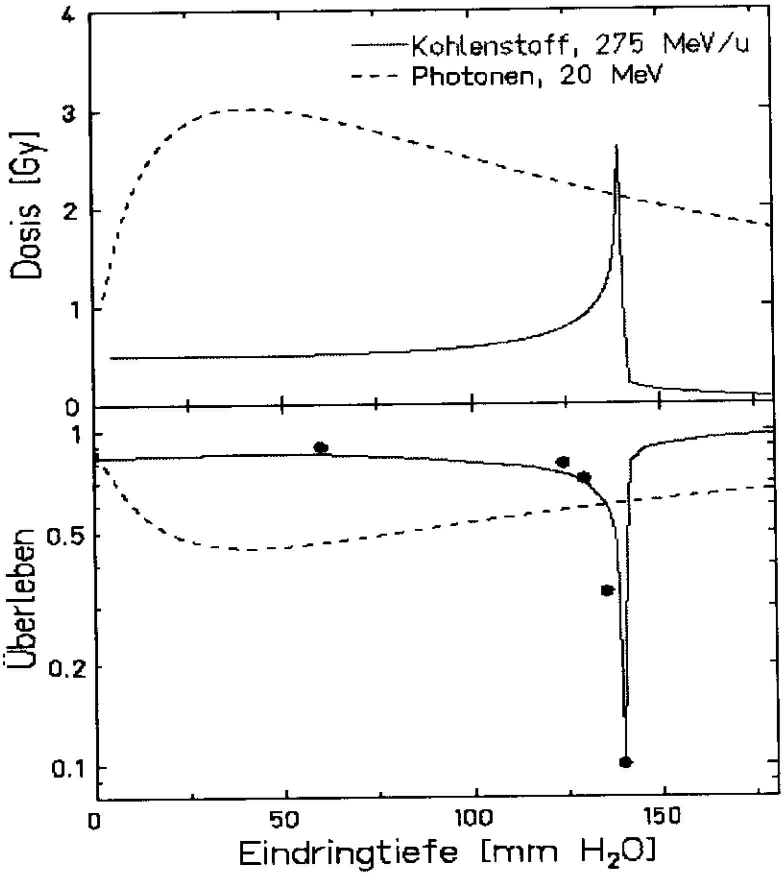


Fig. 19. Comparison of the physical dose distribution (upper dia-gram) and the survival rate of cells (lower diagram) as a function of penetration depth for ion and photon beams. The enhanced energy deposition at the end of the particle range and the corresponding dramatic decrease of cell survival show that heavy ion beams are excellent tools for the treatment of deep seated tumours.

The Rasterscan developed at GSI allows to eliver the dose in arbitrarily shaped target volumes with produced damage in the healthy tissue. The target volume (=tumour) is divided into slices of equal ion beam range. For the sake of clarity the picture shows only three of them, in practice there would be between 20 and 40. Each slice corresponds to a particular ion energy which is requested individually from the accelerator. Each slice is scanned in x-y direction by means of fast magnetic deflection - similar to a TV set. The intensity of the beam is controlled online by a set of ionization chambers together with real-time computer systems. Computerized reatment planning includes physical and radiobiological data obtained at GSI. The positron emission tomography (PET) allows an in vivo dose verification.

Tumours eligible for carbon ion therapy so far are mainly skull base tumours and tumours close to the spinal chord:

In December '97 the GSI heavy ion radiotherapy started with the irradiation of the first two patients.After a machine shut down of six months, two therapy blocks of 4 weeks each were available in 1998. In each therapy block 9 patients have been treated. The tumors were mostly located in the base of the skull. Target volumes up to 300 ccm were dissected into range layers of 2 mm thickness resulting in up to 120 isoenergy slices and up to 20.000 treatment pixels.

Analysis of the first two patients treated in December 1997 yielded an unexpected fast tumor regression although these patients received a boost of 5 fractions with carbon ions only. As a general conclusion it can be stated that the treatment of the first twenty patients with the intensity controlled rasterscan system went extremely well concerning the reliability of the accelerator, the precision of the dose distribution and online PET verification. In 1999 a total of 32 patients has been treated

This success supports the desire for a dedicated therapy machine, where carbon beams for treatment are available every day throughout the year. A proposal of a heavy ion treatment facility to be installed at Heidelberg has been completed and handed over to the minister for science and technology.

Beside different forms of radiotherapy medical applications use wide set of different radioactive isotopes for both therapy and diagnostic. Production of such isotopes requires well tested data on the corresponding reaction cross sections. Formation of recommended data libraries for medical application is a topical task, which now develop on the basis of intensive international collaboration.

There are no doubts that interest to nuclear data for medical applications will increase in the near future and there are no reasons to wait any decrease of such an interest during all 21st century.

Nuclear Data Needs for Nuclear Astrophysics

Nuclear astrophysics involves study of the synthesis of elements and the evolution of cosmic sites where such syntheses occur. Systems as diverse as the early universe, the interstellar medium, red giant stars, and supernova explosions are currently the focus of intense studies utilizing sophisticated computer models -- models which require large quantities of nuclear data as input. Measurements in the nuclear laboratory form the empirical foundation for the current models of element synthesis. These models require, in general, the rates of and energy released in nuclear reactions occurring in astrophysical environments. The rates are derived from laboratory measurements of cross sections of relevant reactions -- primarily fusion, transfer, and decay reactions -- convoluted with a thermal (Maxwell-Boltzmann) relative velocity distribution; the released energies of the relevant reactions (Q-values) are derived from measurements and calculations of masses. Additionally, models require information on properties of relevant nuclei, such as one- and two-particle separation energies, single-particle energy levels, level densities, partition functions, and parameters of resonances near particle capture thresholds.

There are a number of existing evaluations of nuclear data important for astrophysics:

1. **Stellar Nucleosynthesis Data** from the Tables of Reaction Rates for Nucleosynthsis: Charged Particle, Weak, and Neutrino Interactions, Version 92.1, by R.D. Hoffman and S.E. Woosley (1992).
2. **Reaclib Data** Tables of reaction rates based on F. Thielemann, et al., Adv. Nucl. Astro.,525(1987). 1991 updated version (updated to Z=46 in 1995 by Ch. Freiburghaus).
3. Smoker code calculations. A new update of REACLIB is coming soon.
4. **NACRE home page:** Reaction rates for charged-particle induced reactions (p-p, CNO, NeNa, MgAl chains, non-explosive hellium burning).
5. **Argonne National Laboratory Data**. Compilations of rates for specific reactions.
6. **Oak Ridge National Laboratory Data**. Caughlan and Fowler 1988 thermonuclear reaction rates, evaluated rates.
7. **Université Libre de Bruxelles Data**. Reaction and decay rates, level densities, Hauser-Feshbach rates, and partition functions.
8. **Fuller, Fowler, and Newman Weak Reaction Rates** for A=1 and A=21-60 (2.22Mb). Ap. J. Suppl. 42 (1980) 447; Ap. J. 252 (1982) 715; Ap. J. Suppl. 48 (1982) 279; Ap. J. 293 (1985) 1; Ap. J. 252 (1982) 741
9. **Weak Interaction Rates** for A=1 and A=17-39 (1.238 Mb), by T. Oda, M. Hino, K. Muto, M. Takahara and K. Sato, Atomic Data and Nuclear Data Tables, 56, 231 (1994)
10. **Thermal Neutron Capture Data**, gamma ray data and cross sections.
11. **T-2 Information Service Nuclear Astrophysics Data**, Nuclear Properties for Astrophysical Applications, by P. Moller, J.R. Nix, and K.-L. Kratz, LANL report LA-UR-94-3898 (1994),

However, most of these need updating to include recent experimental and nuclear modeling results. Furthermore, more complete, precise, and current nuclear data are required for a new generation of models (*e.g.*, multi-dimensional supernova codes, multi-zone calculations of inhomogeneous big bang nucleosynthesis) attempting to explain new astrophysical observations (*e.g.*, Supernova 1987a, light elements in the interstellar medium and on the surfaces of halo stars). Progress in many fundamental problems in nuclear astrophysics can be significantly aided by more effective utilization of existing measurements., complete compilations, and using nuclear reaction and structure models to extend existing measurements to unmeasured reactions, energy ranges, and isotopes.

This is especially true for a new generation of sophisticated models attempting to explain observations ranging from precision abundance measurements in meteorites to spectacular images from the Hubble Space Telescope and the Compton Gamma Ray Observatory. Launching a nuclear data effort to meet these needs would significantly enhance progress in many fundamental problems in nuclear astrophysics

Co-operation between the nuclear astrophysics and nuclear data communities in a nuclear data effort for astrophysics would minimize duplication of effort and enhance the potential for success. Additionally, co-ordination of such a data effort for nuclear astrophysics on a national scale would maximize the use of available resources and facilitate coordination with international efforts.

We endorse launching a co-ordinated effort to produce and disseminate critically important, high-quality evaluations of nuclear data for nuclear astrophysics. This effort can have a substantial impact on progress in a number of research areas in nuclear astrophysics. Because of the substantial overlap between astrophysics data needs and data community resources, it would be very beneficial to make this a co-operative venture between the nuclear astrophysics and nuclear data communities.

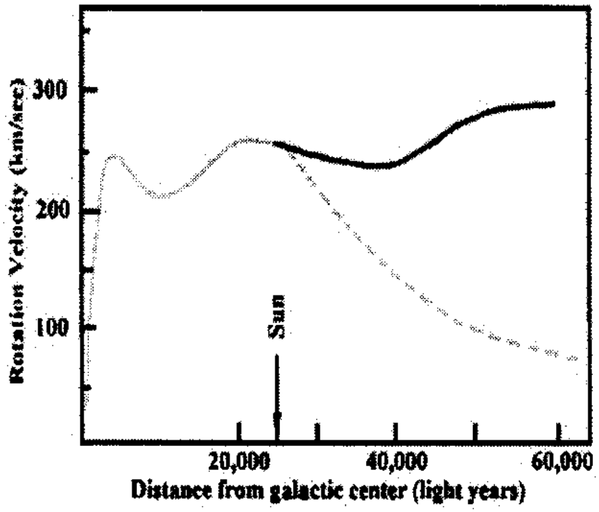
Perspectives of nuclear astrophysics in a solution of cosmology problems and study of Universe are so fantastic today that huge efforts required for a creation of accurate database seem quite justified.

Appendix

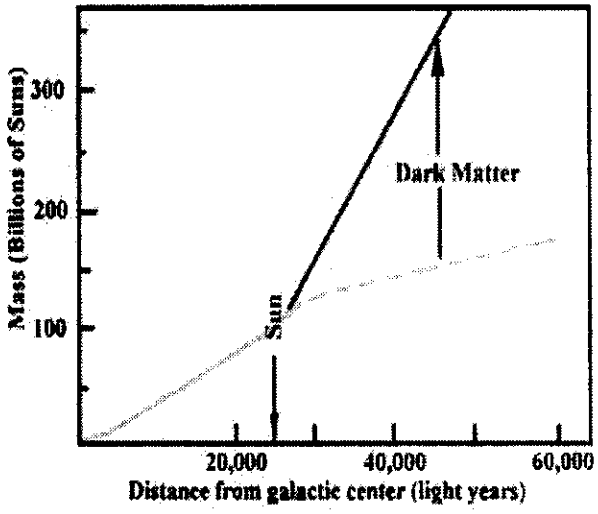
Dark matter

Nearly 50 years ago, Fritz Zwicky realized that clusters of galaxies consisted predominantly of matter in some nonluminous form. The search for dark matter has dominated cosmology for half a century. Precise measurements were obtained over 20 years ago, when dark matter was first mapped in galaxy halos. Only recently has the existence of dark matter over much larger scales than even galaxy clusters been confirmed.

The mass of the Milky Way can be estimated from the velocity of the Sun's orbit about the center of the Milky Way in the same way as a determination of the masses of the Sun and planets from the velocity of their rotation. Of course, there is one important difference: in the solar system, almost all the mass is concentrated in the Sun; but in the Milky Way, the mass is distributed in a bulge, disk, and halo, as illustrated below. In this case the net mass contained within a sphere of radius equal to the orbital radius of the star. (That is true because the force of gravitational attraction is only sensitive to the mass inside the orbit.) Since the mass of the Milky Way is spread out, the mass inferred will increase with increasing radius. This is illustrated in the two graphs below.



The rotation velocities of stars and gas in the Milky Way. The yellow dashed curve beyond the Sun's orbit represents the rotation velocities that could be explained by the mass of the stars alone. The red curve represents the actual velocities of the stars and gas.



The mass distribution in the Milky Way inferred from equation (1). The yellow curve represents the accumulated mass within a given radius. The net mass in stars (yellow curve) is several times less than the mass inferred from the rotation velocities. The difference between the mass in stars and gas and the total mass is called dark matter.

The solid curve on the left is called the rotation curve of the Milky Way. We can use the data of this to calculate the net mass of the Milky Way as a function of distance from the galactic center. The result is plotted in the curve on the right. This exercise gives a remarkable result: the mass of the Milky Way is several times greater than the sum of the masses of the visible stars and interstellar gas! We don't know what this matter is.

Astronomers call this unseen matter dark matter, and they call the ratio of dark matter to visible matter the Mass-to-Light Ratio (M/L). (More precisely, M/L is the mass of the system in solar units divided by its light in solar units. Thus, the Sun has M/L = 1.) The Milky Way has M/L = 5. Likewise, other spiral galaxies have values of M/L ranging from 5 to 50.

By exactly the same logic, astronomers can infer the masses of clusters of galaxies by measuring average random velocities and orbital distances of many galaxies from the center of the cluster. Rich clusters have even higher mass-to-light ratios than galaxies -- in some cases as high as M/L = 300. That fact implies that there is more dark matter between the galaxies in the clusters than there is in the galaxies themselves.

Another way to infer the masses of elliptical galaxies is to observe the X-ray emitting gas in the galaxy. Since this gas is very hot, it would naturally tend to expand and escape from the galaxy. But it doesn't because it is bound by the galaxy's gravity, which depends on the galaxy's mass. Therefore, by measuring the temperature and radial distribution of the X-ray emitting gas, we can infer the mass. Actually, the method depends on the same physical principle as the method of measuring random velocities of stars; the main difference is that we are measuring the random velocities of the atoms in the hot gas when we measure the X-ray temperature.

Up to now, the technique of measuring the masses of clusters of galaxies through their X-ray emission has been limited by the inability of X-ray telescopes to measure their images and spectra simultaneously. But that situation will improve very soon, with the launches of three powerful new X-ray telescopes: NASA's Chandra (July 1999); the European Space Agency's XMM (January 2000); and the NASA/Japan ASTRO-E (February 2000). These X-ray telescopes are far more powerful than their predecessors, so we can expect soon to know a lot more about the distribution of dark matter in clusters of galaxies.

The gravity due to the mass in clusters of galaxies can bend the light of galaxies behind the cluster. This gravitational lensing can magnify, distort, and produce multiple images of the background galaxy. By analyzing the distorted images, astronomers can measure the amount and distribution of dark matter in the cluster of galaxies. Observations of lensed galaxies may be the most powerful method that astronomers have for mapping the distribution of dark matter in clusters of galaxies.

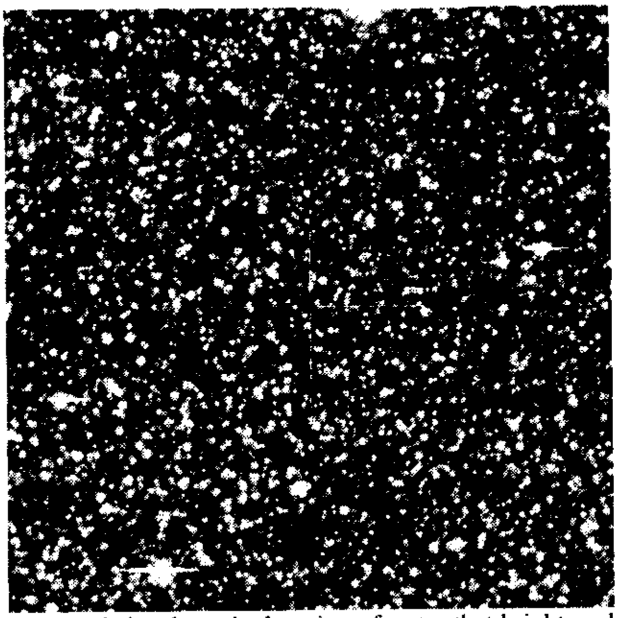
Dark Matter: MACHOS and WIMPS

In fact, more than 90% of all the matter in the universe is dark matter. What is this dark matter? That is one of the outstanding scientific questions of the day. What we do know is that the dark matter is terribly important: it not only holds the Milky Way together, it controls the evolution and fate of the entire universe.

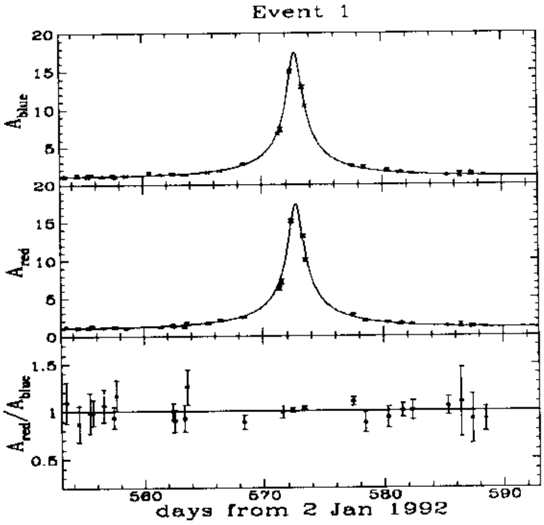
One idea is that the dark matter of the Milky Way might reside in the form of planets, brown dwarf stars, or even black holes. Not knowing what they are, astronomers call them MACHOS ("MAssive Compact Halo ObjectS). Even if such an object is invisible, there's a chance that we may detect one indirectly if it happens to pass nearly directly in front of a star. In that case, the gravity due to the invisible object can focus the light of the star, making its image brighten for several days. This focusing is called gravitational microlensing.

It is very unlikely that a macho will pass close enough to the line of sight to a star to make the star's image brighten appreciably. Therefore, to have a reasonable chance of catching such an event, astronomers must build a special telescope camera and computer software that are capable of continually monitoring the brightness of several.

Astronomers are confident that these events are due to gravitational lensing for two reasons: (1) the symmetric curve of brightening and dimming that you see in the upper right panel has the exact shape that was expected from the theory of gravitational lensing; and (2) there was no color change during the brightening event. The absence of color change rules out the possibility that the events are due to a sudden flare of the star. In fact, some stars do flare (for example, binary stars sometimes flare due to a mass transfer event), but the star's color always changes during a flare.



The cross hairs show the location of a star that brightened due to gravitational lensing by a "macho" that passed in front of it.



The light curves above show that the star brightened by a factor of about 17 over a few days and that there was no change of color during the event.

What are these machos? They are not normal stars. If they were, they would be bright enough to see. For a while, astronomers thought that they might be very faint red dwarf stars, but recent observations by the Hubble Space Telescope rule that out (see Search for Dark Matter). Another possibility is that they might be white dwarf stars; but it is very difficult to understand how there could be enough white dwarf stars in the halo of the Milky Way to cause as many events as have been seen. Right now, we don't know what they are.

Can the machos account for the dark matter inferred from the rotation of the Milky Way? We're not sure. According to best estimates today, if the objects responsible for the observed microlensing events are invisible massive objects in the halo of the Milky Way, their net mass is less than the mass of the dark matter by about a factor of 0.5. But these estimates still have substantial uncertainties.

Astronomers are now building more powerful telescope systems that should be capable of detecting many thousands of microlensing events, and they hope that such observations will provide the crucial clues to answer these questions.

Another popular idea is that the dark matter of the Milky Way might be diffuse matter (some kind of gas). But astronomers have extremely sensitive techniques for detecting ordinary matter (made of the known elements) in gaseous form by looking for its emission or absorption at radio, infrared, optical, ultraviolet, or X-ray wavelengths, and they have searched hard to find such gas in the halo of the galaxy. Indeed, they have observed gas of ordinary matter in the galactic halo, but its density is far less than required to account for the dark matter that we know must be there. Therefore, if the dark matter is in gaseous form, it can't be ordinary matter. Perhaps it is some kind of nearly invisible matter such as neutrinos or some other kind of subatomic particle, as yet unknown. The generic term for this speculative new form of matter is WIMPS -- Weakly Interacting Massive ParticleS. Physicists have built very sensitive experiments to try to detect WIMPS, but they haven't seen anything yet.

We don't know what this dark matter is. But here, we see that the dark matter is everywhere, not just in the Milky Way. As you will see, the amount and distribution of dark matter controls the evolution of the universe -- not only the development of galaxies in the universe, but also its ultimate fate. Therefore, understanding the nature of the dark matter is one of the most important questions in all science.

The only reason we know it's there is that we can see the effects of its gravity. People have spent a lot of money and effort to build ultra-sensitive detectors that might detect the dark matter, but no luck so far. Better review dark matter. Here's a good place: Dark matter.

Possibilities to learn dark matter will increase essentially within the next few years. The MAP satellite will produce much more precise measurements of the fluctuations of the CMB than we have today; and ground-based programs such as the Sloan Digital Sky Survey will provide much more detailed and extensive maps of the distribution of galaxies in the universe. Likewise, the Hubble Space Telescope and several new 8- to 10-meter telescopes will give us a much better view of the very distant universe, at a time when the galaxies and clusters first formed; and powerful new X-ray telescopes such as AXAF and XMM will give us a much better picture of the distribution of the hot gas between the galaxies.

Taken together, these new observations will provide much more rigorous tests of our present picture of the universe. Will the present picture hold up under such scrutiny? Who knows?. If history is any guide, there will be some surprises. We'll have a bit of a mess on our hands. That's what makes science wonderfull!